Investigations into the Segregation of Heaps of Particulate Materials with Particular Reference to the Effects of Particle Size

by

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Abstract

The object of the research programme forming the basis of this thesis has been to provide an improved understanding of the significance of principle variables that determine the propensity that a particulate solid bulk material will segregate. In spite of its ubiquity, and economic significance, segregation of bulk solids is a misinterpreted and vaguely understood phenomenon. An extensive literature review has been undertaken to establish different areas within industry where segregation has proved problematic. The literature review has related segregation and mixing terminology and helped to integrate and collate the current level of understanding of segregation. This review also established that the most productive way forward for enhancing knowledge was to undertake an experimental study into an area that focused on heap segregation and related fields. To achieve this two specially designed rigs were constructed which allowed independent control of variables that were widely documented as affecting the magnitude of material segregation produced when single point charging in plane-flow and conical vessel environments.

Analysis of video footage has provided an increased understanding of the heaping process. Perceived mechanisms of segregation and a recognition of their change in priority during the heaping process has been integrated with reported segregation mechanisms documented in literature. An enhanced and more detailed description of the heap segregation process is presented. It has been recognised that there is a significant facet of segregation behaviour that exists at the point where the vertical charging feed contacts the heap surface. This behaviour increases the severity of a 'hump' pattern that is produced within the vicinity of the heap apex. An embedding mechanism has been identified and attributed to the significant appearance of this behaviour. The significance of this mechanism has not been reported in existing literature and as such has not been incorporated into any predictive techniques used to model heap segregation of this form. Test conditions were configured that successfully removed this behaviour, which allowed the derivation of an empirical technique that successfully modelled segregation patterns being produced in a plane-flow vessel environment. Furthermore, existing predictive techniques published in literature are shown to accurately model the profiles of segregation produced for test results that were devoid of the 'hump' profile. A statistical appraisal of these segregation results was also undertaken that validated the hierarchy of principle particle, process and geometrical variables listed in literature and also provided added information on the significance of their interactions. Test work conducted that vertically filled a plane-flow vessel more commensurate with industrially relevant applications is also presented. Further work is recommended before specific conclusions can be stated regarding the influence that principle variables have on the resulting magnitude of the 'hump' profile produced.

The most important outcome of the work has been the development of a technique that can predict the profile of segregation produced in a conical heap formed under identical conditions to that produced in a plane-flow vessel. There is a significant difference in segregation profiles produced in both vessel geometries. This has been attributed to differences in surface area that the charging feed material is presented with as it descends across the surface of the heap and a model has been successfully developed based on this notion. Providing a relationship between these two vessel environments is of industrial relevance as materials are predominantly stored in a conical geometry as opposed to a plane-flow vessel environment synonymous with the majority of published literature on the topic.

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Author's Note

This work has not been accepted in substance for any degree, and is not concurrently submitted for any degree other than that of Doctor of Philosophy (PhD) of the University of Greenwich. The work presented in this thesis is the sole and original work of the author, except where stated otherwise by acknowledgement or reference.

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CHAPTER 1

INTRODUCTION

1 Introduction

Ever increasing advances in technology has lead to a subsequent increase in the requirements and capabilities of process plant. Amongst other things, this increased burden on process plant arises from a need to handle ever-increasing quantities of particulate material in a variety of powder and granular forms. Particulate materials range from cement, coal, foodstuffs, chemical fertilisers, plastics and minerals at the high volume, low value end of the scale to pharmaceuticals, engineering ceramics and fine chemicals at the low volume, high value end of the spectrum. It has been estimated that at least one third by value and half by volume, of raw materials handled or produced by typical large process companies are in a particulate form.

Particulate solids are very seldom homogeneous in composition. They are often comprised of constituents that vary widely in particle characteristics. Such materials are often classified as being either free-flowing or cohesive in nature, the former being most at risk to the detrimental influence of a phenomenon known as segregation. Individual particles of a mixture that have different physical characteristics will experience mechanisms of segregation that initiate and dictate their differential displacement within a bulk assembly. An environment that permits the prevailing forces to induce such mechanisms of segregation will constitute the re-orientation and congregation of self-like particles of the bulk and hence induce a reduction in homogeneity of the bulk material being handled.

Materials that contain multi-constituent components are widespread and are processed through a wide range of system operations. Therefore, the potential scale and applicability of the segregation phenomenon is enormous. Such segregation can have wide-ranging implications on product quality and efficiency of process operations as well as affecting the economics of production across a wide spectrum of industrial applications. Since much expenditure, effort and time is put into producing a material to an appropriate standard, common sense suggests that great care should be taken to ensure that mechanisms of segregation are restricted in their actions and, therefore, do not decrease product quality to below an acceptable level.

1.1 The Definition of Segregation

Segregation is the name in common usage that is given to the separation of particulate material comprising of single or multiple constituents that differ in physical and/or chemical particle characteristics. The environment in which the particulate material is being handled or processed gives rise to the regime of flow of the mixture. This regime of flow influences possible segregation process, which in turn, dictate the type(s) and extent of segregation mechanism(s). The final segregated mixture is conspicuous by some kind of ordered arrangement of the constituents of the bulk material, the extent of which is dictated by the magnitude of different characteristics of the constituent particles and segregating environment.

1.2 The Manifestation of Segregation in the Workplace

Opportunities for segregation to occur in process plant are as widespread as the methods in which bulk materials are handled. Processing and handling a free-flowing bulk material as a whole, or in part, will, at some stage, comply with the criteria required to initiate segregation of the material. Processes or unit operations that induce the detrimental influence of segregation within such plant can be classified in two categories:

- Segregation in terms of influencing the quality and suitability of the final product:

  In cosmetic or foodstuffs industries, the appearance of the mixture is usually required to be of visual consistency. The required solubility of products such as detergents, or drugs that are formulated as a mixture prior to ingestion, must be achieved. In terms of foodstuffs, there must be the appropriate savoury/sweet smell or taste sensation of the product as well as the correct proportions of ingredients to effect the required cooking process. The consequences of segregation in food stuffs can be quite severe when the segregating ingredient is at low concentration, but has a crucial type of activity or a special nutritional value. Fluctuations in density can result in variations of volumetric packaging systems based on the density of non segregated material. Chemical reaction rates can be affected by either an absent or an insufficient amount of the required active ingredient. In addition, product rejection will result if the final produced item has no active ingredient or is out of specification for the requirements of the process.

  Segregation will dictate the packing arrangement of particles of the finally produced mixture. Often, much time and effort will have been expended to select the required size and shape distribution of particles in order to maximise a mixture with a highest possible packing fraction. This is imperative, for example in industrial applications such as ceramics, pharmaceuticals, detergents, magnetic media, batteries and explosives etc. In these circumstances, the efficiency of the process operation relies on achieving close packing arrangements that maximise the amount of solids per unit volume. Desired packing fractions being sought are difficult to achieve and maintain a direct result of segregation when handling such mixtures. Much work has been undertaken on understanding the complex packing arrangements of multi-constituent particulate materials differing in particle characteristics. This work was attempted in the pursuit of achieving the most efficient packing arrangement of particles of a mixture. A review of literature pertaining to this subject area can be found in Section 4.3.2 and Appendix A.2.

- Segregation in terms of influencing the potential problems of handling the material within process plant:

  This can influence process efficiency, safety and influence costs of different component parts of the total process operation. Inconsistent or erratic flow of material between and within constituent parts of a process, because of segregation, may influence process performance, breach quality control guidelines, and cause inaccuracies in projected production rates. Segregation causing the accumulation of small particles can result in inconsistencies of contents of a packaging process. Accumulation of dust can lead to quality control problems or in excess quantities can stretch or extend the capabilities of dust extraction systems. Excess quantities of such dusts might also heighten a potential dust explosion problem. These can result in plant malfunctions or breaches of health and safety issues.

There are innumerable areas of processing, handling or component parts of a production process that induce material movement. Examples of these include stockpiling, charging and discharging ships, rail and road containers, as well as storage vessels such as hoppers, bins, silos and bunkers. In addition, there are also examples of plant transportation such as, pneumatic, vibration, screw, en-masse, belt and bucket conveyors as well as material transfer points. Furthermore, utilising fluidisation as a means of drying products or sintering of materials to engage chemical reactions are all possible segregation environments for materials that differ in particle characteristics. Any one of these component processes or handling operations is essentially a potential environment for the instigation of the segregation phenomenon.

1.3 Documented Detrimental Accounts of Segregation

Carson et al. [1], Goodwill et al. [2] [3] and Johansen et al. [4] are examples of the many authors who have provided numerous documented examples of the detrimental causes of segregation emanating from the many diverse areas of industry where free-flowing particulate materials are handled. Examples are:

- Size segregation of constituents of a chemical reagent proved problematic when charging an electric furnace. Coke and lime were fed to the furnace via a surge bin, which effected funnel flow of its contents on discharge. Initial discharge into the furnace resulted in decreased bed porosity, and increased frequency and severity of explosions. [1]
- Dose variations and dissolution rates for capsules produced from a standard design of capsule-filling machine were attributed to segregation and overmixing problems of the five capsule constituents. This was resolved by altering the method of mixing and inducing mass flow discharge of the surge bin contents into the capsule filling stage of the process. Consequently, dose variation of the capsule's active ingredient was reduced, and the correct proportions of all the

constituents in each capsule allowed a quicker dissolution rate of the pharmaceutical preparation to be achieved. [4]

- The fluidisation mechanism of segregation was documented as being responsible for the inconsistency of a pharmaceutical tabletting press. As a direct result of this mechanism, the small particulate active ingredient became concentrated in a layer at the top of the bin being charged via a dense phase pneumatic conveying system. This resulted in major inconsistencies in tablet composition throughout the duration of a production run. [1]
- A plant manufacturing metal strip by the cold-rolls compaction method suffered density fluctuations, strip separation and breakage's resulting in substantial loss of production. Losses in production were attributable to size segregation of materials discharged from hopper transfer cars used to feed material to the rolls compactor.[2]
- Size segregation of foodstuff ingredients resulting in cooking fluctuations of a baking process. Serious quality control problems were experienced due to non-uniform amounts of ingredients being found in certain batches of baking mixture. The air-entrainment and fluidisation mechanisms of segregation in handling operations were attributed to the excessive accumulation of non-critical elements of the baking mixture. [2]
- The in-plant transfer of alumina discharging from a flat bottomed centrally charged silo into rail cars resulted in certain rail cars containing excessive amounts of small particles. This rendered the material out of specification and created problems in downstream processes. The air-current mechanism of segregation upon silo charging was attributed to the excessive amount of small particles being present on final discharge of the silo. [2] [3]
- A well-mixed phosphate rock, coke and silica mixture was fed down an inclined chute. This fed three storage bins that were, in turn, used to feed separate regions of a phosphor-producing furnace. The sieving-percolation mechanism proved responsible for segregating the material as it travelled along chutes between the three bins. Hence, non-uniformity of material constituents in the three bins reduced process efficiency. [1] [3]

The deleterious results of segregation highlighted by these examples, are indicative of most published in the literature and is often the underlying reason for the instigation of investigations into the phenomenon. In this context it is important to realise that the examples of segregation documented above were as a result of different mechanisms of segregation that can manifest themselves when processing or handling particulate solids. The recognition, definition and review of these different mechanisms of segregation by authors who have published relevant literature are explained in more detail in Chapter 3 of this thesis.

1.3.1 Desirable Consequences of Segregation

Fortunately, for all the bad press that segregation receives, there are some industrial applications that pursue desirable aspects resulting from this phenomenon.

- Segregation is often enhanced in order to improve permeability or to help control gas flow distribution in blast furnaces.
- Performance of sintering operations could be improved if segregation of certain sinter constituents was enhanced. Fujimoto et al. [5] and O'Dea and Waters [6], documented that inefficiencies of a sintering process occurred when the sintering reactions proceeded insufficiently in the upper layer of a sinter bed due to poor heat distribution. To counteract this detrimental affect, segregation of some added smaller carbon particles within the predominantly large particulate sinter-ore mixture feed was promoted. Increased population of carbon particles in the top half of the bed helped homogenise heat reaction and create a heat balance across the whole sinter bed. A significant contribution to furthering segregation knowledge has been made by authors investigating segregation associated with sintering operations. Consequently, this particular application is documented in more detail in Section 3.1.4.2.

1.4 The Formulation of Investigative Working Bodies

It has been suggested that approximately half of all materials utilised in the world are derived from, or are in the form of, particulate solids at some stage in their production. Furthermore, the 'notoriety' of segregation being widespread throughout many differing industrial sectors has led to segregation being the subject of much investigation. Due to the process of segregation being extremely complex, its study has crossed the boundaries of traditional disciplines. Expertise has been sought from chemical, mechanical and civil divisions of engineering disciplines as well as physicists, mathematicians and statisticians from pure science disciplines. Recently, more industrialised countries, who recognise the potential ramifications of this phenomenon, have formed investigative working bodies, an example of which is the Working Party on the Mechanics of Particulate Solids (WPMS) of the European Federation of Chemical Engineering (E.F.ChE). Members of these parties consist of professionals who are knowledgeable in a variety of the aforementioned disciplines. Task forces such as these have been established to aid the solution of industrial problems and provide education to engineers in industry of advances being made in the field. The British Materials Handling Board has recently produced a 'User Guide to Segregation' [7] and is a recent example of an outcome of one such initiative.

1.5 Thesis Outline, Motivation & Aims of Research

From the aforementioned problematic aspects of segregation published there is a need to enhance the understanding of factors influencing segregation. Therefore, the aims and objectives of the work undertaken and reported in this thesis are as follows:

- To address and standardise the fundamental principles of segregation and clarify the relationship with mixing technology. At present there appears a disjointed level of understanding on segregation published in literature emanating from the various facets of industry in which it appears.
- To provide a brief overview of various environments in which segregation occurs. However, as shown in subsequent chapters, this thesis does not attempt to address all the issues of segregation but will focus primarily on one area that is continually being documented as causing a significant problem to industry. The area in question relates to gravity induced single point charging of stockpiles or storage vessels. This area encompasses the heap segregation process that is highly prevalent in a variety of industrial unit operations.
- The research policy adopted for this project has been to systematically investigate, by experiment, the significance of variables that influence segregation of particulate materials in a heap-forming environment relevant to industrial applications. The use of small 'bench-scale' testing facilities has been avoided since it has been shown that scaling certain variables, when applied to industrial sized bulk handling systems, cannot be reliably undertaken.
- This research is aimed to further equip engineers with an improved understanding on how to eliminate/reduce segregation in a form that could be used to tackle industrially related losses in process efficiency and product quality.

In order to quantify the influence a particular handling or process operation has on influencing particulate material segregation it is a pre-requisite to have a prior knowledge of mixture quality. Segregation's affiliation with mixing therefore forms the basis of chapter 2 and provides information on mixture types, mechanisms of mixing, mixing terminology and measures of mixture quality. The work of previous researchers from a variety of academic and industrial sectors together with current industrial practice that deals with segregation is reviewed in chapter 3. This approach led to the identification and selection of the most significant segregating environment to investigate and the principle variables that contribute to segregation of this type. This information, together with the criteria for selection and characterisation of a suitable test bulk material are presented in chapter 4. Recognition of the segregation environment most relevant for investigation, the known hierarchy of related segregation variables and bulk material characterisation information led to the design and construction of a full scale experimental testing facility; this is the subject of chapter 5. Validation of the reported hierarchy of prominent segregation variables was simultaneously undertaken during the work carried out to commission the test facility. This work helped refine understanding of segregation when stockpiling or filling a storage vessel, the findings of which are presented in chapter 6. Undertaking the work reported in chapter 6 allowed the formulation of the overall experimental plan for the investigation. This involved separating the main experimental programme into three areas. The first was to investigate segregation behaviour of mixtures where the feed is introduced into a plane-flow vessel at an angle parallel with the repose angle formed by the heap of material; this is the subject of chapter 7. The second area was to investigate segregation behaviour of mixtures that are charged vertically into a plane-flow vessel, which is more relevant to industrial filling applications. Findings from undertaking this work are presented in chapter 8. This approach formed the basis of comparison for the results obtained from a substantial part of the study where the same principle variables that induced segregation were used for investigating an environment where a conical heap was formed. This is the subject of chapter 9. A predictive technique, which permits profiles of segregation in a plane-flow heap to be projected to an equivalently built conical heap has been devised and is also included in this chapter. As a consequence of various points to emerge from undertaking the three stage experimental programme, conclusions and recommendations for further work are presented in chapter 10.

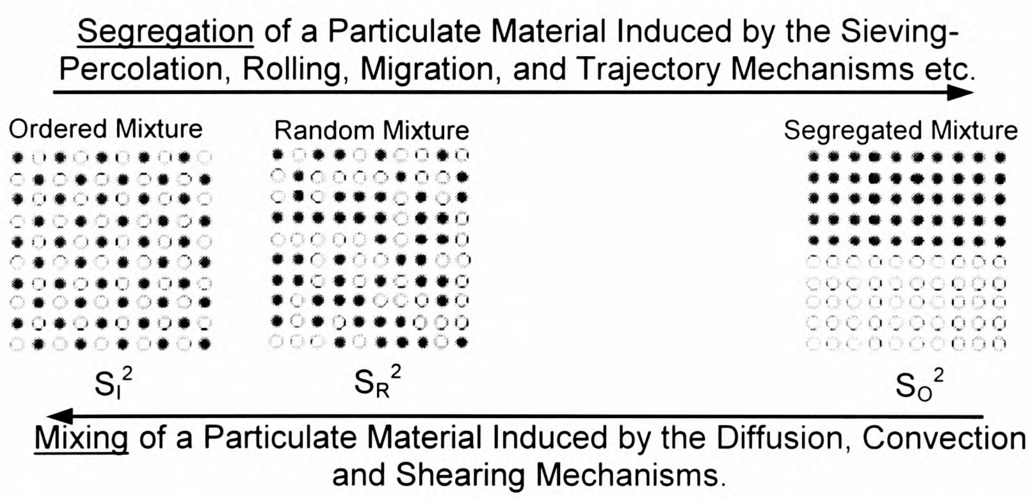
CHAPTER 2

RELATIONSHIP BETWEEN SEGREGATION AND MIXING

2 Relationship Between Segregation and Mixing

Within the area of bulk solids handling, segregation and mixing behaviour of materials are often closely related. Indeed, a multitude of techniques employed to counteract segregation are often applicable to techniques that homogenise or mix materials that are, initially, in a separated form. To quantify the degree of segregation a material has experienced during a process or handling operation requires emphasis of two areas. Firstly, it is imperative that characteristics of the mixture are recognised. Secondly, there is the need to make an assessment of the state of mixture quality prior to passage though the process or handling operation. Therefore, if segregation is to be quantified with any degree of accuracy it must be addressed with a knowledge of classifying the type of mixture being segregated and also the state of mixedness prior to experiencing mechanisms of segregation.

Segregation and mixing are, by definition, distinguishable in their actions of influencing a mixture to move between two extremes that define mixture quality.



S_I^2, S_R^2, S_O^2 Statistical variances developed that describe theoretical mixture qualities.

Figure 1 Mechanisms of Mixing and Segregation that Induce an Equilibrium Position of Mixture Quality between Two Extremes.

The equilibrium position is dictated by the magnitude of differences of constituents of the mixture and suitability of the mixer to the mixing process. Although one is the inverse of the other, mixing and segregation terminology and the environment in which each performs is closely related. For example, the action of a mixer is to reduce inhomogeneities of mixture composition i.e. it engenders a reduction in both the scale and intensity of segregation of the mixture ingredients. (The definitions of these terms are documented in Section 2.3 of this thesis). However, the mixer is very often thwarted in its a attempt to randomise particles of the mixture by the reverse action of segregation. It is evident from a review of the literature pertaining to mixing and segregation that the mechanisms and the environments in which both exist are comparable and prevail under similar circumstances. The performance of a mixer is often quantified as the speed at which the mixer can bring about the equilibrium position of mixedness. This position is reached when segregation tendencies equal mixing tendencies of the material and denotes a limit to the quality of mixing that can be achieved with the specific mixer being used. Due to the environment required to facilitate the mechanisms of mixing, it is virtually impossible to initiate mixing of the material without inducing some detrimental segregation.

It is important to recognise that the type and extent of a mixing mechanism is dictated by the flow characteristics of the mixture. Due to their propensity to segregate, the method of mixing free flowing materials is more problematic than that of cohesive materials. This therefore warrants initial classification of different mixture definitions and the clarification of mechanisms of mixing. It is considered essential to understand mechanisms of mixing and their relationship with the flow characteristics of a mixture, prior to undertaking an in depth investigation of the phenomenon of segregation.

2.1 Classifications of Particulate Material Mixtures

A particulate mixture can be defined as the formulation of a material where the particles have a disparity in a specific characteristic. The formulation of such mixtures is often pursued to effect a desirable visual, flow or chemical reaction behaviour brought about by the formulation of the constituents of the mixture.

A particulate mixture can be classified in any of the following forms:

1. A single constituent mixture varying in one or more particle characteristics.
2. A multi-constituent material where one characteristic of the particle is identical.
3. Various connotations of 2. ranging from one to all particle characteristics being dissimilar.
4. A multi-component material where no particle characteristics are identical.

The composition, concentration and magnitude of the differentiating characteristic properties of constituent particles will dictate the classification of the mixture. Harnby [8] provided a concise layout of the classifications of such mixtures according to the interaction of particles with their neighbours, Figure 2.

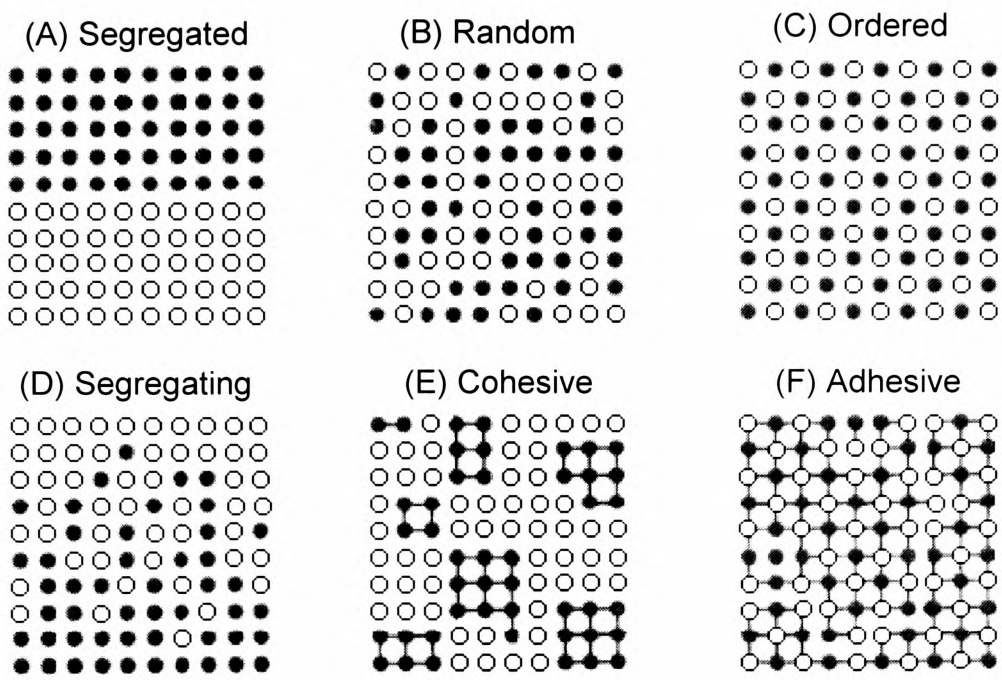


Figure 2 Schematic Representation of Mixture Structure Classifications [8]

The definitions of how particle characteristics dictate the type of mixture formulated and its resulting susceptibility to the influence of mixing and segregation can now be clarified.

2.1.1 A Free-Flowing Particulate Mixture

This mixture type encompasses many of the mixtures that are handled and processed in industrial applications. The absolute size of mixture particles is generally greater than approximately 500μm and to inhibit cohesive tendencies any constituent particle size should be greater than approximately 100μm. The gravitational force associated with large particles is far greater than any possible restraining interparticulate forces and therefore the individual particles retain their freedom of movement with respect to each other. This freedom of movement can initiate segregation due to differences in properties of mixture constituents. If measures are not implemented to alleviate segregation during the mixing and segregating process, Figure 2(d), the material, on a severe scale, can completely separate Figure 2(a). The time taken to progress to a completely segregated state is dependent on the dominance of the influencing segregating characteristic. Examples of particle characteristics which dictate how free-flowing a particulate material is, include, absolute size of the constituent particles and the presence of inherent or surface moisture.

2.1.2 A Cohesive Mixture

A cohesive mixture can be defined as the resistance of a bulk solid to shear at zero compressive normal stress and relates to interparticle attractive forces. When the absolute size of some or all of the mixture constituents is reduced to a critical size, (approximately. 100μm) the interaction and behaviour of particles with their neighbours change. As the particle size decreases and falls below this level, various interparticulate forces can potentially dominate the potential movement of a particle from its neighbour and can contrive to retain a structured arrangement. This may be problematic if the mechanism of mixing does not overcome the cohesive structure of the mixture. This inhibits an individual particle from having an opportunity of relocating itself.

Harnby [8] documented detailed analysis of interparticulate forces associated with cohesive mixtures. For the purposes of mixing and segregation, there are essentially three types of inter-particulate forces commensurate with the classification of a cohesive mixture.

1. Forces due to electrostatic charging.
2. Van der Waals' forces.
3. Forces due to moisture.

As the cohesivity of the particulate material increases still further with a reduction in particle size, the mobility of all particles of the mixture, irrespective of their size, is also greatly reduced. Assuming satisfactory mixing has been achieved, subsequent handling or processing of mixtures of the classification will inhibit the detrimental influence of segregation.

When analysing cohesive mixtures with respect to the criteria of scale and intensity of segregation, it is often considered that for a large scale of scrutiny, the scale and intensity of segregation will be deemed small, thus indicating a high degree of mixedness. However, if a small scale of scrutiny is selected there could well be regions where high degrees of intensity of segregation are measured. The implications of utilising the appropriate scale of scrutiny for a specific situation are discussed in Section 2.3.

2.1.3 An Ordered Mixture

An ordered mixture, as illustrated in Figure 2(c) is the theoretically best quality mixture attainable. Any sample withdrawn from the mixture will have exactly the same composition. Similarities of mixing and segregation mechanisms coupled with handling the mixture ensures that the formation of an ordered mixture of this kind is almost impossible to achieve. Therefore, it is recognised that the goal of a mixing operation is to facilitate a lesser quality randomisation structure of a mixture.

2.1.4 A Randomised Mixture

The majority of industrially available mixers aspire to achieve a randomised state of mixture quality, as represented by Figure 2(b). This classification of mixture is defined as the probability of a sample containing the given component being the same at all sampling positions in the mixture and is equal to the proportion of that component in the whole mixture. For a given mixer, the mixing process is usually slower but the final equilibrium position of mixture quality within the two boundary conditions as shown in Figure 1 is much higher.

2.1.5 An Adhesive Mixture

Mixtures of this type are often comprised of differing constituents. Wet mixing is often employed to naturally inhibit the mechanisms of segregation associated with the interparticulate movement of a mixture. The definitions and environments in which this mechanism exists are outlined in Section 3.5 of this thesis. This classification of mixture type has been investigated by Barbosa-Canovas et al. [9] who documented that it is widely utilised within the foodstuffs industry in the formulation of food powder mixtures. Particle sizes significantly larger than 100μm are often used when formulating adhesive mixtures. Adhesive mixtures are defined as mixtures where small particles are absorbed or are attached to the surface of larger particles (often moisture induced), thus losing their ability to move independently, and hence change position in the powder bed. The method of inducing this classification of mixture is often referred to as coating [8]. One could interpret that the structures of both the random mixture, Figure 2(b) and adhesive mixture, Figure 2(f) are similar in arrangement. However, the differentiating factor lies in the fact that for randomised mixtures, the surfaces of the particles do not interact. With an adhesive type of mixture as shown in Figure 2(f) it is possible to approach closely, but not achieve fully, an ordered state of mixture. This is because any movement of a large particle will take with it an attached smaller particle.

2.2 Mechanisms of Mixing

Classifications of different mixture structures is recognised by mixer manufacturers who tailor specific mixer designs to induce the most appropriate mechanism of mixing for the particular mixture under consideration. A substantial amount of groundbreaking work was undertaken by Lacey [10] on types of mixing mechanism. These can essentially be classified into three broad definitions. Analysis of these mechanisms suggests that the regime of flow described that induces mixing is similar to that required to initiate segregation of the mixture:

- Diffusive Mixing: The environment, which initiates this mechanism, occurs when individual particles of the bulk have the opportunity to randomly disperse themselves when moving over a newly developed surface. If a particle can move independently of its neighbours within this mixing environment, preferential movement of particles dictated by differences in particle characteristics can give rise to segregation tendencies e.g. small particles can pass through the surface layer.

- Shear Mixing: The environment, which initiates this mechanism, occurs when slip zones are established in a material, thus allowing the interchange of individual particles between adjacent layers. As per diffusion mixing, differences in particle characteristics such as size and density can determine preferential transfer of particles between shearing layers.
- Convection Mixing: This mechanism involves movement of groups or clusters of particles from one region of the mixture bed and displacing them to another location. The scale of this movement is dictated by the vigorous nature of movement initiated by the mixer. As this mechanism does not incur individual particle movement, it can be considered generally less prone to the affects of segregation.

In terms of flow characteristics of materials, diffusive and shear mechanisms will induce both mixing and segregation of the material when handling free-flowing particulate materials differing in particle characteristics. The mixing of cohesive materials is more accommodating to any of the three stated mechanisms of mixing as a consequence of interparticulate bonding, thereby reducing their tendency to segregate.

It would be beneficial to promote cohesion of mixtures when handling and processing materials as it would subsequently inhibit segregation tendencies. However, increasing the cohesion of materials subsequently incurs problems of consistently and efficiently handling materials of this type.

2.3 Statistical and Qualitative Measures of Mixture Quality

Essentially, the arrangement of constituents of a mixture at any stage, in any mixing or segregating process, will lie between two boundary conditions of an ordered, or segregated state of mixedness. Overmixing as a result of excessive mixing time can lead to a lower equilibrium position of mixture quality between the two boundary conditions. These boundary conditions were shown previously on Figure 1. There is a recognised optimum period of mixing in order to achieve the highest possible quality of mixture, beyond which, the quality reduces to an equilibrium position where the influences of mixing are counterbalanced by those of segregation. This optimum period of mixing is due to mechanisms of mixing predominating compared to the detrimental influences of segregation. The equilibrium position of a mixture is dependent on the magnitude of differences between mixture constituents, the type and performance of mixer employed to effect mixing and the duration of mixing. It is therefore a common misconception to assume that mixture quality always improves with increased mixing time and all the variations in mixer type are equally suitable for all requirements of mixing.

It is often common practice to utilise statistical techniques to establish the state of mixedness of a particulate mixture prior and post experiencing the influences of segregation. In order to assess the mixedness of a material, samples are often taken from the bulk material, the statistical analysis of which is widely used to typify the bulk mixture quality. However, the statistical experimental variance obtained from these samples is of little value if a quantitative assessment is to be made. This is because the theoretical limiting conditions of mixture quality under investigation must also be determined. For a typical binary mixture, it is possible to determine the theoretical limiting variance values for an ordered mixture arrangement, S^2_{I}, randomised mixture arrangement, S^2_{R}, and a totally segregated mixture arrangement, S^2_{O}, as shown on Figure 1. This gives a theoretical indication of the best possible quality of mixture one could hope to achieve. As previously documented in Section 2.1.3, the attainment of a randomised mixture is the pursuit of most mixers used in industrial environments. The theoretical values of variance representing different binary mixture arrangements have been developed further to encompass two component multi-sized particulate mixtures [11] and also multi-component, multi-sized mixtures [12]. It is claimed that these values have the potential of determining the affect that altering the size distribution of ingredients has on the theoretically best attainable mixture quality. This theoretical approach for determining the best possible quality of mixture for a given situation has allowed various mixing indices to be derived. These indices allow the quantitative measurement of the mixedness of the mixture to be obtained by comparing values of variance obtained from sampling the mixture with the theoretically determined limiting variance values of the mixture being analysed. The applicability of using such statistical techniques has been called into question by Rollins et al. [13]. This author has published a critical evaluation of the accuracy of employing such techniques based on the form of statistical theory used that utilises the variance values of a sample. The author suggests disregarding the current types of statistical approaches in determining mixture quality in favour of an analysis of variance technique, details of which can be found in Section 3.9.2 of this thesis.

When designing or evaluating a process or handling operation that involves some mixing or segregation of constituents of the material, there is a need to assess mixture composition. Terminology used to describe the qualitative assessment of mixture quality produced from such operations was proposed by Danckwerts [14] [15] and are found common place in many diverse industries concerned with mixing and segregation of particulate materials.

- The Scale of Segregation

  The scale of segregation is a measure of the size of unmixed, totally segregated regions within a mixture. It therefore follows that the smaller the scale of segregation the better the quality of mixture being analysed. In terms of flow characteristics, cohesive type mixtures have small scales of segregation due to the inhibition of individual particles to move relative to one another. Conversely, free-flowing materials can exhibit large scales of segregation due to the preferential mixing and segregating movement of individual particles.

- The Intensity of Segregation

  The intensity of segregation encompasses all other regions of a mixture being analysed that are not totally separate regions of individual constituents. For these remaining regions, the intensity of segregation is the measure of the concentration of the constituents in these regions. The intensity is not dependant on the size of these regions, but more a reflection of the extent to which the concentration deviates from the mean of mixture constituents in regions in which they are present. As with the scale of segregation, a low value represents a better quality mixture. The derivation of this term is more tailored to the mixing and segregation of fluids. With respect to fluids, the intensity does not depend essentially on the size of the regions, but on the extent to which one component has been diluted by another. Although derived for fluid type mixtures, this does not negate this terminology being utilised as a representation of the assessment of particulate solid materials.

Often the simplest procedure to determine the scale and intensity of segregation is to take a number of samples from the mixture and apply a technique of a statistical nature in order to gauge the mixedness of the mixture. The scale and intensity of segregation are qualitative measures of the mixedness of the mixture. As the intensity and scale of segregation are reduced by the action of the mixer, a critical point is reached when the mixer has mixed the contents satisfactorily to meet the requirements of its intended use. Proceeding with mixing after this point has been reached is not necessary. The concept of this point of criticality is deemed the scale of scrutiny at which the mixture should be analysed. The identification of the scale of scrutiny for a product fixes the size of the sample to be taken in order to determine the scale and intensity of segregation of the mixture that signifies the quality of mixture. When the intensity and scale of segregation have been reduced by the process of mixing to a value commensurate with the volume of the associated sample dimension, further reductions in scale and intensity of segregation are not ascertainable as they are limited by the dimension(s) of the sampling mechanism/device.

- The Scale of Scrutiny

  The scale of scrutiny is a measure of the level of examination for assessing mixture quality. This measure can be defined as the limit of size of regions of segregation in the mixture under investigation that would classify the mixture as being out of specification for its intended use. The scale of scrutiny set is unique to the size of the regions of segregation that can be tolerated by the process in which the mixture will be used. For a particular application, the decision on the scale of scrutiny selected should only be made by consideration of the use to which the mixture will be put. This decision must be made by considering the mixtures allowable variation from the mean composition and the frequency with which this variation may be exceeded. These criteria may be stipulated by legislation or specified by standards. The concept of the scale of scrutiny does focus attention on the importance of identifying the weight, volume or area of mixture that should meet a pre-determined standard of quality. This is of paramount importance within the pharmaceutical industry where very small scales of scrutiny are selected to comply with the statutory requirements that ensure the minor active component is homogeneously dispersed within the bulk.

2.4 Concluding Remarks on Mixing and Segregation

- Essentially, cohesive and adhesive mixtures are the only characteristic mixture, which inhibits independent movement of particles, and thus reduce the influence of segregation in a mixing process.
- For free-flowing materials, the mechanisms of mixing and segregation, generally, cannot be separated for a majority of handling and process operations undertaken within a powder-handling system.
- The final quality of mixture will be influenced by the mechanisms of both segregation and mixing, but it is the challenge of the mixer to limit the mechanisms of segregation in favour of mixing ones.
- One cannot classify a segregating or non-segregating mixture according to the flow characteristics of the mixture itself.

As documented by the work undertaken by Rollins et al. [13] there are numerous mixing indices available. The selection of one may, in principle, present a value of the measure of the degree of mixedness, which has fluctuated in its measurement for reasons other than segregation, as described in Section 3.9.2. In general, it should be feasible to apply a mixing index to quantify the degree of de-mixing or segregation that a mixture has experienced on passage through a process operation. However, there has been an increase in research into mechanistic approaches associated with segregation. These are used to quantify segregation based on mechanisms of the segregation phenomenon. Indices of this kind are introduced and critically reviewed in Section 3.9.1. Such mechanistic based indices have cast aspersions on the applicability of utilising statistical mixing indices as a means of quantifying segregation in bulk solids handling systems.

CHAPTER 3

LITERATURE REVIEW

3 Literature Review

Physicists have long been accustomed to dividing matter into classifications of gases, liquids and solids. Granular materials, however, show a number of easily observed phenomena (e.g. arching, segregation, pressure distributions etc) that are immediate manifestations of properties not exhibited by conventional classifications. Granular materials therefore, cut across these pre-defined boundaries and behave in a manner different to that observed in all other classifications. Of the literature available, much research effort has been conducted on the flow and equilibrium properties of granular materials in order that improvements in design of equipment employed for handling such materials can be made.

As outlined previously in Section 1.5, the majority of segregation problems reported in published literature, pertain to the handling and process operations that utilise some form of storage or material holding vessel. An understanding of the regimes of flow and environmental conditions, which facilitate mechanisms of segregation when charging and discharging such vessels show that segregation behaviour is essentially similar in nature. Despite its wide-ranging application to various facets of modern industry, limited research has been produced that describes this form of segregation to an extent where it can be controlled or eliminated for industrially relevant mixtures. This seems to be somewhat at odds with the importance that this area of research has, in terms of the immense variety and scale of products that are handled in such a way.

Undertaking the literature review highlighted that the majority of investigations into mixing/segregation of free-flowing particulate solids could be categorised into two distinct regions of analysis:

- Analysis of the pattern of segregation of constituents of a mixture in a vessel which has been subjected to rotation or vibration for a known period of time.
- Analysing samples at various locations in a flowing powder stream or an assessment made of segregation from withdrawing samples from different positions within a vessel that has been charged with a mixture.

3.1 How Processes Induce Different Regimes of Flow

An industrial process will initiate a regime of material flow, which, in turn, provides an opportunity for segregation. This process will influence the number and extent of segregation mechanisms that result in producing the pattern of segregation of the mixture. It is an initial requirement therefore to establish the regime of material flow that these industrial processes impress on the mixture being handled or processed. Once this has been addressed, then the processes of segregation associated with these regimes of flow can be classified. Subsequently, the number of mechanisms functioning in a segregation process can then be established. This methodical breakdown of segregation in terms of regimes of flow, processes and mechanisms allows the systematic assessment of the requirements of a predictive technique and applicability to a process operation. An example of this approach, which forms the focus of this research, is given below:

- Industrial Process: ⟶ Vessel Charging
- Regime of Flow: ⟶ Gravity Induced Centre-Point Charging
- Process of Segregation: ⟶ Heaping
- Segregation Mechanisms: ⟶ Percolation, Migration, Rolling etc

A particulate material will often be subjected to numerous process and handling operations. It has already been stated in Section 1.5 that the main emphasis of this investigation is to focus on segregation associated with stockpile formation or vessel charging, where the gravity charged regime of flow induces the heap segregation process. However, a full understanding of segregation behaviour in this area does not provide a complete understanding of the wide-ranging appearance of this phenomenon. To review literature pertaining to this area alone would eliminate a substantial proportion of available literature that provides valuable information on the segregation behaviour associated with different regimes of flow. It is therefore appropriate to include a description of segregation associated with different regimes of flow in order to provide a complete understanding of the potential for segregation.

3.1.1 Fluidisation

A large number of industrial process operations such as carbon combustion, mineral processing, mixture heating, drying and waste recovery etc are undertaken utilising the benefits commensurate with fluidised bed technology. However, the movement of individual particles under the influence of the fluidising gases does create an environment that allows segregation of the material to be sustained. Sometimes segregation is openly pursued and is the objective of the fluidisation process. However, when fluidised beds are used as chemical reactors its occurrence is not always appreciated. Segregation resulting from minor differences in particle characteristics of the constituents can result in significant patterns of segregation.

3.1.2 Vibration-Induced

Segregation under the influence of vibration will cause two mechanisms to interact, one inducing the large particles to float upwards, the other inducing the small particles to sink downwards.

- Vibration induced into a binary mixture can cause agitation of the particulate structure that induces voids to appear in the bulk in which the small particles can percolate downwards through the mass

- This vibration can also initiate a particle migration mechanism, sometimes referred to as a displacement [16] or stratification mechanism. The same driving force of vibration is present. This force influences the larger or denser particles of the mixture to migrate upwards towards the surface of the mixture bed. Williams [17] defined this mechanism as being due to a large or denser particle having the ability to cause an increase in pressure on the region immediately beneath itself and thus stop itself from moving downwards. Any upwards movement of the particle is not restricted and as a result, any rise in the large particle will vacate a space which is preferentially replaced by the smaller or lighter descending particles.

Experimental validation of this philosophy has been provided by Fiske et al. [18] who investigated size segregation of binary mixtures equal in density. These were packed into different geometry columns and subjected to varying magnitudes and duration's of vibration.

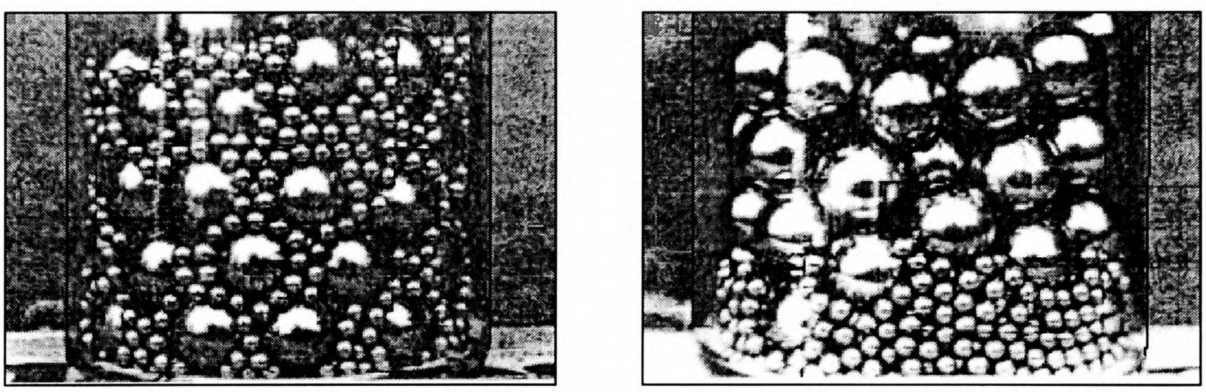


Figure 3 Complete Size Segregation for a Binary Mixture Influenced by the Vibration-Induced Regime of Flow. [18]

Figure 3 shows a binary mixture of chrome-plated steel balls that has completely segregated. The mixture, which had a size difference of four to one, was vibrated at a frequency and amplitude of 7.5 Hz and 15mm respectively for a duration of 30 seconds. It has been postulated that a mixture could be formulated whose segregation tendencies, because of size, could be cancelled out by differences in density to produce a non-segregating mixture under this regime of flow. However, this has yet to be proved. Further information on the interaction of size and density characteristics can be found in Section 3.7.4.1. Vibration induced segregation can be classed as a regime of flow in its own right in the absence of any other applied external forces. However, it often occurs (in the form of background vibration) within other regimes of flow and has an influence on the resulting pattern of segregation. This regime of flow is often observed in transport containers such as, sacks, big bags IBC's, etc. It may also present itself in rail, lorry, ship containers etc. The presence of this affect is often conspicuous by the appearance of large or dense particles at the particulate material surface.

3.1.3 Pneumatic Conveying

When employing air as the conveying medium to transport free flowing particulate solids, segregation of mixtures can often be prevalent when charging storage vessels in this regime of flow. Segregation of the charged material can occur if provisions are not made for removing the air from the conveyed mixture on entry to the vessel, or venting displaced air in the vessel is not taken into consideration. Two mechanisms associated with this regime of flow will cause segregation of particles within the vessel. These mechanisms are conspicuous in their actions by producing two different patterns of segregation, which flourish because of the large volumes of air associated with pneumatic conveying. Johanson [19][20] and De Silva and Enstad [21] have provided documented accounts of industrial situations where these two mechanisms were recognised as contributing to the segregation of a material.

3.1.3.1 Air-Current Mechanism

The method by which the conveyed particulates are introduced into the storage vessel will dictate the resulting pattern of segregation of particulates of the charging mixture. Inverse patterns of segregation, (small particles at the periphery of the vessel and large particles under the fill point) such as those documented by Arnold [22] [23] are typical of those created when experiencing segregation associated with this regime of flow. Furthermore, Johanson [19] has stated that even a belt conveyor used to charge a vessel may induce the air-entrainment mechanism of segregation into the charging material. Some examples of the patterns postulated by these authors can be found on Figure 25, Section 3.7.2.1.2. Carson et al. [1] reported that the potential for this mechanism to act is greatly enhanced when utilising mixtures whose constituent sizes are less than approximately 100μm and are charged into relatively tall vessels. However, whilst this may be applicable, the evidence provided by Fürll [24], Figure 4(a) suggests that larger particles might exhibit this behaviour. Figure 4 shows that when pneumatically charging storage vessels with a crushed grain particulate mixture of sizes significantly larger than 100μm, patterns of segregation attributed to the air-current mechanism is found.

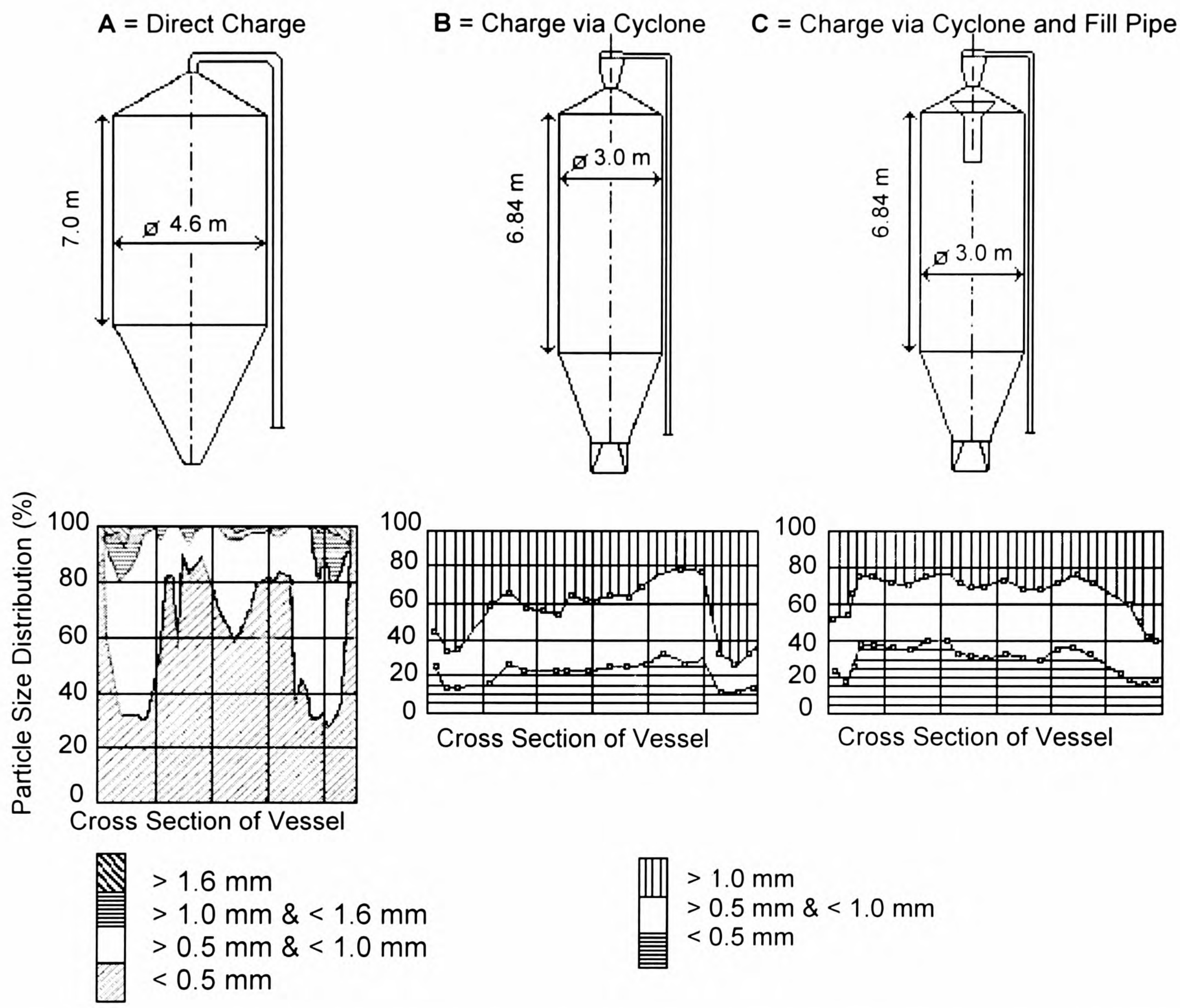


Figure 4 The Influence the Air-Current Mechanism has on Dictating Patterns of Segregation when Pneumatically Charging Various Vessel Configurations. [24]

As can be seen from Figure 4(a), single point, pneumatic charging of a crushed grain particulate material results in a pattern of segregation that boarders on the classification of a 'reverse segregation' pattern associated with this regime of flow. The entrainment of the particles in high-velocity air causes the charging air/mixture stream to enter the vessel and descend rapidly down from the charge point until contact is made with the heap apex of stationary material in the vessel. At this point the large or denser particulates of the mixture will fall out of suspension and embed in the heap surface, therefore accumulating under the fill point. The finer, less dense particles however, are entrained in the airflow that descends over the heap surface towards the intersection of heap periphery and vessel wall. At this point the velocity of the air is at its lowest and results in the small particles dropping out of suspension, thus accumulating at the heap periphery.

A cyclone separator as illustrated in Figure 4(b) is often used to detach the particles from the conveying air prior to charging the vessel and contributes to the reduction of segregation of this type. The cyclone reduces the velocity of the particulates of the mixture, which in turn reduces their ability to travel to the far reaches of the heap periphery. Fürll [24] provides further evidence, Figure 4(c), that feeding the discharged material from a cyclone directly into a 'filling pipe' will concentrate the charging mixture stream. This then provides a charging stream composition similar to that required to induce the mechanisms associated with normal gravity induced heaping process, thus resulting in a pattern of segregation more akin to the generally documented cases of vessel segregation.

3.1.3.2 The Fluidisation Mechanism

Carson et al. [1] report that small particulate powders generally have a lower permeability than large particles and, as a result, produce a distinctive pattern of segregation which differs to that described above in Section 3.1.3.1. If the required environment and elements are active to facilitate this behaviour, a charging stream of particulate material will descend inside the vessel until contact is made with the heap apex of previously charged material. At this point, the charging mixture will encounter a fluidised layer of small particles produced from the previously charged mixture. This fluidised layer envelops the entire heap surface. The large particles of the subsequent charging stream can penetrate through this layer and embed into the heap surface whereas the small particles remain captivated in the fluidised layer. This behaviour continues throughout the whole vessel filling cycle until charging has ceased. This then allows the fluidised layer to de-aerate, resulting in small particles settling out of suspension. Consequently, a vertical pattern of segregation of the vessel contents is produced conspicuous by a high concentration of small particles in the top part.

Emphasis has often been placed on recommending the design of a vessel that will discharge its contents in mass flow in order to take advantage of the benefits of such behaviour. One claimed benefit of mass flow discharge is its ability to discharge vessel constituents in similar proportions to those charged. It is claimed that this is achievable because there is flow across the whole width of the vessel upon discharge. However, if the charging mixture has suffered the mechanisms of fluidisation segregation, or the vessel contents have been sequentially batch loaded then the vessel material will comprise of segregated vertical layers of large and small particles. Employing mass flow discharge of vessel contents will not remix contents upon discharge. Further details of the claims of mass-flow discharge and its relevance to segregation can be found in Section 3.8.2.

3.1.4 Gravity-Induced

This regime of flow encompasses the majority of handling and process operations that are influenced by the action of gravity and forms the focus of this investigation. Within virtually all realms of industry, it is rare to find a process operation that induces whole bulk movement without incurring some gravity induced inter-particulate movement of bulk constituents.

3.1.4.1 Methods of Material Transfer

Segregation may manifest itself in various process operations, transfer operations or feeding devices i.e. bucket, belt, screw chute and en-masse etc. Movement of bulk material in these devices often makes advantageous use of gravity. Unfortunately, one side affect of utilising gravity in this way is that it also creates an environment in which mechanisms of segregation may be present. The mechanisms that regulate segregation in these areas of material transfer are further documented in Section3.5. These mechanisms, however, are essentially similar in nature to the mechanisms that encompass the segregation process of heaping when charging storage vessels, upon which this study is based.

3.1.4.2 Sintering Operations

As previously documented in Section 1.3.1, the phenomenon of segregation has been actively pursued in the area of sintering technology in order to effect the desired particle and chemical size distribution across the vertical height of a sinter bed. However, segregation is compounded by the slight cohesivity of the material, which in turn resulted in the formation of the sinter bed being highly influenced by the phenomenon of avalanching. To improve the performance of the sintering process, research by Fujimoto et al. [5] was directed into the area of segregation associated with the feeding devices of sintering processes in order to alleviate segregation associated with the avalanching process.

The subject of sintering warrants its own section in this thesis due to the valuable literature published on sintering operations that complement the regime of flow that initiates heap segregation. A considerable amount of relevant work of significance to heap segregation has been documented by Fujimoto et al. [5] and O'Dea and Waters [6]. This work has culminated in a significant contribution to understanding not only sintering technology but also heap segregation. As detailed in Chapter 7, work undertaken on theoretical modelling of segregation in sintering operations can be applied to the heaping process of segregation.

Fujimoto [5] reported on findings that suggested a common underlying trend was being experienced within sintering technology. The yield and productivity of large sintering machines were found to be much less than smaller machines. The maximum values of yield and productivity tended to decrease with the associated increase in sinter strand area of larger machines. These larger sinter strands required a higher feeding rate in order to maintain the most efficient height of sinter bed for the sintering process. Smaller sinter strands indicative of smaller machines required lower feedrates of the charging mixture to achieve the same bed height. The increased feedrate of the larger machine and the design of the device used to feed the sintering mixture onto the sinter strand influenced the resulting efficiency of the sintering process. The raw sinter mix was fed onto the sinter bed via a feeding device that induced significant avalanching behaviour into the sinter mix. The period and magnitude of avalanches was observed to increase with an increase in raw mix feedrate. The avalanches caused the small particles in the top layer of the pile to be uncharacteristically positioned at the bottom layer. Consequently, avalanching created a packing structure of the sinter bed that consisted of a vertical 'sandwich' like structure of interchanging small and large particle layers along the bed length as shown in Figure 5(a). The periodic width of the alternative layers of small and large particles approximately agreed with the period of avalanches. The higher the raw mix feed rate, the larger the periodic width of the alternative layers and the higher the magnitude of the avalanches.

It follows that the greater the duration for which the sieving-percolation mechanism can flourish the greater the segregation of the sinter mixture. However, the higher feedrates reduced the time available for the percolation mechanism to influence the resulting distribution of small particles in the sinter bed. The increased feedrate also increased the frequency of avalanching, which dictated the displacement of more small particles to the bottom of the sinter bed across the total length of the sinter strand. These were considered the two main reasons for reducing the efficiency of the large sintering plant in comparison to that of the small plant. The smaller particles deposited in alternative layers at the bottom of the sinter bed have a higher heat transfer coefficient from gas to solid than the large particles. Furthermore, the smaller particles have improved ignition capabilities, due to their increase in specific surface area to that of large particles. Avalanching and larger feedrates resulted in non-uniform heat distribution of the sintering reaction, which was insufficient in the upper layer and excessive in the lower layer of the sinter bed. It was felt that increasing the proportion of small particles towards the top of the sinter strand would increase the overall efficiency of the sintering process. A modification of the method of feeding in order to promote the normally observed segregation pattern commensurate with the heaping process in the absence of the detrimental affects of avalanching was attempted. To achieve this, the chute component of the feeding device was replaced by an 'Intensified Sifting Feeder' (ISF) [5]. This proved successful in promoting an environment that facilitated the mechanisms of the heaping process without the inherent detrimental affects of avalanching. The ISF design partially classified the material and dispersed the feeding stream evenly when charging it to the sinter strand.

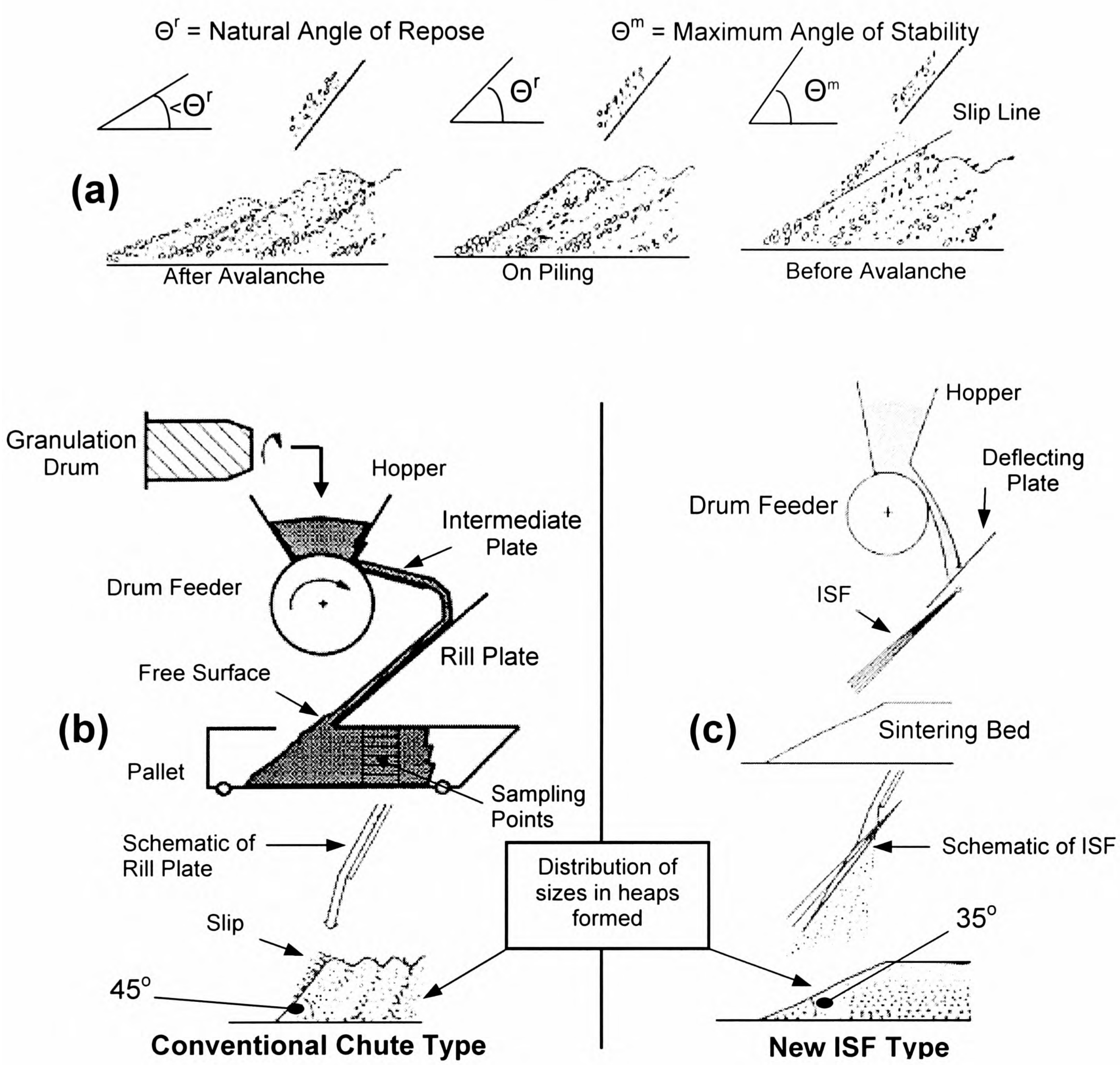


Figure 5 **(a) Avalanching Behaviour and Spread of Sizes. [5]**
(b) Conventional Method of Feeding Raw Sinter Mixture and Subsequent Distribution of Sizes in Heap Formed. [6]
(c) Improved ISF Method of Feeding Raw Sinter Mixture and Subsequent Distribution of Sizes in Heap Formed. [5]

The ISF feeder fed the sintering mixture in a manner that eliminated avalanching and hence stratification of the mixture. A significant degree of consistent size segregation across the vertical depth of the bed was achieved along the entire length of the bed. Enhanced segregation of the sintering feed mixture achieved an overall improvement in permeability and also heat and melt balances in the vertical direction of the sinter bed. Uniform sintering was accelerated and both the yield and permeability were improved. Documented efforts by O'Dea and Waters [6] [25] on modelling the segregation mechanisms associated with this regime of flow can be found in Section 3.9.3.5 and is of significance in the development of predictive modelling techniques.

3.1.4.3 Unconstrained Heap Formation

An experimental study of the packing density and segregation behaviour of coal resulting from stockpiling has been investigated by Standish and co-workers [26] [27] [28]. They suggest that the majority of industrial coal stockpiles are formed in the shape of elongated conical heaps. These are formed by single point feeding methods such as the example shown in Figure 6. This method of charging an unconstrained heap may, given favourable circumstances, produce a different pattern of segregation to the fixed single point method of stockpiling as shown in Figure 7. Fixed and traverse charging of unconstrained stockpiles can induce two segregating scenarios relating to the delivery of the charge material to the stockpile surface.

The first scenario concerns the charging of the heap in which the feed point is traversed horizontally in conjunction with the rate of heap formation. This is done in order to charge the front edge of the stockpile being formed. If the feedrate is sufficient, this regime of flow will produce a constant avalanching layer that descends one side of the heap being formed. When the avalanche has reached the heap periphery the onset of another avalanche is instantaneously achieved. As there is no intermittent avalanching of the stockpile, a cross-section taken along the stockpile length would reveal a segregation pattern resembling the heap formed in Figure 5(c).

Figure 6 **A Typical Method of Stockpiling Coal can Induce a Continuous Avalanching Layer down Across the Front Face During Heap Formation.**

The second scenario of flow concerns single-point fixed charging of an unconstrained heap. The feed that charges the heap is not constrained to flow down one side of the heap, as per Figure 6. The feed is free to avalanche down a preferential path towards the stockpile periphery. As a result a similar feedrate of charge that induced a continuos avalanching layer down the stockpile surface in Figure 6 would not be sufficient to maintain the same flow behaviour for a fixed point stockpile. Therefore intermittent avalanching of the feed material occurs and induces significant stratification and segregation of the feed mixture. It is therefore conceivable that a cross-section through a stockpile charged in this manner would reveal a pattern of segregation similar to that shown in Figure 5(b).

The pattern of segregation for an unconstrained fixed-point charged binary mixture stockpile is shown in Figure 7(a). The typical measured distribution of particle sizes sampled from the unconstrained formation of a stockpile of coal shown in Figure 7(b) is indicative of the distribution of particle sizes expected for an unconstrained heap of this kind.

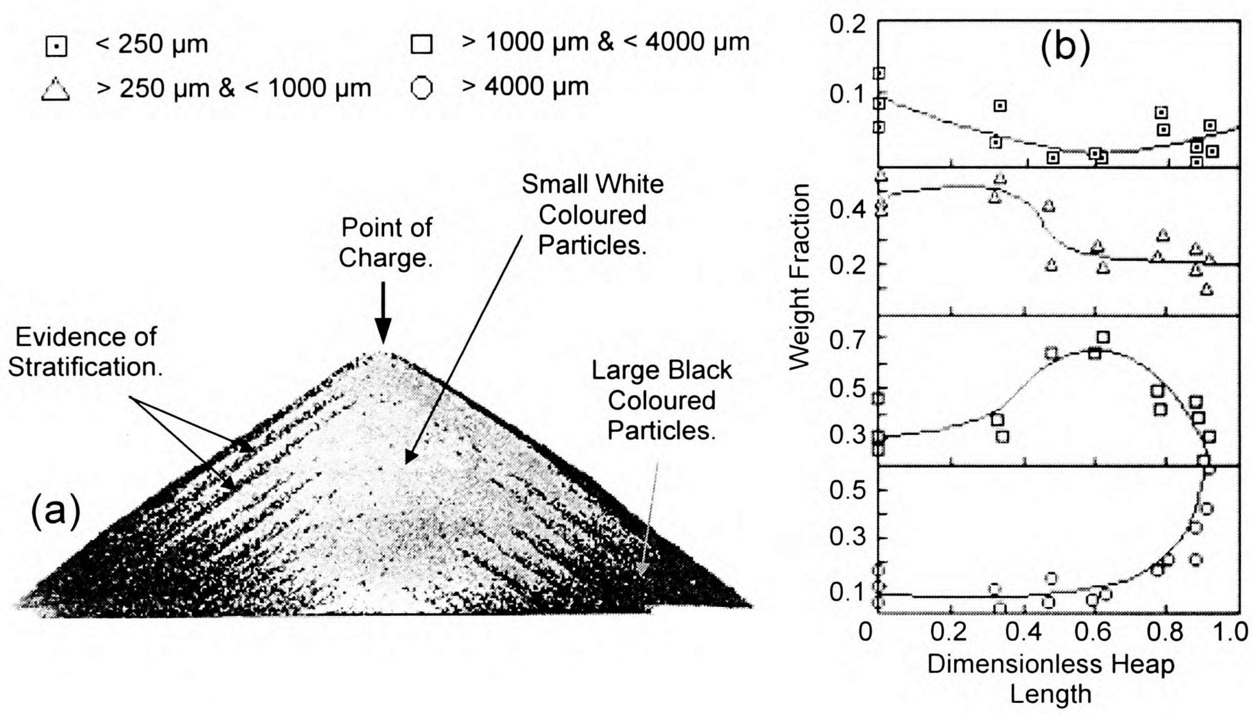


Figure 7 **(a) Typical Pattern of Segregation for an Unconstrained Binary Mixture Heap Shown in Cross-Section [29]. (b) Typical Distribution of Coal Sizes as a Direct Result of Unconstrained Heap Formation. [28].**

Both charging scenarios can induce stratification, however, scenario two is more likely to encourage any stratification tendencies of the mixture. Measurements of segregation as shown in Figure 7(b) are representative of what would be expected from analysing patterns of segregation associated with constrained heap segregation when charging storage vessels.

The appearance of an increase in small particles at the heap periphery, as shown in Figure 7(b), is due to the coal having approximately 8.5% moisture content. This moisture provided the necessary circumstances for the coal to form an adhesive mixture type (defined previously in Section 2.1.5) where the very small particles adhered to or agglomerated with larger particles and were subsequently transported to the periphery of the heap. Standish [26] reports that the results produced from the laboratory scaled stockpile, shown in Figure 7(b), compared favourably to those taken from an industrial sized stockpile. However, it is important to re-emphasise that care must be taken to recognise that the regime of flow for model experiments should mimic those of actual stockpile process conditions. In general, the segregation behaviour documented by Standish and co-workers [26] [27] [28] when investigating the stockpiling of coal will in principle, be applicable to all stockpile systems, irrespective of the granular materials involved.

Yu and Standish [27] compared results of fixed-point conical stockpiles with elongated stockpiles. The authors suggested that elongating stockpiles has little or no influence on packing density compared to fixed-point charging. This infers that both elongated and fixed-point stockpiles provide similar quantitative measurements of segregation although there is a clear difference in the patterns of segregation produced. This is possible if the feedrate is insufficient to instigate immediate successive avalanches when constructing an elongated stockpile. If this is the case then both methods of stockpiling will be subjected to heap segregation that includes intermittent avalanching, as defined in Section 6.4.

The appearance of stratification of constituents of the mixture in Figure 7(a) is evident in some but not all cases of heap segregation analysed. Postulations as to its sporadic occurrence and preliminary modelling of the stratification of constituents, conspicuous during the heaping process has been attempted by Makse et al. [30]. Stratification is related to the separation of the mixture constituents into separate layers' normal to the direction of the avalanche, which is an indicative part of the heaping process when charging storage vessels. Preliminary results of this published work has been evaluated in Section 3.9.4.2.

3.1.4.4 Constrained Heap Formation When Filling Vessels

Changes in particulate material quality from utilising storage vessels for holding materials prior, during and post processing/handling operations was discussed qualitatively by Reed [31]. The author's findings are typical of published literature that refer to the affects of segregation encountered throughout various facets of Industry. Patterns and mechanisms of segregation are similar to those encountered for the flow regime when charging single-point unconstrained stockpiles, as documented previously in Section 3.1.4.3. However, the differentiating factor for constrained heap formation concerns the vessel walls, which arrests movement of avalanching layers and hence 'freezes' the pattern of distribution of small and large particles in the avalanching layer at that point.

Examination of Figure 7(a) indicates a definite demarcation of constituents of the mixture. This separation is initiated by the mechanisms of segregation that encompass the heaping process commensurate with the gravity-induced regime of flow. If sampling of the heap shown in Figure 7(a) was conducted, then the distribution of mixture constituents would be comparable to those in a vessel as documented by Standish [32]. Here, the author investigated the segregation of ternary sized mixtures of ore and coke that are commonly handled in the iron-making industry. Sampling and analysis of segregation of these materials was achieved by filling the charged vessel with water and freezing its contents. After removing the frozen contents, samples were extracted at different positions in the material mass, melted, and subjected to a standard laboratory screen analysis.

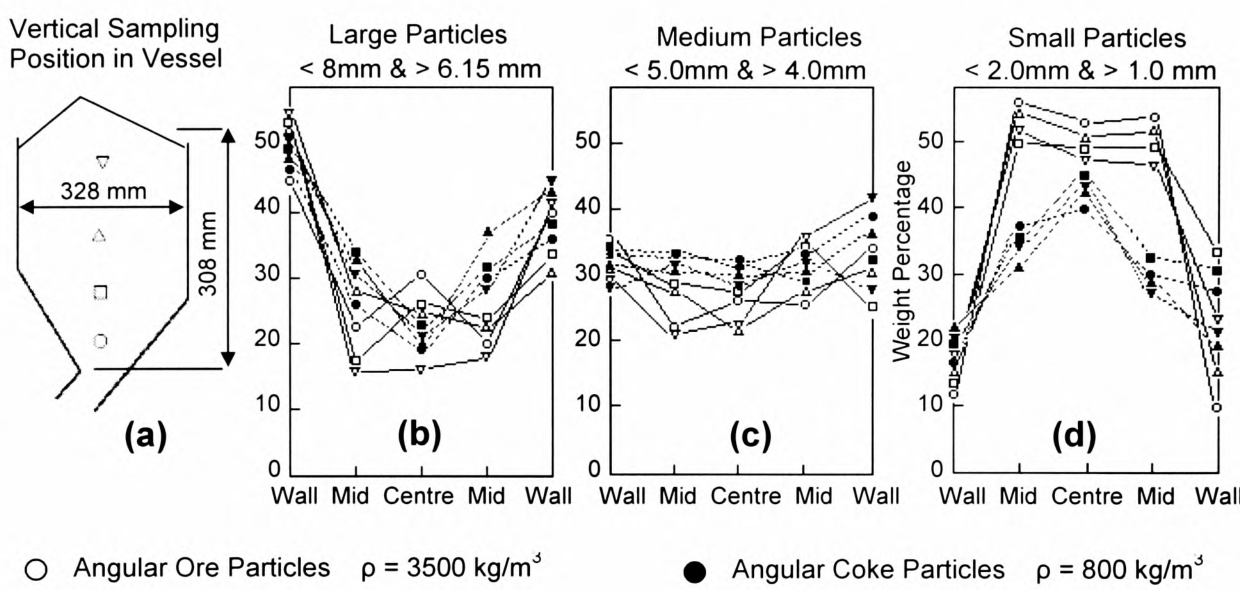


Figure 8 Pattern of Segregation Commensurate with the Gravity Induced Single-Point Regime of Flow. [32]

Separate test trials of Ore Mixture and Coke Mixture segregation were conducted, which are both shown in Figure 8. The slight non-symmetric geometry of the test hopper was necessary in order to mimic the geometry of the blast furnace feed hoppers under investigation. However, this geometry of vessel does not invalidate analysis of the resulting pattern of segregation of the charged contents. The pattern of segregation produced in this geometry was characteristic of the majority of patterns found when gravity, single-point charging standard vessel geometries. The mechanisms of segregation associated with the heaping process essentially caused small particles to accumulate under the fill point and large particles to accumulate at the walls of the vessel. The number and influence of the mechanisms of segregation that caused this distribution are considered in detail in Section 3.5. It can be seen from Figure 8 that the ore material segregates less than the coke material under identical test conditions. This maybe attributed to the combined influence of the free fall height of the charging material and its interaction with differences in material density. This interaction is only one example of many that can dictate different patterns of segregation. Detailed analyses of various combined interactions are documented in Section 3.7.4.

3.2 Focussing on Appropriate Area of Investigation

As highlighted in Section 3.1, segregation can occur during many process operations. The considerable amount of segregation literature available is symptomatic of the enormity of the segregation phenomenon. Carson et al. [1] has published findings that agree in principle with those made by Johanson [20]. Carson states that more than eighty percent of the segregation problems encountered in solids handling and storage systems are due to the sieving-percolation, angle of repose, fluidisation, air-currents and trajectory mechanisms of segregation. Furthermore, analysis of a variety of literature suggests that the natural gravity induced movement of materials is the underlying reason why the majority of process and handling operations experience detrimental segregation. Williams [17] reported that the process of segregation in which the majority of mechanisms of segregation thrive was the heap segregation and is the most frequent and serious cause of size segregation. It appears that the majority of segregation problems reside in heap formation resulting from the mixtures passage through a storage vessel or a material holding section of a process.

Given the 'evidence' from respected authorities in the field this suggests the focus of any investigation would be best served looking at heap segregation. It is suggested that initial mixtures for investigation should be comprised of particulate solids that differ in particle size and, in addition, the mixture should be charged under the influence of gravity into a storage vessel. At present, there is a lack of an industry standard working tool to tackle the phenomenon of segregation under these circumstances when handling free flowing particulate materials. Therefore, one goal of the investigation is to establish a means of quantifying this phenomenon based on utilising standard engineering practices.

3.3 Circumstances that Exhibit Heap Segregation

Examples of heap segregation are generally dictated by flow regimes created in various handling and unit operations comprising processes. The regime of flow associated with heap segregation takes place in a variety of operations:

- Charging of storage vessels
- The formation of stockpiles
- Discharge of storage vessels
- Material flow down an inclined chute
- Charging sinter mixture into a sintering operation
- Mechanical means of material transfer between unit operations of a process

A similar environment that exhibits heap segregation tendencies is the surface of a mixture that is subjected to a rotational movement such as in a mixer, drier or kiln. The manifestation of the heaping process in such differing forms of process plant operations directs attention to the commonality of the flow regime that exhibits the heaping segregation process. The common flow regime that exists within all the aforementioned process or handling operations is the avalanching of a flowing layer that descends across the surface of a static heap. Unit operations such as sintering induce a continuously avalanching flowing layer of material whereas with single-point vessel and stockpile charging, the flowing layer movement exists mainly due to the existence of intermittently occurring avalanches. A concise account of literature that reviews the subject of avalanching pertaining to heap segregation is given in the next section, whereas results of research undertaken on the phenomenon are reported in Sections 6.4 and 6.7.

3.4 Avalanching

Avalanching is a classification of a behavioural flow pattern that occurs within heap segregation and has received only fragmented attention in published literature on the subject of heap segregation. Avalanching allows an intermittently sustainable environment to be created that facilitates some of the more recognised mechanisms of heap segregation.

The phenomenon of avalanching has been investigated by Brown et al. and Creasey [33] [34] with the aim of characterising the rheology of coal blends according to their avalanching behaviour. Both authors report that the formation of a pile of solids is akin to a system which is said to be in a state of self-organised criticality. This implies that a heap of solids remains in a marginally stable state until disturbed by the addition of further material from the charging feed stream. This gives rise to a local increase in the gradient of the heap until a critical state is reached and collapses by issuing an avalanche. This avalanche occurs until the heap is again in a marginally stable state. The fluctuation of heap gradient between the two marginally stable states is shown on Figure 5(a). The duration of each avalanche may be small, so that it progresses only part way down the slope. Conversely, depending on its momentum, it may continue unabated until it reaches the heap periphery or wall of a containing vessel.

The coal blends selected for investigating avalanching behaviour were deemed representative of extremes of good and poor handling materials. Experimental data generated was graphically analysed by producing a plot that was generated as follows. Sequential pairs of avalanche masses measured from the apparatus (W_n, W_{n+1}) were plotted. Thus, if avalanche masses were represented by W1 W_2 W_3 etc. the first co-ordinate would be (W_1, W_2), with the second being (W_2, W_3) and so on. The resulting data points were linked by joining successive points with lines to create the plot. This enabled the qualitative assessment of the avalanching nature of the material.

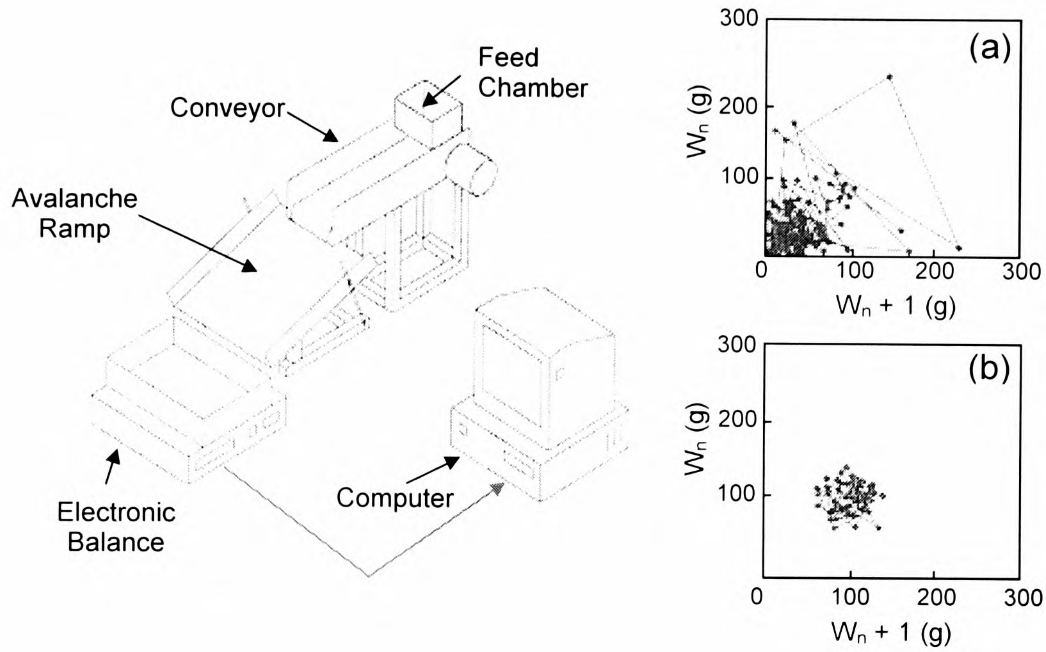


Figure 9 Test Apparatus Used to Measure Avalanching Behaviour and Resulting Plots of Structures for Good and Bad Handling Coals. [34]

As can be seen from Figure 9 the two distinct behaviours that characterise a good or bad handling coal are highlighted by the differences in the plots shown. On analysis of the plot, a qualitative assessment of the level and repeatability of the avalanching nature of the material could be made. If a coal blend has good handling characteristics then it will be conspicuous by having constant, regular and predictable avalanching and would thus produce a plot that is equidistant from both axis, Figure 9(b). It is claimed that when the highly condensed regions of low weight avalanches on the plots were expanded, the patterns observed possessed the same structure as that of the larger weight avalanches. This, the authors claim implies that statistical self-similarity or self organisation of the avalanching process is occurring and that there is some degree of scaling of the interacting forces causing the phenomenon. An assessment of the avalanching potential of a material by this procedure gives an indication of the potential free-flowing nature of the material, a behaviour in which heap segregation thrives. Therefore, this practical procedure for determining the handling characteristics of coal in terms of avalanching is, by inference, a possible method for determining the potential propensity that a material will segregate when exposed to heap segregation.

Jaeger and Nagel [35] undertook a review of literature associated with behaviour of avalanching as part of a publication that focussed on geometry of packing, vibrations and flow of particulate solids. They concluded that the motion of particles within the avalanching layer involved a balance of gravitational forces connected with particle inertia and friction forces resulting from dissipation. Many of the theoretical models reviewed by the author are based on a completely over-damped situation; that is, the friction term far outweighed the inertia term. However, their experiments indicated a regime of flow where the two terms were of comparable magnitude. Experimentation to determine the avalanching behaviour of a granular material was often undertaken using a number of different experimental configurations, Figure 10. The principle aim of the work was to form a pile of material, where the slope approached and extended beyond the natural angle of repose formed. This was undertaken in order to investigate the steady-state behaviour of the material.

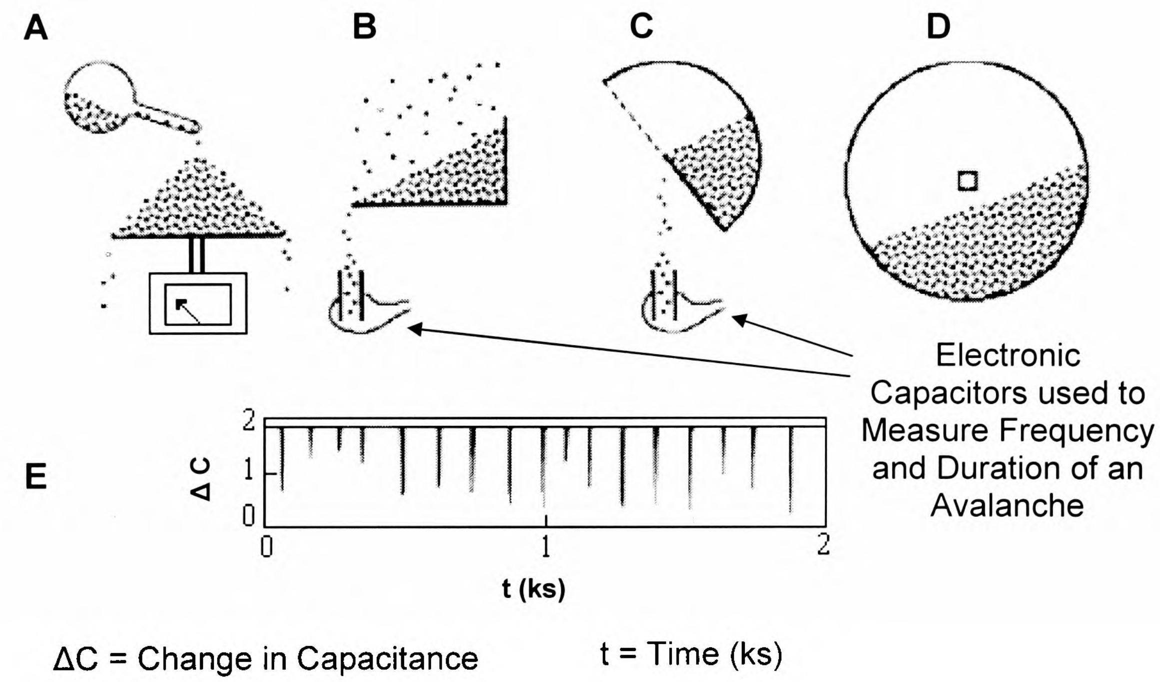


Figure 10 Schematic of Experimental Configurations used to Study Avalanching and a Typical Plot of a Capacitor Measurement using configuration (B). [35]

Rig configurations B & C utilised a capacitance technique to quantify the material discharging from a drum, results of which are shown in Figure 10(E). Each large spike corresponded to an avalanche that spanned the entire system. Spaces in-between defined intervals between successive avalanches. It was proposed that the avalanching behaviour produced in such experimental devices was analogous in behaviour to the periodic avalanching of free-flowing particulate materials when charging storage vessels. A similar definition of avalanching previously postulated by Brown et al. [33] and Creasey et al. [34] has been suggested by Jaeger and Nagel [35]. The thickness of an avalanche is often restricted to ten particles or less in depth. Each avalanche occurs after a well-defined interval of time has elapsed. The avalanches start at a maximally stable angle θ_m and returns the pile to an angle less than the lower angle of repose θ_r, Figure 5(a), Section 3.1.4.2. Jaeger and Nagel [35] highlighted an absence of avalanches that did not span the entire system in some experiments undertaken. However, the authors did give credence to the fact that in heap formation, the feedrate of the charging mixture will dictate the presence of avalanches of the type that do not descend the entire length of the heap surface.

Further investigations on the relationship between feedrate and the frequency of avalanching can be found in Section 6.7.

Avalanching and its association with segregation has been documented as far back as segregation literature has existed. However, modelling and statistical analysis of the phenomenon is relatively new. The increased computational capacity of modern computers has seen the first steps undertaken into modelling avalanching associated with heap segregation. These results are presented in Section 3.9.4. However, these attempts are very simplistic and rely on heap formation being constructed based on an individual particle being fed to the heap apex at any given time.

3.5 Mechanisms of Heap Segregation

Pouring of a free flowing material of varying size distribution into a heap will instigate the heaping process. There is a need to recognise the number, hierarchical preference and interaction of mechanisms of segregation that can occur within the heaping process.

The heaping process has two predominant segregating mechanisms that dictate the extent of size segregation produced. These are interparticle percolation and particle migration. Clearly, if there is sieving or percolation of particles within the flowing avalanching layer, they will sink through the avalanching layer. As the avalanching layer descends over the static surface, it leaves behind the particulates that have sunk to the bottom of the avalanching layer. Consequently, a high proportion of material being deposited on the heap surface is small. Particle migration of larger particles as well as the sieving or percolation of smaller particle occurs simultaneously within the flowing avalanching layer and cause the large particles to ascend within the flowing layer. The influence of these two mechanisms is dictated by the proportions of small and large particles in the feed mixture. The mechanisms of segregation result in preferential depositing of small particles under the fill point and the large particles at the heap periphery, as shown in Figure 7 However, these are but two of the various recognised mechanisms, which are perceived to act within heap segregation, under the influence of intermittent avalanching. It is clear that the extent to which a mechanism acts singularly or in combination is a function of process, geometrical and particulate mixture variables.

3.5.1 Differentiating between Percolation and Sieving

There is widespread ambiguity as to the definition of these two mechanisms and in this context it is suggested that the movement of a particle under the influence of each mechanism is identical. The differentiating factor is the regime of flow that exists which allows the mechanisms to be categorised into two separate definitions. Segregation literature often classifies percolation as a low shear segregation mechanism and sieving as a high shear segregation mechanism, although the resulting difference in action of the mechanisms is often difficult to distinguish.

Johanson [20] and Carson et al. [1] provide documented examples of the adverse influence of the sieving and percolation mechanisms of segregation on binary mixtures used in many industrial applications. From their observations, it is apparent that four conditions must be present in order for either mechanism to occur:

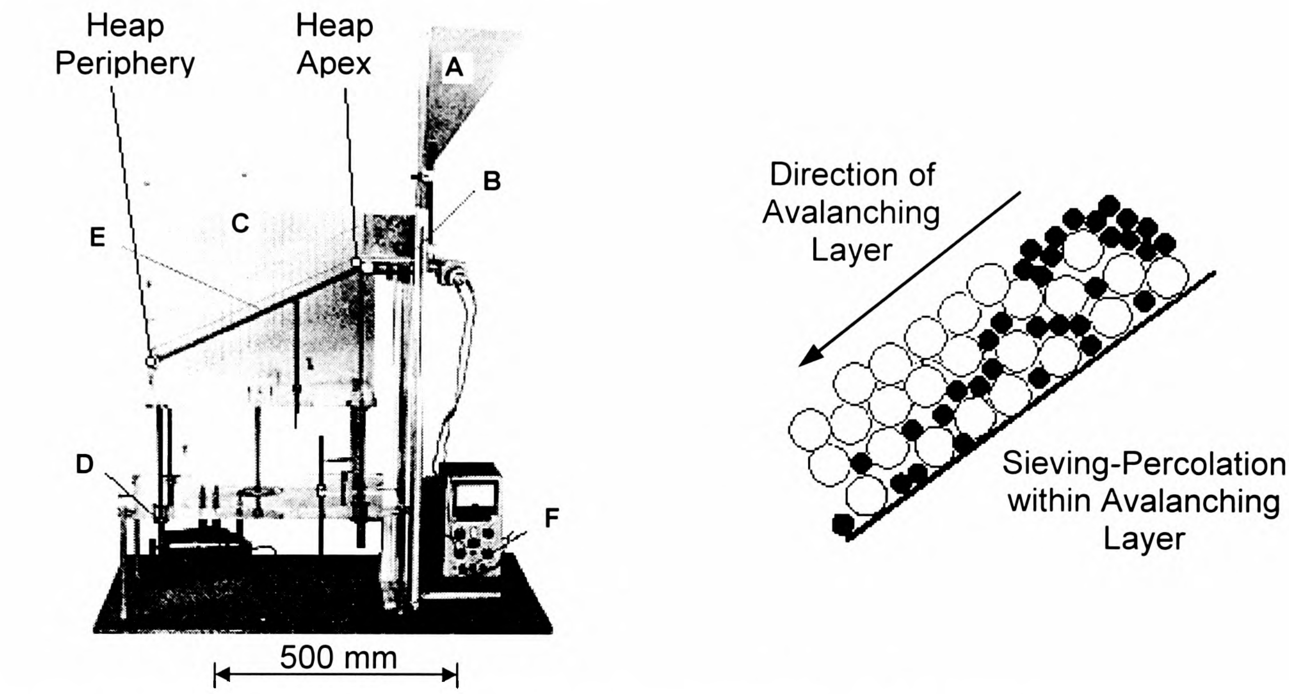
- A difference in particle size between the individual components. See Figure 16.
- A sufficiently large mean particle diameter. Also see Figure 16.
- A free-flowing material.
- Interparticulate motion i.e. a velocity gradient through the flowing material.

3.5.1.1 The Sieving-Percolation Mechanism

For the purposes of clarity when undertaking this literature review, the sieving mechanism has been re-defined as the sieving-percolation mechanism. The sieving-percolation mechanism is essentially defined as the separation of smaller constituents through a matrix of large particles, which themselves are being progressively deposited on the heap surface as the flowing layer descends over the heap. This layer is in a state of rapid agitation under the influence of high shear rates. Handling or process operations that facilitate such an environment occur when shearing of layers under the influence of avalanching are initiated, such as the heaping process when vessel charging or stockpiling. Rotational environments such as kilns, mixers etc and also transfer points and various mechanical conveyors offer similar environments which can cause a highly dynamic state of material movement.

Within such an environment, the flowing avalanching layer can be considered as consisting of the accumulation of a number of overriding shearing sub-layers. Consequently, the particle arrangement within each sub-layer is continually undergoing structural change resulting in the continuous random fluctuation in voidage and contact force network of particles of a sub-layer, Figure 61. The sieving-percolation mechanism can then essentially be related to the formation of a continually expanding and contracting matrix of large particles that creates the necessary voidage for the smaller particles to fall through into a relative sub-layer. The occurrence of the sieving-percolation mechanism is applicable only when there is a sufficient proportion of large particles within the flowing layer to allow a matrix of large particles to be formed.

To clarify the different environments in which the sieving-percolation and percolation mechanisms act is best illustrated by providing an example of the testing facilities used to investigate each phenomenon. To investigate sieving-percolation within a highly dynamic flowing layer, Drahun & Bridgwater [36] [37] constructed an experimental testing facility in order to mimic the conditions which facilitated the numerous mechanisms of heap segregation. They recognised the sieving-percolation mechanism as being one of the most influential active mechanisms of the heaping process. Consequently, the authors devoted a considerable amount of time into how the sieving-percolation was influenced by independent variables such as size, density, shape, free fall heights etc.



A = Feed Hopper for Bulk Material B = Belt Conveyor
C = Clear Plastic Box D = Motor for Lowering Box
E = Inclined Plane
F = Hinge for Setting Free Surface Face Horizontal During Analysis

Figure 11 Testing Facility used by Drahun & Bridgwater [36] [37] to Create the Desired Flow Regime that Instigated the Sieving-Percolation Mechanism Associated with Heap Segregation.

The base of the vessel, E, as shown in Figure 11 consists of a roughened plate set at an angle commensurate with the materials natural angle of repose. Bulk material and test tracers were allowed to form one half of a two-dimensional heap in a regime of flow that instigated the sieving-percolation mechanism of heap segregation. After the vessel had filled, vertical plates were inserted into slots in the Perspex box. This compartmentalised the heap and allowed analyses of sections of the heap length in order to determine the position of tracer particles.

3.5.1.2 The Percolation Mechanism

The sieving-percolation mechanism thrives within a relatively dynamic flowing layer where there was some removal and layering of particles from the avalanching layer onto the static surface as the avalanche descended over it. The percolation mechanism itself does not require an avalanching layer of material to be present.

Investigations have been performed in such environments in order to determine the percolation rates of small particles through a bed of large particles that are subjected to relatively low shear. Some investigators have chosen to concentrate solely on this form of percolation and ignore the part of the sieving-percolation mechanism which deposits material onto the surface akin to heap formation. Percolation is therefore defined as the movement of a particle through a reasonably coherent bed, which is often static in nature, such as when vibration is present, or where the material bed is in a settling condition.

If there is a sufficient size difference between the two components of the mixture then spontaneous percolation of small particles can occur in the bed. The definition and prevailing conditions that initiate this phenomenon are defined in Section 3.5.2. However, in this case the process by which small particles percolate down through the material bed can be considered the 'ratchet' or 'release-capture' type of behaviour [38]. A small particle will be prevented from moving freely within the voidage available by contact with bulk particles surrounding it. The bulk particles are experiencing agitation induced by shear. Eventually the bulk particles will leave enough of a gap through which the smaller particle can pass through completely and contact with a particle lower in the bulk, or remain lodged in between the surrounding larger particles. This ratchet behaviour will prevent the gap from closing until a period of time has elapsed where enough agitation has permitted the small particle to pass through its self made gap. The extent to which this happens is dependent upon the surface properties of the particles of the mixture. The neighbouring larger particle may experience a random upward motion in a similar way. The upward movements of large particles can exist within the percolation or sieving environment and this behaviour is defined as the migration mechanism, Section3.5.4.

The different environment in which percolation occurs in a relatively coherent agitated bed and the sieving-percolation mechanism found in heap formation is best be illustrated by the results of the work undertaken by Bridgwater and co workers [38] [39]. They conducted various investigations into the percolation behaviour dictated by size differences of free flowing particulate materials. The analysis of this characteristic behaviour can be found in Section 3.7.1.1. The authors employed the use of several configurations of rectangular shear cells, where the bed of material was subjected to a uniform shear strain. The principles of applying unlimited shear of the material in the shear cell and the resulting influence of size on percolation rates is shown in Figure 12.

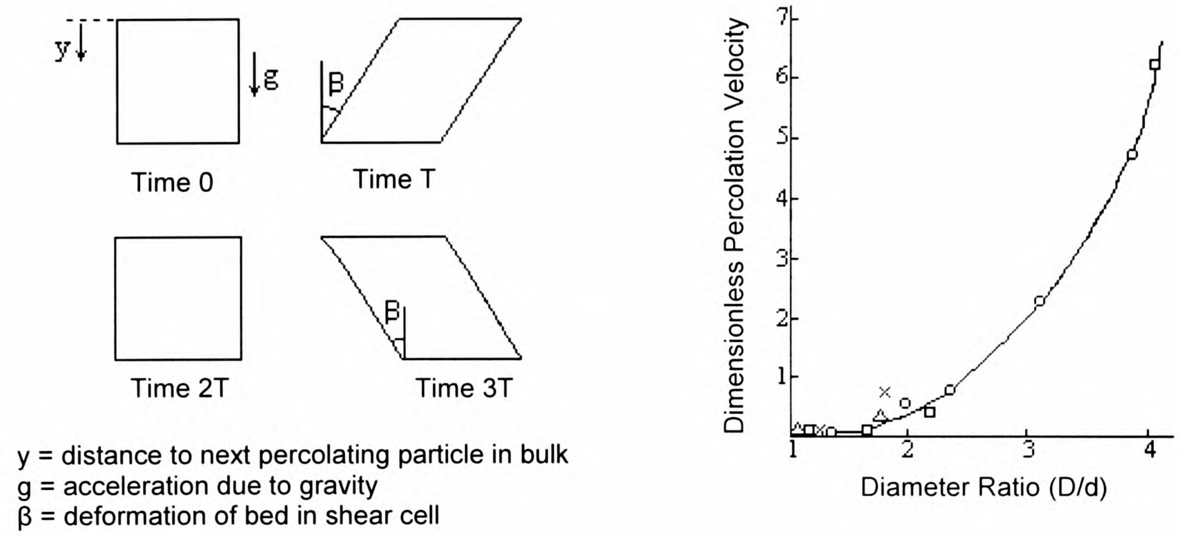


Figure 12 Principle of Deformation of Material in a Simple Rectangular Shear Cell and percolation behaviour induced by particle size variations. [39][44]

An unlimited amount of strain could be applied by reversing the direction of the cell. This was undertaken in order to measure the time taken for small particles to percolate through a bed of large particles. The dimensionless percolation velocity was defined as the number of particle diameters moved per unit of strain.

3.5.2 Spontaneous Percolation

Spontaneous percolation is defined as the percolation of small particles through a static bed of material. This mechanism is often initiated by external vibrations induced into the material thus causing the small particles to percolate downwards through the voids formed by interlocking large particles. There is some ambiguity in the literature as to the critical size difference between particles that initiates spontaneous percolation. This is because there are various possible packing arrangements of particles in both a static and dynamic state. The analysis of these packing arrangements, quantification of their voidage and determination of the diameter ratio at which spontaneous percolation is initiated can be found in Section 4.3.2 and Appendix A.2. In general, denser particles spontaneously percolate at a higher rate than light ones and rates of spontaneous percolation are generally perceived to be lower in dynamic surroundings as opposed to those in a static bed.

3.5.3 Rolling

This mechanism resides in the behaviour of particles at or near the surface of an avalanching layer or the movement of an individual particle that is moving on top of a stationary structure. In such circumstances, the thickness of the avalanching layer is sufficiently small to allow the unrestricted independent movement of particles whose inertia properties are not inhibited. The rolling mechanism is influenced by the degree of protuberances found on the heap surface on which the particle is travelling.

Matthée [40] took a mechanistic view of the rolling or sliding mechanism of particles travelling down an inclined surface and derived theoretical expressions of a particles mobility. The author considered a particle's mobility to be a function of the following criteria:

- The nature of the heap surface, whose scale of roughness is defined as being less than the diameter of the largest particle of the mixture. A large particle is less likely to be halted by the roughness elements of the surface than a small one.
- The coefficient of friction between constituents of the mixture.
- The momentum of individual particles of the mixture.

Experimental evidence of segregation resulting form centrally pouring a bunker with a binary sized material are presented by Matthée [40] but there is no evidence to substantiate the derived theories. One could argue that the flow regime that the mathematical model considers is representative of low feedrate conditions, where the sliding or rolling of individual particles is deemed the sole significant mechanism influencing the pattern of segregation produced. However, Drahun and Bridgwater [37] provide evidence that contradicts this conclusion. Their testwork suggests that for the same flow regime, percolation is the significant mechanism of segregation with sliding and rolling being secondary contributory factors. Nevertheless, the rolling mechanism induced into an individual large particle moving away from the charging point will still influence the final pattern of segregation produced. This mechanism can, given the right circumstances, significantly dictate the final stationary position of a large particle on the heap surface.

3.5.4 Floating Migration

This mechanism is sometimes defined as particle stratification in the segregation literature. The driving force that induces the floating migration mechanism is similar to that which instigates the percolation mechanism. As explained in Section 3.5.1.2 percolation via the ratchet or release-capture behaviour of the mixture bed causes the small particles to sink into the lower regions of the mixture bed. A similar behaviour causes the large particles to move or float or stratify to regions of greatest strain rate, which in the case of heap formation is at the surface of the avalanching layer. Consequently, large particles will tend to move in the opposite direction of small particles. Once at or around the vicinity of the surface the large particles are then susceptible to the influence of the rolling mechanism.

This mechanism was recognised and observed in the work documented by Stephens and co-workers [41] [42]. The authors stated that when certain mixture characteristics are present, large particles could move to the surface of the material bed. This movement is initiated under the influence of the migration mechanism and was shown to be on a par with percolation of small particles.

3.5.5 Sinking Migration

This mechanism is sometimes referred to as the push-away mechanism and is highly influential within heap segregation for mixtures that have a wide difference in particle size and density. Large particles will remain at the surface of the avalanching layer if their density is less than the average particle density of the avalanching layer. This remains true irrespective of the proportions of large and small particles in the mixture and the subsequent mechanism of segregation that the large particles will be subjected to in this case is rolling. However, if the large particles have a density greater than the average density of particles of the flowing layer then they will have a tendency to push their way down and sink within the avalanching layer. Consequently, this sinking continues until they embed themselves into the static heap. The mechanism of segregation in this case is sinking migration, the concept of which was documented and referred to as the push-away mechanism by Tanaka [43]. However, this is only applicable for low concentrations of large particles in a flowing layer of predominantly small particles. At greater concentrations of larger particles, the behaviour of the large particles will change to behave like 'floaters' rather than 'sinkers'. This is because at higher concentrations the percolating mechanisms ability to segregate the small less dense particles of the mixture is far more potent than the sinking ability of the larger denser particles. This forces the larger particles to remain at the surface of the avalanche. It is clear that the occurrence and influence of both the floating and sinking migration mechanisms are a function of the size, density and concentration ratio of the mixture. The interaction of these variables and its affect on the resulting pattern of segregation are discussed in more detail in Section 3.7.4.5. The movement of particles induced by the sinking migration mechanism is similar to the ratchet percolation mechanism, discussed in Section 3.5.1.2. However, the sinking migration mechanism resides in the ability of a particles momentum to force its way through a particle mixture bed rather than percolation through a gap that presents itself.

3.5.6 Trajectory

The trajectory mechanism can be categorised into two areas:

- Drag forces on a particle as it moves through a fluid.
- Bouncing due to the resilience of feed particles contacting a surface.

Trajectory segregation as a direct result of a particles resilience relates to the behaviour of feed particles impacting onto a static surface or by means of particle to particle contact. This behaviour is often quantified using the coefficient of restitution and is defined further in Section 3.7.1.5 page 63.

Trajectory in terms of drag relates to momentum of mixture particulates as they travel through a medium, usually air. This can be induced by material discharge from a chute, mechanical conveyor i.e. belt bucket, screw, etc or the aggressive tumbling action within a mixer. For vertical free fall charging of vessels, ignoring any inter-particulate collisions, the forces acting on a particle are a function of the particle weight and the resistance offered by the air. Although the terminal velocities of different particles may vary, their trajectories will not. However, if a horizontal component of velocity is introduced, the forces are no longer entirely vertical and hence the differences in the ratio of these forces will cause the air-drag trajectory mechanism to become active. Therefore, in relation to a non-vertical vessel-charging environment, larger particles of higher momentum will be discharged further away from the point of charge than small ones, Figure 24 page 68. Williams [44] quantified the trajectory distance of particles according to their velocity, density, fluid viscosity, and particle diameter. The author concluded that a doubling of particle diameter will represent a quadrupling of its distance of trajectory.

Holmes [45] provided documented evidence on patterns of segregation resulting from heap formation via an inclined chute. Consequently, the air-drag mechanism of trajectory influenced a non-uniform composition of charging mixture upon contact with the heap surface. This subsequently affected the final resting positions of constituent particles of the mixture. The author found that the surface of the heap nearest the chute high in proportion of small particles, whereas the surface of the heap furthest away from the chute was high in proportion of large particles.

3.5.7 Embedding

The definition of this mechanism has been proposed by analysing the findings of a substantial test program as documented in Section 6.8. Detailed explanation of the environment required to initiate this mechanism and its influence on the resulting pattern of segregation can be found in Section 6.6. This mechanism emanates from the interaction of the vertical charging feed stream upon contact with the static heap surface. This results in the uncharacteristic displacement of large particles around the feed point.

3.5.8 Angle of Repose

A variation of angle of repose behaviour has been presented in the form of a mechanism that has been documented in Section 3.7.3.1 and refers to batch charging a vessel with individual mixture constituents in successive stages. The process of batch charging constituents differing in angles of repose will cause a subsequent charging constituent to come into contact with a heap surface whose angle of formation will be dictated by the former charged constituent. If this angle is shallower than the angle of repose of the charging constituent then this constituent will not flow to the outer periphery of he heap. Conversely, if the heap angle is steeper than the angle of the charging constituent then this constituent will be encouraged to flow to the outer heap periphery. The final vessel mixture will exhibit a pattern of particle size segregation similar to that produced by the mechanisms associated with heap segregation. However, the inner core of mixture will be a formulation of constituents of steep angles of repose and an outer annular region of constituents of shallow angles of repose.

Another variation of this mechanism resides in its contribution to magnifying other mechanisms of segregation occurring during heap segregation. The affect of this form of angle of repose mechanism is illustrated in Section3.7.4.2. Differences in the angle of repose of mixture constituents induce both visual stratification and measured segregation of the mixture when charging a vessel.

The classification of whether the angle of repose is a particulate material characteristic or a defined mechanism of segregation is one of conjecture. However, the aforementioned examples of its influence in dictating various patterns of segregation associated with the heaping process warrants its inclusion as a contributory influence on mechanisms of segregation occurring when charging vessels.

3.6 Conflicting Views on Mechanisms Present Within Heap Segregation

It is evident from the considerable literature reviewed so far that authors of segregation related literature have tailored their own hypothesis on the mechanisms at work within heap segregation to satisfy their experimental or modelling results. It was often the case that authors considered the heaping process to be only a one or two mechanism process to the exclusion of others.

Brown [46] undertook early attempts to explain the mechanisms of the heaping process and considered it to be a 'two priority' process. Firstly segregation was considered a function of the '*collisions*' of particles that flowed down the heap surface; the size of the particles influencing their final deposited position on the slope surface. Secondly the size distribution of the mixture dictated protuberances of the slope surface, and this in turn dictated the '*rolling*' potential of particles as they descended the slope. Bouncing was not incorporated into the authors hypothesis. A more recent hypothesis by Williams [17] postulated heap segregation as being attributable to the percolation of small particles through the voids that present themselves in the particle arrangement on the static surface over which the avalanching layer is descending. To complement this affect Williams also suggested that particles within the avalanching layer formed a matrix and acted as a screen in which the small particles could sieve through. Large particles that could not fit into these gaps were deposited to the periphery of the heap under the influence of the rolling mechanism. Drahun & Bridgwater [37] implied that the assumption that the large particles in Williams hypothesis arrive at the periphery as a consequence of rolling and as a by product of the sieving mechanism was inappropriate. They argue this point by stating that for low concentrations of large particles in a binary sized mixture, the large particles still progress to the heap periphery, even though there are insufficient large particles to form a matrix to facilitate the sieving-percolation of small particles. Movement of large particles in this form of the heap segregation is defined by Stephens and Bridgwater [41][42] as particle migration.

Lawrence and Beddow [47] described the heaping process as being solely influenced by the percolation of small particles as a direct result of the sieving-percolation mechanism in the avalanching layer descending down the heap surface. For mixtures that contain a low concentration of large particles, they are unable to flow readily through the matrix of small particles, and therefore sink into the heap surface and are deposited under the feed point. This contradicts the findings of Drahun & Bridgwater [37] and Williams [17], who, although state different connotations of mechanisms of the heaping process, still agree that the majority of large particles will reach the periphery of the heap. Drahun and Bridgwater [37] indicate that free-fall height variations when comparing test work to Lawrence and Beddow [47], is the differentiating factor in causing incompatibility of segregation results. This may well be a justifiable reason for this contradiction as Lawrence and Beddow utilised lead shot as opposed to Drahun & Bridgwater who utilised glass spheres. Different values of density associated with lead and glass particles combined with the affect of free fall height could initiate the onset of the embedding mechanism. The particles having increased momentum embedded themselves underneath the fill point and therefore did not travel to the heap periphery. Drahun and Bridgwater did not incorporate any free fall height; therefore, large particles did not embed into the heap under the fill point. They did in fact travel upwards through the flowing layer towards the region of highest strain rate under the mechanism of floating-migration.

From the contradictory views emanating from the literature reviewed that attempts to identify mechanisms of the heaping process, it appears that mechanisms other than sieving-percolation can significantly govern heap segregation providing certain conditions exist. The behaviour of particles within the avalanching layer and the avalanching layer's interaction with the static heap surface incurs embedding, bouncing, sliding, and impact influences on the particles. This results in the separation of constituent particles of the mixture that reside outside the definition of the sieving-percolation mechanism. The aforementioned examples of authors' perceived differences in mechanisms of heap segregation are only a few of the contradictory postulations available from the majority of relevant literature available. A conclusion to be drawn from this observation is that the influence and interaction of the numerous mechanisms of heap segregation are extremely sensitive to changes in mixture type and the environment in which it is being handled. These changes can take the form of particle characteristics, geometrical variables or process variables of the handling or process operation being performed. When the influence and contribution of all these factors is understood fully a more definitive assessment can be made as to the hierarchical structure of mechanisms of heap segregation as relevant to the charging of storage vessels.

3.7 Factors that Influence Mechanisms Within Heap Segregation

A specific mechanism by which separation of particles occur in heap segregation depends fundamentally on the characteristic motion of the material. This in turn is dictated by the physical properties of the constituent particulate material and its flowing environment. These influencing factors can be grouped into three categories:

- Particle and Mixture characteristics. Apart from individual particle characteristics, mixtures comprised of different constituent particle characteristics will engender its own mixture characteristic behaviour i.e. angle of repose, angle of internal friction and voidage fraction of the mixture bed etc.
- Geometrical variables. These can take the form of vessel size, point and angle of charge etc.
- Process variables. Examples of these include feedrate of charging mixture, batch or continuous feeding and proportions of constituents of the mixture.

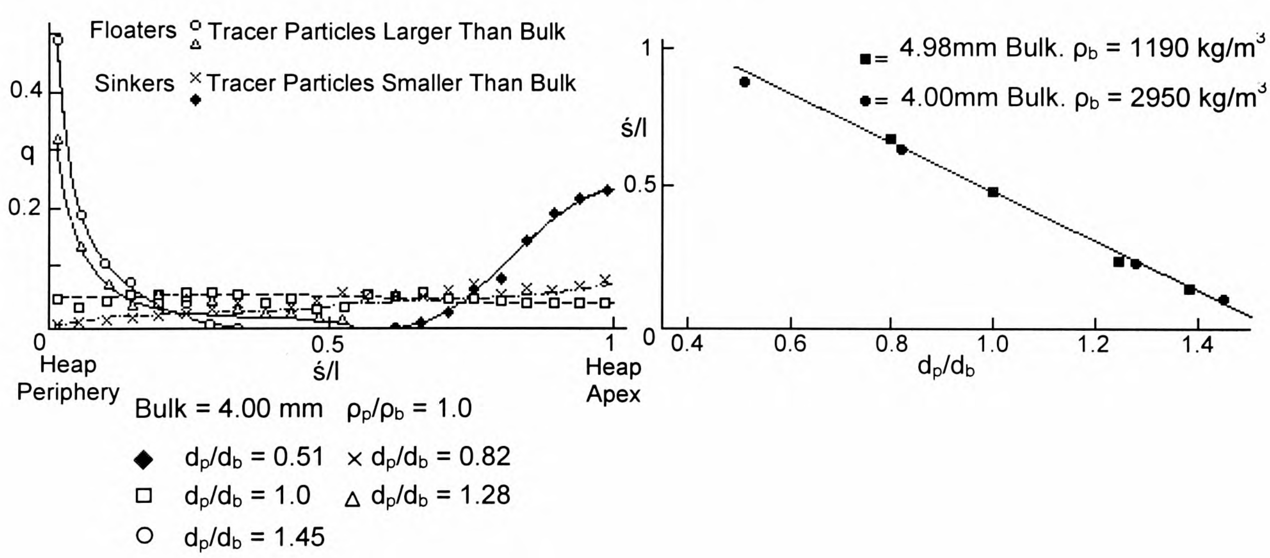
3.7.1 Particle Characteristics

One major difficulty, evident from the literature reviewed is that particle characteristics such as size, density or shape, which are known to be potential factors influencing segregation are in themselves difficult to quantify. Consequently, this compounds the subsequent quantification of the segregation process. Perhaps not surprisingly, the amount of documented literature pertaining to the influence of a particular particle characteristic tends to diminish, the more diverse the particle characteristic considered. Hence, there is a multitude of work relating to the affect of particle size in comparison to documented information on characteristics such as particle attraction, roughness and coefficient of restitution etc.

3.7.1.1 Particle Size

Bridgwater et al. [38] [39] investigated size segregation of a free-flowing particulate mixture utilising a rectangular shear cell testing facility. The fundamental approach used to initiate segregation of the material according to differences in particle size was shown previously in Figure 12, Section 3.5.1.2. Different sized free-flowing binary mixtures were subjected to shear in order to gauge the percolation velocities in a sub-layer-shearing environment of a shear cell. Quantification of sizes of the binary mixture were based upon the principle that diameters of the small and large non-spherical particles represented spheres of the same volume. The relationship between the percolation rate and diameter ratio produced from this method is shown in Figure 12. The greatest change in percolation velocity occurs at a diameter ratio between two and four. Beyond this diameter ratio, the curve takes on the form of an asymptotic relationship and is indicative of findings published in other documented literature that use similar sized mixtures. This can be attributed to the fact that when diameter ratios approach a critical value the behaviour of the percolation mechanism becomes less influential in favour of the spontaneous percolation mechanism as documented in Section 4.3.2.

Drahun and Bridgwater [36] [37] investigated the distribution of different sized tracer particles, added to a particulate bulk when charging a half heap storage vessel. The salient features of the experimental testing facility used and the regime of flow initiated are shown on Figure 11, Section 3.5.1.1. According to the direction of movement, the tracer particle in the tests performed was classified as being either a '*floater*' or a '*sinker*' In terms of size segregation, the smaller particles were deemed sinkers when they sank below the surface of the bulk material, initiated by the mechanism of sieving-percolation. Larger particles were deemed floaters when they rose to the surface of the bulk material, initiated by the mechanism of floating migration. The results of monitoring different sizes of tracer particles after exposure to the influence of the heap segregation process can be seen below.



The variables are defined as:

ṡ	Average horizontal position of tracer from heap periphery		
d	Particle diameter.		
q	Spatial frequency distribution of tracers.	p	Tracer particle.
s	Horizontal position of tracer from heap periphery.	b	Bulk particle.
l	Heap length projected onto a horizontal plane.	ρ	Particle density.

Figure 13 Graphical Illustration of the Distribution of Tracer Particle Sizes and their Linear Relationship with Diameter Ratio. [37]

It was evident upon analysis of Figure 13 that when the tracer particles are larger than the bulk they accumulated at the edge of the heap, conversely when they were smaller than the bulk they congregated under the feed point. To eliminate these affects being influenced by another characteristic of the particulate solid under test, they undertook identical size segregation tests using different materials. They concluded that changing the bulk material did not affect size segregation results. Figure 13 also illustrates clearly that there exists a linear relationship between the average position of a tracer particle along the heap length with diameter ratio of the binary mixture, irrespective of nature of mixture constituents used. It can be concluded that for the diameter ratios tested the average position of a tracer particle down the slope length is a function of the diameter ratio of the mixture. As these tests used tracer particles whose population by weight did not exceed 1% of the bulk material, direct comparisons with other authors results are difficult to undertake. The mechanism of rolling has not been incorporated into their heaping philosophy and may be of significant influence when the tracer particles are larger then the bulk. However, in general the physical behaviour and finishing positions of tracer particles in the segregated bed is generally commensurate with published literature who use significantly higher proportions of tracers in the bulk.

Lawrence and Beddow [47] undertook a thorough investigation of size segregation when central point charging a die with a binary sized lead shot mixture. The authors investigated the affect of varying the diameter ratio and maintaining the diameter ratio constant whilst varying the mean diameter of the binary mixture. For a selected size of large particle and diameter ratio, the proportion of small to large particles that gave the worst case measure of segregation in the experiential facility was quantified as $-\Delta_{max}$, Figure 14. The geometrical construction of the test facility and graphical representation of results taken for one particular size ratio at various different large and small particle concentrations can be seen on Figure 31, page 75.

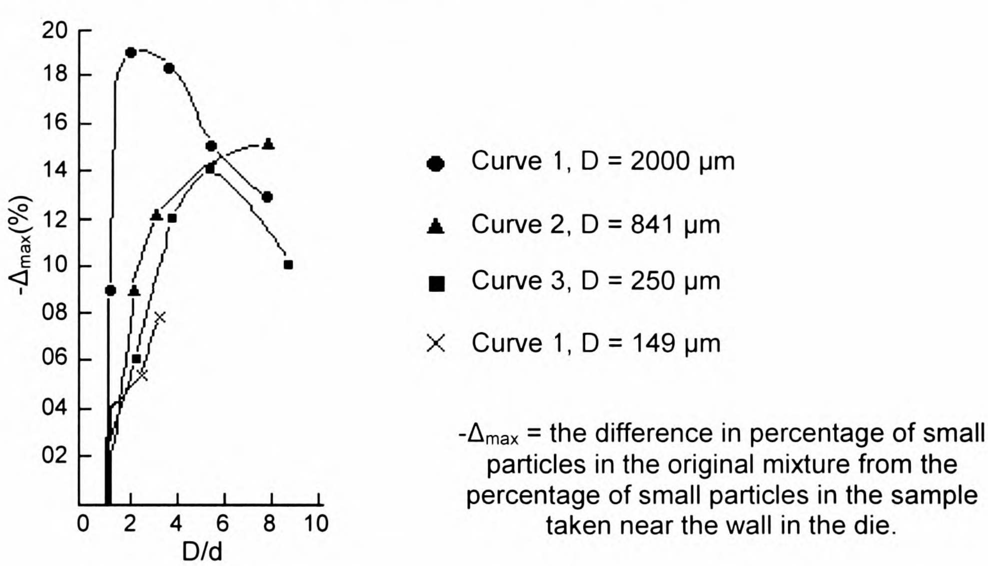


Figure 14 Segregation Measured at Heap Periphery when Charging a Die with Binary Sized Mixtures. [47]

A substantial amount of tests were undertaken for different size ratios in order to find the desired proportion of small to large particles that gave the worst case value of $-\Delta_{max}$ at the heap periphery. As can be seen from Figure 14 the worst case value of $-\Delta_{max}$ was approximately –18% for a diameter ratio of 2.4:1 that contained 30% of small particles. The actual result for this test condition can be seen on Figure 31 page 75. Values of D ranged from 2000μm to 149μm and D/d ranged from 1.2:1 to 8:1. Figure 14 shows that the larger the diameter of the large component D, the greater the segregation, i.e. the less likelihood of finding any small particles at the periphery of the heap/wall of die. For the four curves of D illustrated on Figure 14, decreasing the diameter of the small particle in order to increase the diameter ratio, caused an initial marked increase in segregation which then started to level off. This substantiates the evidence provided by Williams and Khan [49] that not only is the diameter ratio of a binary mixture influential on the resulting segregation suffered but also the absolute sizes of the mixture. This change in the slope of $-\Delta_{max}$ for large diameter ratios is attributable to the function of the size of the small particles comprising the binary mixture. In order to create large diameter ratio mixtures, the size of d has been reduced, and therefore the population of the small particles has increased in order to maintain the same mass proportions in the initial mix. To maintain the maximum rate of segregation, top of curves on Figure 14 it would be necessary to increase the number of smaller particles percolating per unit of percolation time. Furthermore, the size of d has been reduced to such an extent that the small particles now border on the size where they will be subject to the influential forces akin to a cohesive material. One characteristic behaviour of a cohesive material is that a particle that will not be as readily able to flow, thus restricting its vulnerability to the sieving-percolation mechanism associated with heap segregation. As the size of d is reduced, the influence of this will subsequently increase.

Harris and Hildon [48] investigated the segregation tendencies of binary mixture washing powders comprised of different sized detergent powders and bleaching agents. The authors were interested in how segregation of the washing powder mixture was affected by changing the size distribution of the bleaching agent when charged into a vessel of the kind shown in Figure 15. Samples taken from the segregated mixture in vessel C represented the cumulative segregation suffered as a result of movement through the entire testing apparatus. This included discharge from vessel A, charging vessel B, core flow discharge of vessel B and finally charging vessel C. Any subsequent measurements of segregation in vessel C was representative of the segregation suffered in all parts of the segregation test apparatus.

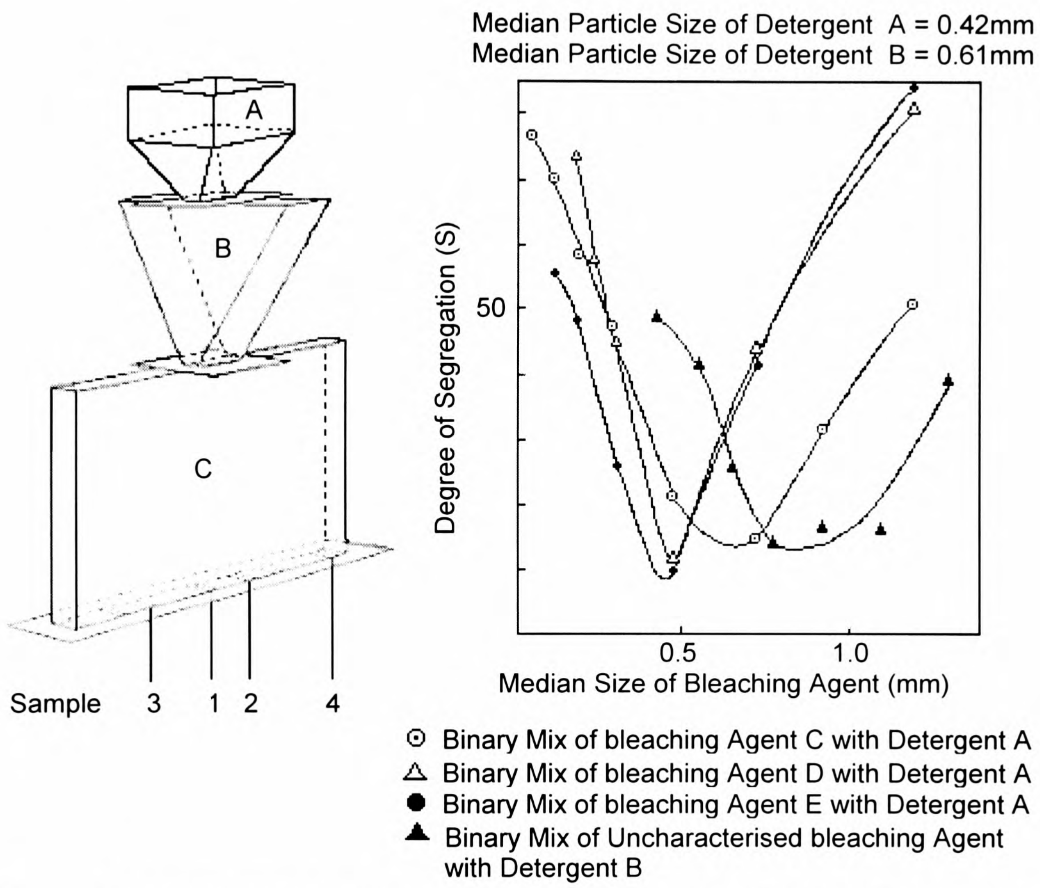
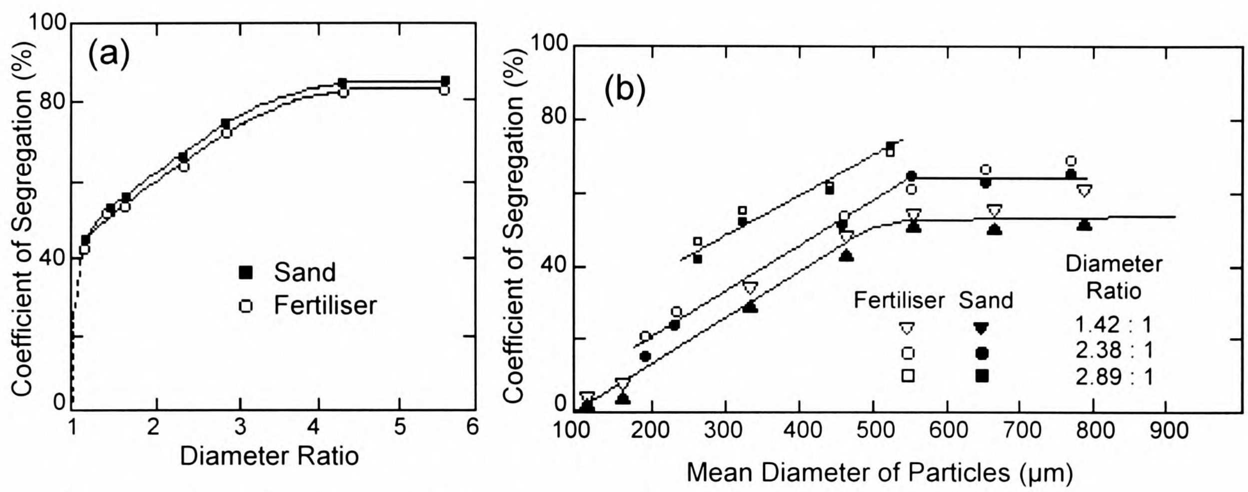


Figure 15 Measurements of Heap Segregation when Mixing Detergents with Bleaching agents. [48]

Segregation tests were conducted using carefully screened narrow size fractions of four bleaching agents, mixed with two types of detergent. The detergent was of a uni-modal size distribution with a median particle size as denoted on Figure 15. An index of segregation, defined in Section 3.9.1.2, was used to quantify the degree of segregation of the mixture as a direct result of its movements in the experimental testing facility. Figure 15 suggests that the major reduction in measured segregation occurs when the median particle size of the bleaching agent is approximately the same as the median size of the detergent. At this point, the majority of particle sizes of detergent and bleaching agent were of the same order. When the bleaching agent size was either greater or smaller then the median size of the detergent there was a marked increase in the propensity that the washing powder mixture segregated.

Williams and Khan [49] undertook size segregation investigations in order to compare results produced from their laboratory test apparatus to those produced by five industrially relevant mixer types. The authors equipment consisted of an inclined rotating drum whose contents were rotated for a finite time in order to facilitate the mechanisms of segregation associated with the regime of flow within the apparatus. They quantified the mixtures propensity to segregate by employing the same segregation index as that of Williams and Shields [50] who themselves investigated size segregation of binary mixtures that travelled along a vibrated plate. The segregation index used to quantify the resulting segregation measured is defined in detail in Section 3.9.1.1. A valuable contribution to heap segregation knowledge was produced by the work undertaken by these authors. They focussed on investigations to determine segregation for different diameter ratio mixtures whose mean diameter was maintained constant. Furthermore, mixtures were tested where the diameter ratio was maintained constant whilst the absolute mean diameter of the mixture was varied.



Constant Mean Diameter of Components = 540 μm
Mixture Ratio = 1:1 by Mass

Figure 16 Measurements of Binary Mixture Segregation for Constant Diameter Ratio Mixtures and Constant Mean Diameter Mixtures. [49]

The authors provided evidence to suggest that mixtures tested for segregation in their test apparatus showed comparable magnitudes of segregation to those in the mixers. This would indicate that the regime of flow initiated in the segregation tester was comparable to the regime encountered in the mixers. This shows the applicability of the test rig as a means of assessing the segregation potential of particulate solid mixtures that are subjected to this regime of flow. The authors reason that reducing the mean particle diameter of the mixture below 500_{μ}m can markedly abate segregation. They attribute this affect to differences in coefficient of restitution of the particles of the sand and fertiliser materials used in the testwork. The coefficient of restitution characteristic is further documented in Section 3.7.1.5. In addition, there will also be an increasing influence of inter-particulate forces akin to cohesive powders for particle sizes of this order.

Shinohara et al. [51] undertook theoretical modelling of heap segregation and compared model predictions with experimental results for binary sized mixtures that charged a vessel of the type shown in Figure 17(a). The derivation of a theoretical model was based solely on the sieving-percolation mechanism. The parameters of the model that dictated the pattern of segregation were considered two types. Firstly the sieving-percolation rate of smaller particles through the voids created by a matrix layer of larger particles, and secondly the packing of smaller particles into the inter-spaces of stationary large particles on the stationary heap surface. A graphical illustration of the authors correlation's between model predictions and experimental results are shown in Figure 17(b) & (c).

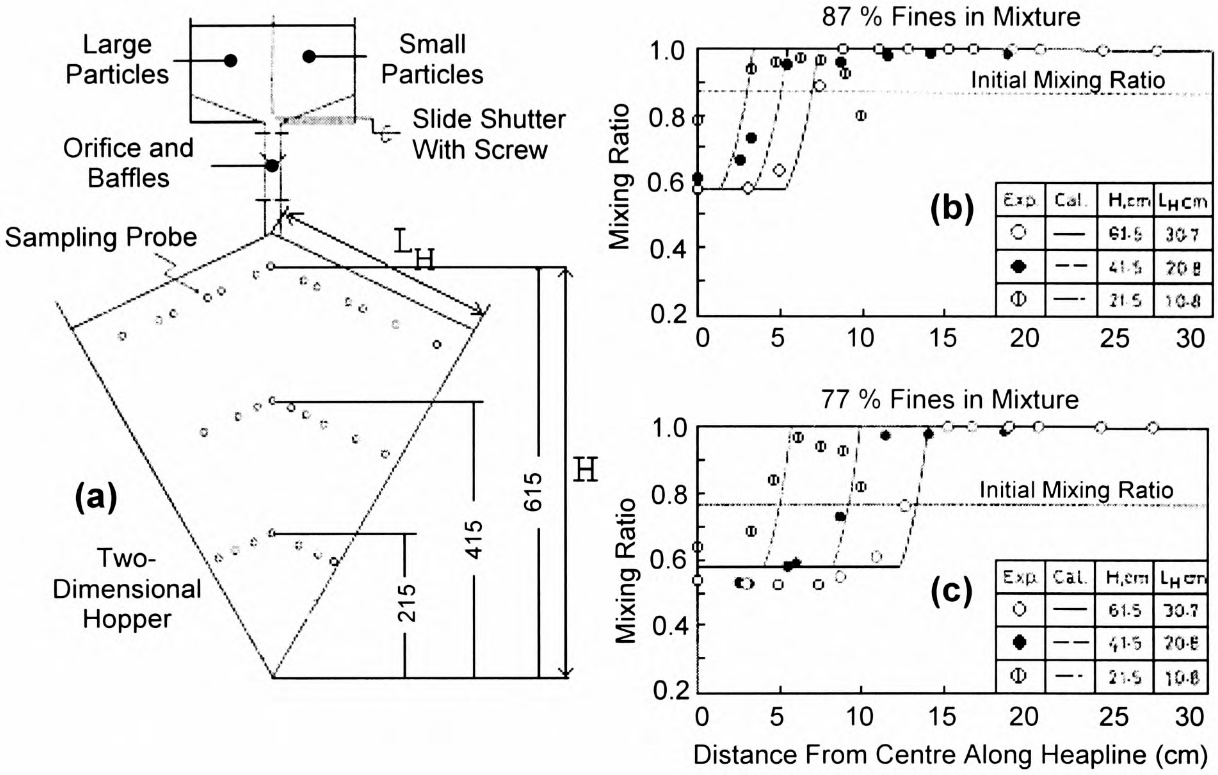


Figure 17 Comparison of Experimental and Theoretical Size Segregation According to Shinohara et al. [51]

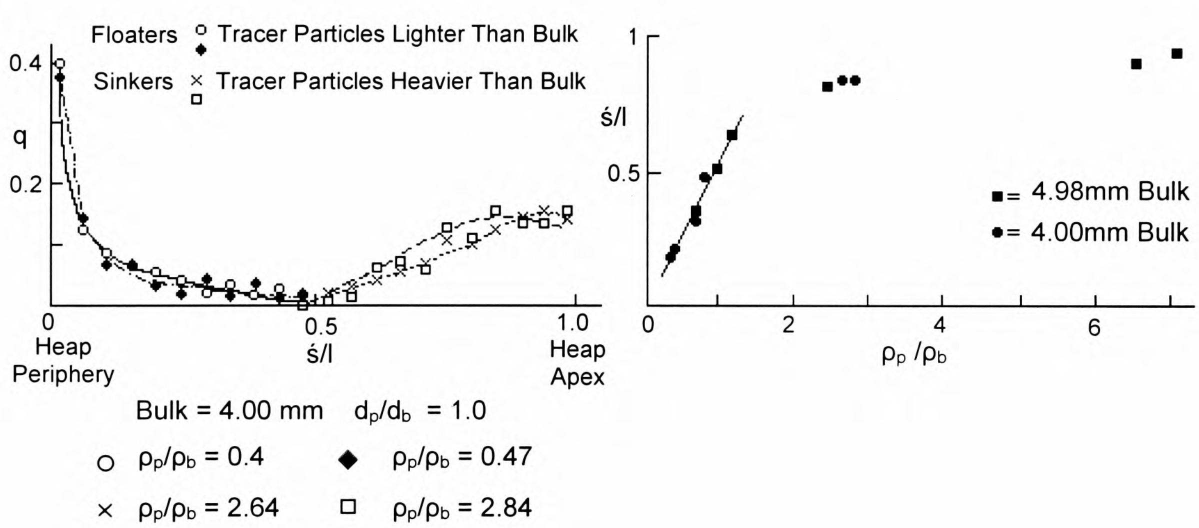
As shown on Figure 17(b) and (c) the small particles are concentrated around the vicinity of the feed point and a mixture completely absent of small particles is evident before half the distance of the heap length is reached. However, this is expected as the diameter ratio of the mixtures used by Shinohara was approximately 14:1. This therefore categorises the mixture well within the region of mixtures that are influenced by the spontaneous percolation mechanism and as such would be the significant mechanism of segregation. This affect is confirmed by the clear and immediate demarcation of sizes into two separate boundaries on Figure 17(b) & (c). There is good correlation between predicted and experimental segregation patterns for Shinohara's [51] proposed 'screening-layer' model, although no provisions in the model take into account spontaneous percolation. However, this is not unusual and is expected as the relationship of sieving percolation is known to be asymptotic in nature for the order of sizes used by the author, see Figure 12. Therefore, the rate of sieving-percolation for a 6:1 diameter ratio would be similar in magnitude to that of the 14:1 ratio mixture used by this author. The general derivation of Shinohara's screening layer model can be found in Section 3.9.3.1.

3.7.1.2 Particle Density

Although the majority of the work documented by Harris and Hildon [48] was concerned with particle size segregation, they did investigate particle density segregation using identical size distribution fractions that were comparable in particle shape. They did quantify segregation for a 200µm equal sized, 1.7:1 density ratio mixture. However, the lack of any quantifiable information on other characteristics of the particulate mixture such as coefficient of restitution, shape, roughness etc suggest that the resulting segregation measured may not be solely attributable to differences in density.

Bridgwater et al. [39] investigated how particle density influenced percolation rates of particles in a shear-cell type device. These tests were conducted with a binary mixture of hollow spheres where half were filled with a substance to increase the particle density by a ratio of approximately 10 to 1. By adopting this method, all other surface properties remain unaltered. Resulting percolation tests showed that density caused a significant increase in percolation velocities.

Drahun and Bridgwater [37] undertook investigations into how mixtures segregated according to differences in particle density when exposed to heap segregation in the vessel shown on Figure 11 page 44.



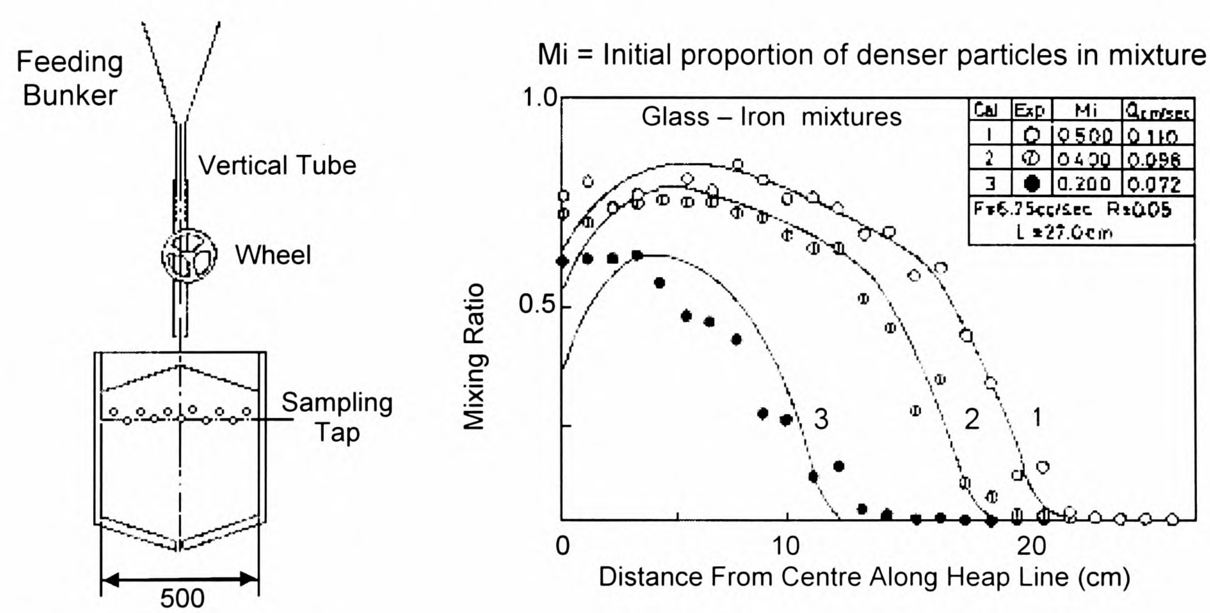
The variables are defined as:

ś	Average horizontal position of tracer from heap periphery		
d	Particle diameter.		
q	Spatial frequency distribution of tracers.	p	Tracer particle.
s	Horizontal position of tracer from heap periphery.	b	Bulk particle.
l	Heap length projected onto a horizontal plane.	ρ	Particle density.

Figure 18 Illustration of the Distribution of Tracer Particle Densities and their Non-Linear Relationship with Density Ratio. [37]

Figure 18 indicates that binary mixtures varying in density undergo significant segregation when exposed to heap segregation akin to charging a storage vessel. Profiles of density segregation are of comparable magnitude to the size segregation experiments illustrated on Figure 13. In terms of directional movement, the denser particles were deemed '*sinkers*' as they sank below the surface of the bulk material. They did so under the influence of the sinking migration mechanism. Consequently, they accumulated around the heap apex. The lighter particles were deemed '*floaters*' as they rose to the surface of the bulk material. This was induced by the mechanism of floating migration and caused particles to accumulate at the heap periphery. The right hand side of Figure 18 indicates a significant difference in density segregation trend compared to size segregation shown in Figure 13. For density ratios greater than approximately 1.2, the average horizontal position of tracer particles down the heap length becomes non-linear in relationship and hence independent of density ratio.

Shinohara et al. [52] undertook experimental investigations into density segregation of binary mixtures of constant size when charging a vessel of the type shown in Figure 19. The general screening-layer model, as defined in Section 3.9.3.1, was adapted to incorporate different segregating mechanisms that dictated the pattern of predicted segregation. One mechanism was considered the penetration rate of denser particles through a layer of less dense particles induced by the sinking migration mechanism. A second mechanism involved the velocity ratio of the avalanching layer and the ratio of velocities of the sub-layers of the avalanching layer. The authors findings are shown in Figure 19 and indicate a good comparison between experimental and predicted results.



Two-dimensional Hopper

Figure 19 Test Facility and Illustration of Actual and Predicted Segregation for Mixtures Differing in Density. [52]

The three different volumetric fractions of the segregating denser component in the mixtures formulated (Mi), segregated and accumulated around the vicinity of the feed point. The patterns of segregation for differences in density compliment patterns of size segregation of small particles. However, although the observed patterns of segregation may be similar, the mechanisms of segregation pertaining to each characteristic are different. The sinking and floating migration mechanisms, Sections 3.5.5 and 3.5.4 are the major acting mechanisms within heap segregation for mixtures differing in density. The sieving-percolation or rolling mechanisms, Sections 3.5.1.1 and 3.5.3 respectively characterises the size segregation process. The measured difference in density for the glass and iron sphere materials utilised in Figure 19 is approximately 3.1:1.

Holmes [45] undertook density segregation experiments for an anthracite granular flourspar binary mixture where both materials were screened < 6.4mm & >3.2mm. The density ratio of the two components was 2.2:1. Sampling a conical heap formed with this mixture showed that the heavier flourspar particles accumulated in the centre of the heap.

The characteristic of density was analysed in isolation to all other influencing factors by the authors stated in this section. They show density to be a significant characteristic in contributing to mixture segregation in the absence of any other characteristic.

3.7.1.3 Particle Shape

Shape factors are often used to describe the shape of two fractions that form a binary mixture. However, the type and magnitude of the shape factors must be selected carefully so that they describe sufficiently the shape of both fractions under consideration.

Drahun and Bridgwater [37] conducted investigations into the shape characteristic where they monitored the segregation of tracer particles that were different in shape compared to the bulk material. In conclusion, they stated that only for extreme differences in particle shape does this characteristic have any significant contribution to play in any resulting mixture segregation.

Shinohara et al. [53] undertook experimental investigations into segregation of binary mixtures that varied solely in particle shape when charging a vessel of the type shown in Figure 20. The general screening-layer model was adapted to accommodate for shape and used to predict the resulting segregation pattern in the experimental apparatus. The governing factor of particle movement used in predictive calculations was deemed the penetration rate of angular particles. This mechanism was induced by the sieving-percolation mechanism, through a layer of spherical particles when voids in the continually expanding and contracting spherical particle layer permitted. Results of the authors work are shown in Figure 20 and indicate a good comparison between experimental and predicted results.

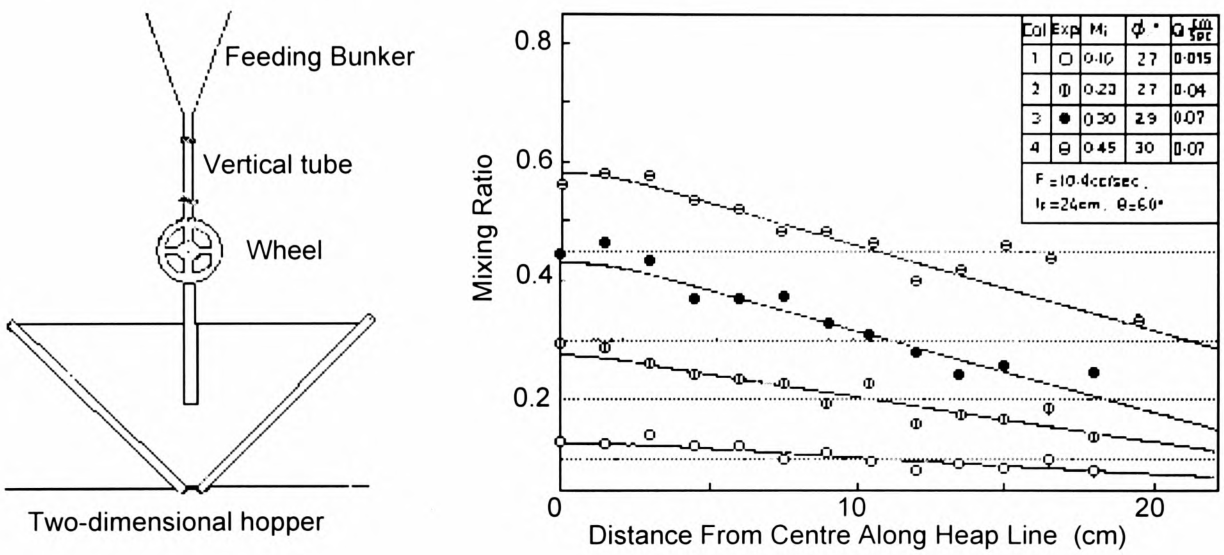


Figure 20 Actual and Predicted Patterns of Shape Segregation for Different Initial Mixing Ratios of Angular Particles. [53]

For the four different volumetric fractions of the segregating angular component (Mi) of a spherical and angular mixture, the angular component was found to segregate around the vicinity of the feed point. This indicates that a pattern of segregation for mixtures different in shape is similar to that of mixtures differing in density and size. However, the mechanism of segregation pertaining to shape is different. According to the author, the non-spherical or angular particles percolate through the flowing mixture when permitted to do so by the expanding/contracting flowing spherical layer under shear stress until they attain a lower heap position. At this point the angular particles separated from the mixture slide down slowly under the influence of the upper flowing layer of particles remaining from the original poured mixture. There is a slight difference in density between the spherical glass and the angular calcite particles of approximately 1.1: 1 used by Shinohara [53] therefore, some caution must be taken on drawing any conclusive statements from his work. However, there is good correlation of predicted segregation patterns with experimental results using the proposed form of the screening layer model, the derivation of which can be found in greater detail in Section 3.9.3.1 page 95.

3.7.1.4 Particle Roughness

There is some conjecture as to the point where the roughness of a particle is deemed excessive enough to be deemed a separate entity to that of particle shape. The roughness properties of particles that comprise the mixture, are often characterised as the coefficient of friction, which influences the frequency and duration of avalanching within the heap process. Particle roughness will dictate the influence of the sieving-percolation and rolling mechanisms. Of the number of articles included in this review, only Drahun and Bridgwater [36] make any definitive statements as to the influence of this characteristic. They suggest that from their experiments the influence of surface roughness was slight. Particles used by the authors rendered smooth by coating with P.T.F.E. or rough by coating with adhering powder showed unchanged segregation behaviour.

3.7.1.5 Particle Resilience

This characteristic was documented by the work undertaken by Bridgwater et al. [39] who reference particle resilience as being important given appropriate mixture constituents and segregating environment. Williams and Khan [49] undertook some coefficient of restitution experiments to determine whether its influence was significant in altering the segregation tendencies of binary mixtures that they were investigating. The coefficient of restitution values of different sized fertiliser granules was determined by dropping particles onto a Perspex plate from a fixed height and measuring their rebound height. The authors found that the value of the coefficient of restitution varied from 0.45 for 914μm particles to 0.04 for 138μm. They concluded that this variation in coefficient of restitution for the sizes tested was partly responsible for differences in patterns of segregation experienced for some of their test conditions.

Lawrence and Beddow [47] investigated the influence of the restitution characteristic. They considered it a significant factor in contributing to the segregation of a binary mixture when centrally filling a die that has an incorporated free fall height factor. The authors concluded that the coefficient of restitution is a function of particle size and below a critical value the segregation of small mean diameter mixtures are unaffected by bouncing associated with coefficient of restitution induced by free-fall heights. Experimental evidence of the relationship of coefficient or restitution with particle sizes of lead shot used in their die filling test program is shown below

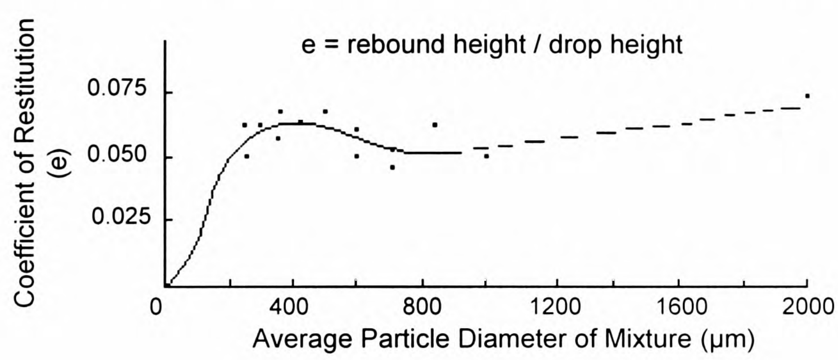


Figure 21 Relationship of Coefficient of Restitution for Various Sizes of Lead Shot Particles. [47]

The marked reduction in measured coefficient of restitution for particle sizes below 250μm indicates that the coefficient of restitution is greatly influenced by particle size. This suggests that any mixture comprised of particle sizes of this order which employ a free fall height when forming a heap will not readily segregate when the size of particles fall below this critical size. Validation of this can be seen from analysis of Figure 27

Under certain circumstances, the coefficient of restitution, which describes the resilience of the particle, can produce obscure patterns of segregation within the realms of the heap segregation. It is possible for the characteristic of restitution to influence a pattern of inverse segregation as shown on Figure 25 in Section 3.7.2.1.2. Carson et al. [1] documented this phenomenon for a plastic pellet mixture of various sizes, shapes and resilience. The resilience of the small particles was very high and because the mixture was centrally charged into a vessel the dominant particle characteristic of resilience dictated the resulting pattern of segregation. This subsequently caused the small particles to congregate at the periphery of the bin and the less resilient, large particles to accumulate in the centre of the vessel.

3.7.1.6 Particle Attraction

In terms of free-flowing particulate solids, particle attraction as a function of particle size is not common for particles greater than approximately 100μm or when the absolute particle mixture size is greater than 500μm. Constituents of a mixture whose sizes are of this order or less will succumb to the influences of particle attraction commensurate with the classification of a cohesive powder, as described in Section 2.1.2. Therefore, in terms of particle attraction, forces to be considered are those directly influencing the individual movement of particulates of the bulk. These may take the form of electrostatic, magnetic or adhesive forces induced by inherent or surface moisture etc.

Particle attraction has been documented as being very influential and utilised throughout the foodstuffs industry [9]. In only a few cases are foodstuffs regarded as totally inert, an example of which are grains, which follow the segregation patterns associated with model cohesionless mixtures. More often than not, large groups of food powders exhibit some degree of particle affinity between mixture constituents. This therefore makes them susceptible to segregation and mixing in a significantly different manner to that of classic free flowing cohesionless powders.

3.7.1.6.1 Moisture

Part of an extensive investigation of work undertaken by Bagster [54], [55], [56] involved analysis of how segregation was affected by the presence of moisture in binary sized mixtures. The salient parts of the experimental testing facility utilised by

Bagster can be found on Figure 26, Section 3.7.2.2. A graphical interpretation of the affects of adding moisture to binary mixtures tested in this form of rig can be seen in Figure 22.

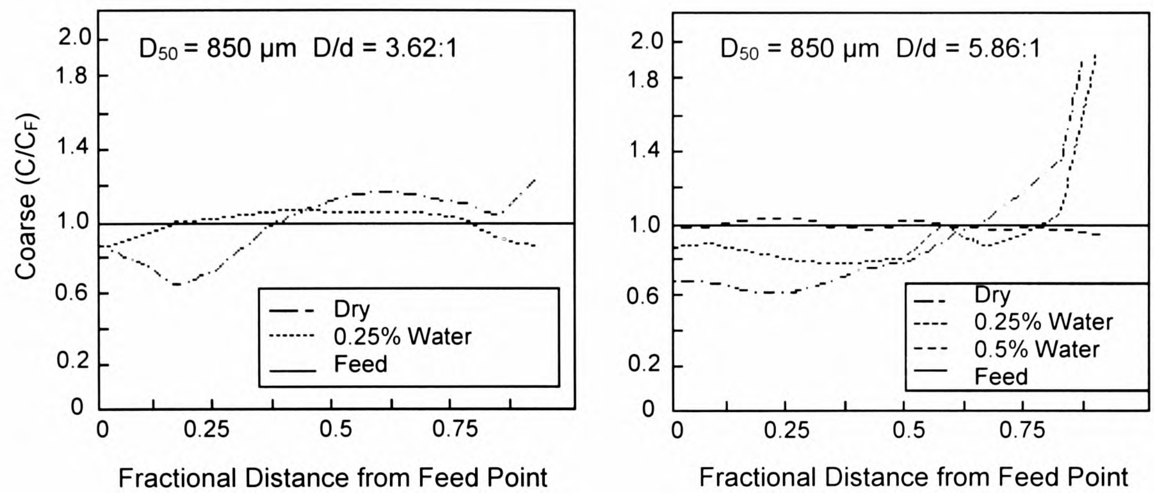
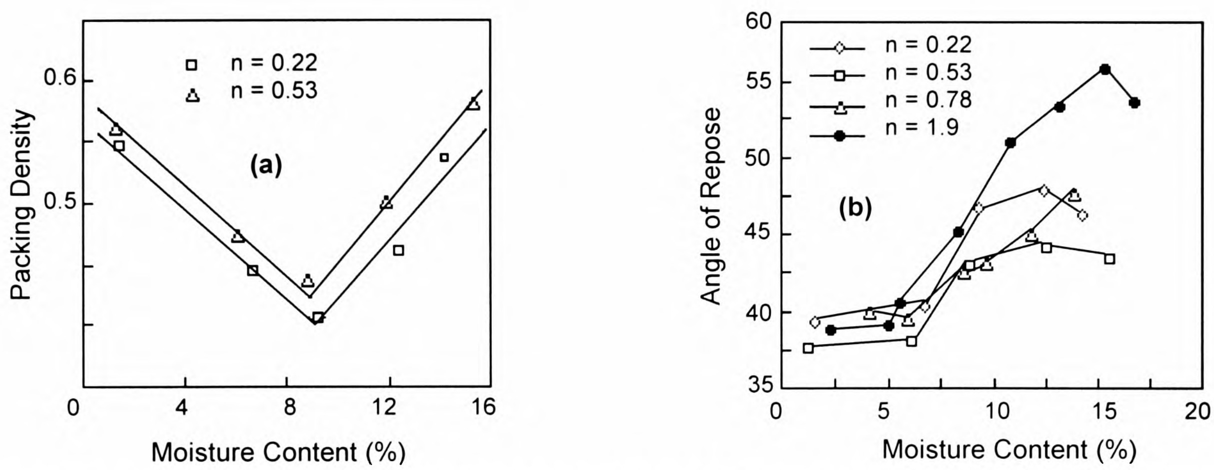


Figure 22 The Affect of Adding Water to Two Grades of Binary Sand Mixtures [54]

As can be seen moisture inhibits the susceptibility of the particles to segregate within this regime of flow. Adding only one quarter percent of water to the various small particulate sands made a significant difference to the pattern of segregation produced. Adding half of one percent was sufficient to counterbalance segregation completely to produce a mixture with relatively no segregation due to size differences of the mixture. Although only a small amount of water is sufficient to alter the segregation pattern of the mixture, this may not be applicable in practice, if for example you are handling or processing hygroscopic materials. However, in terms of handling minerals and ores this may be a practical solution to the segregation problems experienced when handling materials of this type and could conceivably reduce the possibility of dust problems.

Standish et al. [26] [27] provided documented evidence that the addition of moisture to coal when stockpiling changes the packing density of the bed. The packing density was defined as the ratio of bulk density to particle density and was dictated by segregation of particles sizes when forming the stockpile. Coal was sieved into appropriate size fractions. The magnitude and number of particle size fractions was represented by the Rosin-Rammler [57] size distribution function for which the mixture was graded to fit. Mined coal has a naturally occurring particle size distribution that is described well using the Rosin-Rammler function. Two variables of the function describe the size distribution of the coal. Firstly, the median size gives a description of the absolute size of the distribution. Secondly, a variable 'n' characterises the magnitude and range of sizes incorporated into a formulated size distribution i.e. 'n' characterises the 'steepness' of the cumulative undersize curve of the size fraction. For the purposes of the work undertaken by Standish et al. the restriction of the maximum particle size of the material meant that the size distribution of the mixture could be successfully represented by using only one variable, '*n*'. As '*n*' increases the width of the size distribution of the coal mixture decreases. This technique was used to quantify the size distribution of the mixture tested and then applied to assess the influence moisture has on the resulting packing density produced.



n = Method used to quantify size of coal fraction based on Rosin-Rammler distribution function [57]

Figure 23 The Influence Moisture Has on the Packing Density and Angle of Repose of Coal Mixtures When Stockpiled. [26]

As can be seen from Figure 23(a), the addition of moisture has an unusual influence on the overall packing density of the stockpile formed. As the moisture content is increased up to approximately 9%, the packing density decreases. This is because agglomerates are being formed, resulting in an adhesive mixture structure where small particles attach to large ones, as per the definition in Section 2.1.5. The resulting segregation of the stockpile is restricted and hence the stockpile packing density reduces. Up to this point, the quantity of moisture has no affect on the frequency and duration of avalanching. However, further increases in moisture content resulted in increased packing density due to cohesive forces among all particles becoming high enough to alter the occurrence and extent of avalanching. This subsequently increased the overall packing density. Analysis of Figure 23(b) for the four particle size distributions used, indicate that the addition of moisture in similar proportions to that on Figure 23(a) increases the angle of repose formed by the stockpile. It was also shown that the particle size distribution affected the angle of repose formed. Indications are that increasing the moisture content still further would start to decrease the angle of repose formed when stockpiling the coal.

The available evidence suggests that where appropriate, the addition of moisture can greatly reduce the segregation tendencies of free-flowing particulate materials. This may significantly benefit the handling and processing operations that can utilise such a counteractive measure to tackle detrimental segregation.

3.7.2 Geometric Variables

The geometry of any proposed storage vessel or holding section of a process will dictate an environment that influences the type and extent of mechanisms that comprise the heap segregation process.

3.7.2.1 The Position and Angle of Charge

During the filling stage of a vessel a heap will be formed. The geometrical location of the subsequent heap apex will be dictated by the angle and position of charge. This may cause an offset of the normally encountered concentric heap being formed and therefore greatly influence the predominant direction of the flowing layers within such a vessel. This can result in an obscure pattern of segregation being formed in the bin after charging, which can subsequently influence preferential flow patterns upon discharge, leading to erratic discharge and eccentric structural loading on the vessel walls. A schematic illustration of these patterns of segregation can be seen inFigure 24 and Figure 25.

3.7.2.1.1 Segregation with Gravity Flow

As outlined previously in Section 3.5.6, charging a vessel via an angled chute or conveyor can present an already partially segregated mixture to the charging point of the vessel. This view was well documented by Johanson [20] and Carson et al. [1] who highlighted that mechanisms of segregation could be induced into the material as it travels in its conveying environment to the point of vessel charge. The subsequent mixture being discharged from a conveyor into a vessel will often be pre-segregated with small particles at its base, large particles at the top. Therefore, segregation due to the trajectory mechanism when charging will be encouraged to de-mix this material still further.

Arnold [22] [23] highlighted that in the majority of documented literature pertaining to segregation, the majority was concerned with the variability of the bulk solids discharging from the vessel. It was often an oversight that segregation, as a direct result of charging, could significantly dictate the resulting preferential pattern of flow of the bulk material upon discharge. Segregation due to point of charge or position can initiate the trajectory mechanism to induce an uneven segregation pattern across the width of the vessel. An illustrative example of such a pattern can be seen in Figure 24.

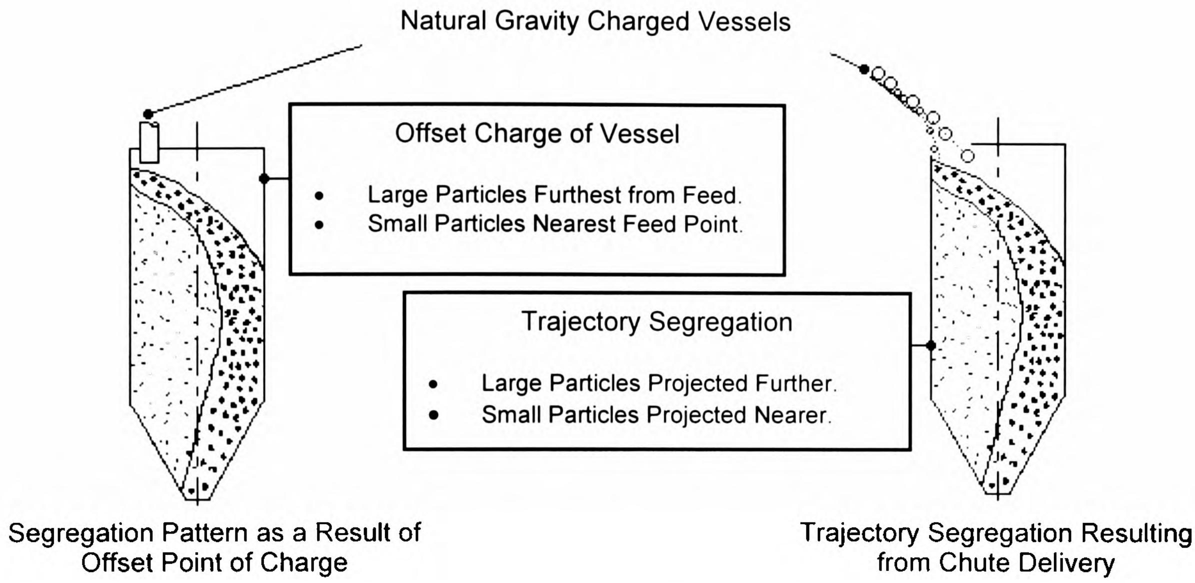


Figure 24 Non-Symmetric, Eccentric Discharge from a Symmetrically Designed Vessel as a Direct Result of Point and Angle of Charge. [22] [23]

Material that should yield a symmetric flow pattern upon discharge if centre point charged now results in a non-symmetric, eccentric flow pattern with uneven loading and preferential wear on certain areas of vessel walls.

3.7.2.1.2 Segregation When Pneumatic Charging

The combined affects of the point or angle of charge with non-gravity induced methods to convey the charging material could dictate a complete opposite pattern of segregation within the vessel. Mechanisms of segregation induced by pneumatically charging a vessel have previously been outlined in Section 3.1.3. Arnold [22] [23] documented this behaviour and suggested that it can severely alter the resulting preferential pattern of flow in the bin upon discharge.

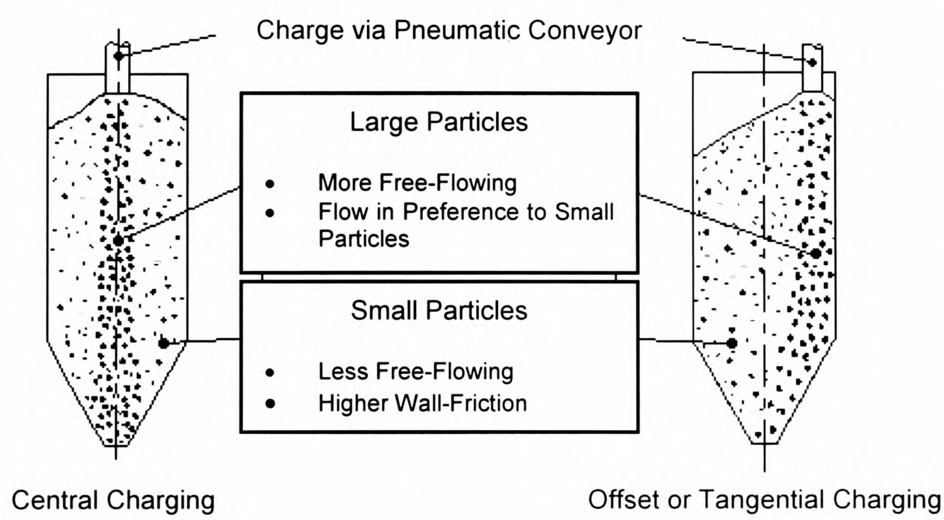


Figure 25 Potential Distribution of Small particles as a Direct Result of Point of Charge Utilising Air as Conveying Medium. [22] [23]

As can be seen from Figure 25 the geometrical position of the charging point coupled with the high proportion of air associated with pneumatic conveying results in types of the 'reverse segregation' pattern. The resulting pattern of flow upon discharge will be affected by the position of the free-flowing large particles in the vessel. Their position within the vessel may induce it to exhibit a funnel flow regime of discharge with a severe tendency to flooding. A cyclone separator is often incorporated into the system prior to material being charged to a vessel in order to alleviate conditions that induce inverse segregation. Results of this were shown previously on Figure 4, Section 3.1.3.1. However, care must be taken when utilising a cyclone that discharge from the cyclone does not produce resulting drop heights that can still promote an environment for initiating some form of inverse segregation pattern. Devices such as the fill pipe utilised by Fürll [24], Figure 4(c) in Section 3.1.3.1, are common additions to such systems to inhibit an environment in which an inverse segregation pattern is created.

3.7.2.2 Vessel Geometry

Lawrence and Beddow [47] recognised that by reducing the diameter of their die, segregation of the subsequent charged material was reduced. A reduction in die geometry subsequently reduced the time taken for it to fill, which in turn reduced the time available to allow mechanisms of segregation to propagate.

Matthée [40] provides experimental evidence of different magnitudes of segregation, measured as a function of vessel diameter. The author observed that the number of small particles that reached the periphery of the heap being formed is reduced as the diameter of the vessel increases. This is to be expected, as an increased vessel geometry would subsequently increase the heap length produced. Consequently, this increases the probability of a small particle being removed from the flowing/avalanching layer by one of the mechanisms of the heap segregation process.

Bagster [54] [55] [56] provided documentation of experimental investigations into how heap lengths influenced the resulting segregation pattern in his experimental testing facility. In order to gauge the affects of the heap length it was imperative to the author to recognise the influence of other variables that affected segregation i.e. size, shape, density, resilience and roughness etc. Such recognition would allow each variable to be either eliminated or held constant in order to analyse one aspect of segregation. The schematic layout of the rig used to achieve this aim along with results of investigating the variation in heap length can be seen inFigure 26.

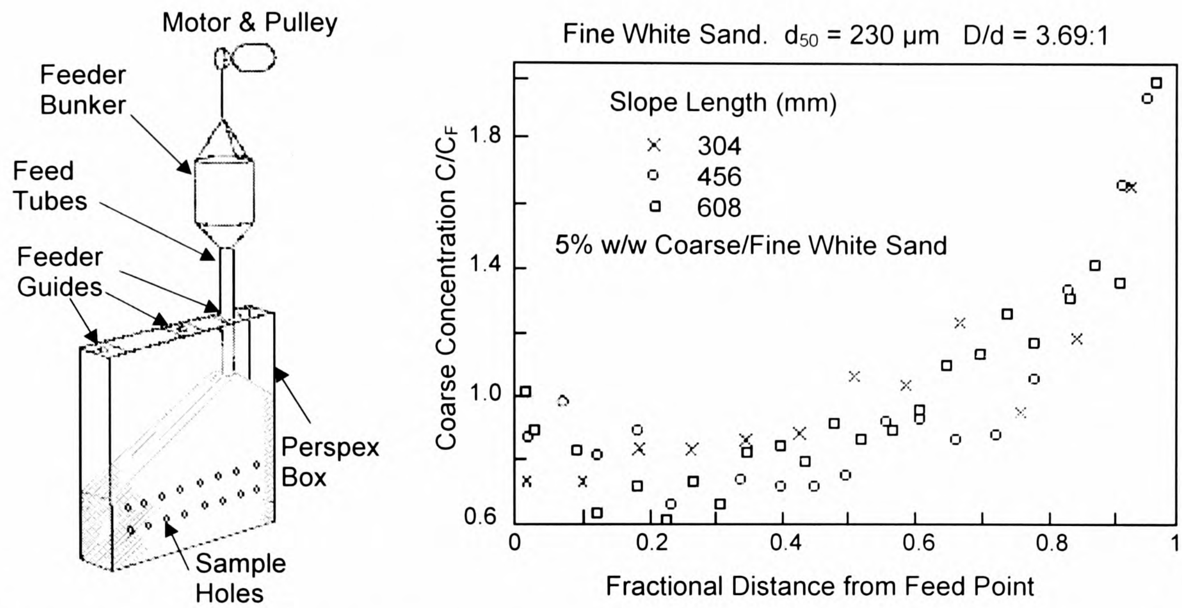


Figure 26 Pattern of Segregation for Different Heap Lengths Using a Regime of Flow Initiated by Illustrated Testing Facility. [56]

One inherent advantage of using a rig of this design was that a constant build up of heap could be achieved without any free fall height and hence kinetic affects influencing the resulting pattern of segregation. Lateral velocity of particles, which might have induced an environment that facilitated the trajectory mechanism, was eliminated. The concentration profiles of mixture segregation produced in this rig for different slope lengths are shown on Figure 26. This indicated that for the heap lengths tested, vessels charged with mixtures that are restricted to the same regime of flow and whose vessel diameter dimensions compare to those tested in the rig by Bagster will segregate to the same degree. There is some spread of the points for the profiles but this may be attributable to possible inhomogeneities of the feed mixture, and the fact that the sample points are not parallel with the heap surface being formed. This non parallel positioning of probes resulted in the sample probes directly under the feed point containing material built from a small heap whereas the probes farthest from the fill point will contained material formed from a bigger heap.

Although Bagster indicated comparable patterns of segregation irrespective of vessel geometry used, it was felt that in general, large differences in geometry will reduce the time of fill and hence the time that permits segregation to occur.

3.7.2.3 Free-Fall Height

Free-fall height induced into a charging mixture is a function of the geometry of the storage vessel. Lawrence and Beddow [47] investigated the affects of variations in free-fall height of the feed stream during vessel charging. Their investigations focused on how the free-fall height was influenced by variations in diameter ratio and mean diameter of binary mixtures tested. These results can be seen on Figure 27.

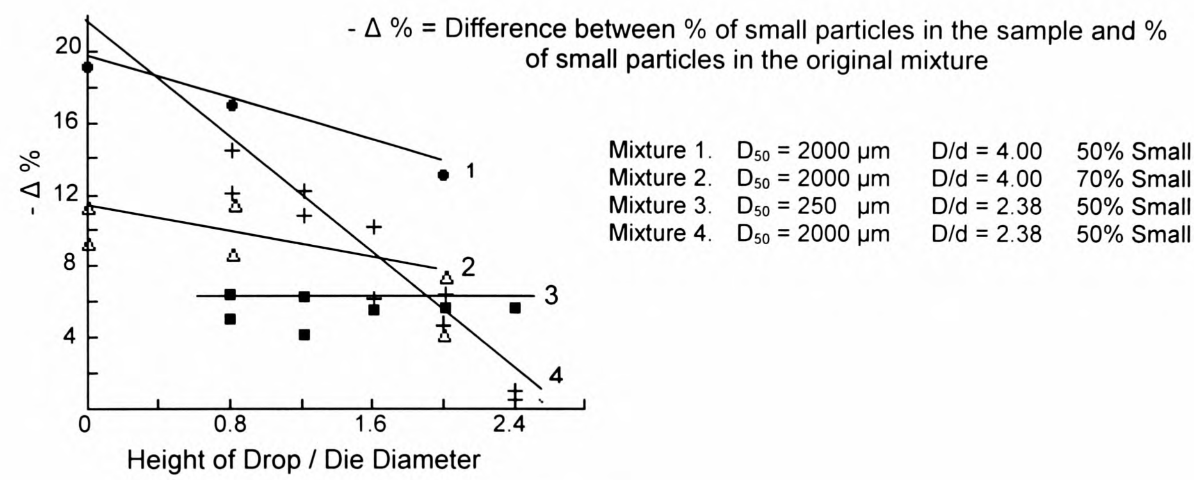


Figure 27 Influence of Varying the Height of Drop Upon Segregation for Various Lead Shot Particulate Mixtures [47]

When the mean diameter of the mixture was sufficiently large, the segregation was observed to depend inversely upon the height of drop and was relatively unaffected by the proportion of small particles in the mixture. However, for low values of mean diameter the free-fall height was insignificant in altering the pattern of segregation of the charged mixture. The authors claimed that the small mean diameter mixture was unaffected by the free-fall height due to the 'coefficient of restitution' particle characteristic, as documented in Section 3.7.1.5. According to the definition, low mean diameter mixtures have reduced bouncing behaviour and subsequently the influence of the free-fall height is restricted. It is also possible that the number of particle-to-particle collisions as a direct result of their reduction in size can affect the final resting position of particles of the mixture.

Drahun & Bridgwater [37] undertook some investigations in order to ascertain the importance of free-fall height, the results of which can be seen on Figure 28.

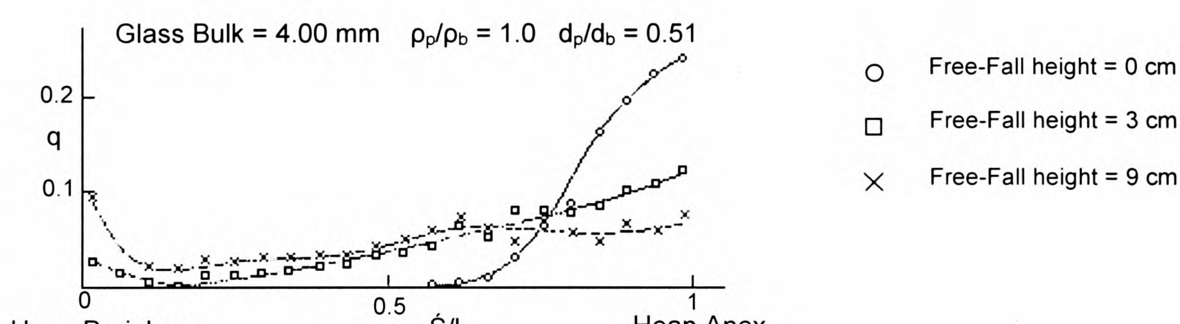


Figure 28 Distribution of Glass Tracer Particles for Three Different Free-Fall Heights. [37]

The definition of the symbols on Figure 28 can be found on Figure 13. The distribution of tracer particles along the heap length is noticeably affected by the three different free-fall heights tested. The authors state that it was possible to achieve a bi-modal distribution pattern as a direct result of small particles being positioned near the feed point and others being displaced to the end of the heap. The reasoning behind this is attributed to the following behavioural characteristics of the particles. Firstly, free-fall height will increase the momentum of small or less dense tracer particles in the feed. However, this is insufficient for them to embed or force their way through the avalanching layer. Consequently, particles bounce off the heap surface to a position away from the heap apex. Secondly, free-fall height increases the momentum of large or denser tracer particles of the feed. These are more likely to break through the avalanching surface and embed around the feed point.

Holmes [45] undertook investigations into the influence of free-fall height when charging a conical heap with a binary mixture differing only in density.

Section Number	Percentage Sink	
	Test No 1 Approximately 6-in Fall	Test No 2 Approximately 6-ft Fall
1	13.3	17.5
2	13.7	15.2
3	12.6	13.6
4	16.3	19.3
5	17.5	19.4
6	3.9	1.5
7	4.2	1.3
8	7.5	2.8
9	7.9	3.1
10	12.0	18.6
11	8.8	17.3

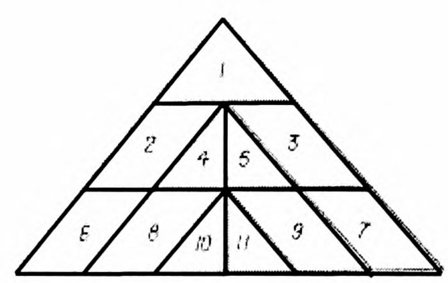


Figure 29 Distribution of Particles as a Direct Result of Free-Fall Height during Stockpiling. [45]

As can be seen from Figure 29 increasing the free fall height from 0.15m to 1.8m significantly altered the pattern of segregation of the heavy and light particles of the charged mixture.

In relation to stockpiling, the results provided by Standish [26] [27] of laboratory scale stockpiling of coal compares favourably to industrial stockpiles with respect to the influence of free fall height of the charging mixture.

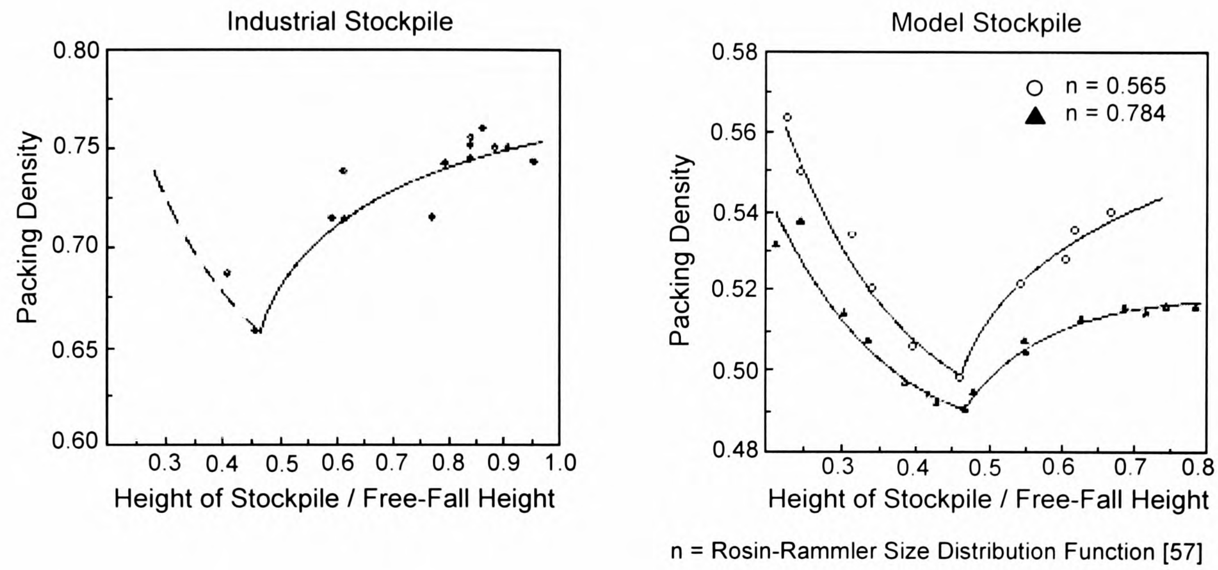


Figure 30 The Influence Free-Fall Height has on the Packing Density of a Stockpile. [27]

The author explains that as the size of the heap increases, the free fall height reduces and hence the compaction due to the momentum of the charging particles is also reduced. Subsequently, the overall packing density reduces. However, after the size of the heap has increased further the weight of the material within the stockpile together with increased impacting of the feed onto the heap surface will cause compaction of the material. Consequently, the overall packing density increases. The author also stressed that the feedrate of the charging mixture will also dictate a reduction and increase in packing density associated with free-fall height affects.

Standish [32] highlighted the combined influence free fall height and particle density had on dictating the different patterns of segregation for iron ore and coke mixtures that charged a storage vessel. Graphical representations of these results were shown previously on Figure 8, Section 3.1.4.4. There is a difference in segregation pattern between small ore particles, Figure 8(d) and large iron ore particles, Figure 8(b). This was attributed to a mechanism of segregation induced by a particle characteristic other than size. This profile or pattern of segregation was dictated by the difference in densities of ore and coke. The density of ore was approximately 4.5 times greater than coke, resulting in different momentum's of particles of the coke and ore mixtures. Examination of Figure 8(b) indicates that as the free fall height is reduced as a consequence of vessel filling, the momentum of the large ore particles is reduced and subsequently the influence of the embedding mechanism is inhibited. This is denoted as the inverted hollow triangle symbols on Figure 8(b) which shows a systematic reduction of concentration of large ore particles at the centre of the vessel as the height of the vessel increases. The large coke particles were generally unaffected by the embedding mechanism due to being less dense in comparison to the ore particles. Therefore irrespective of their free fall height, the pattern of segregation of large coke particles entering the vessel remained consistent. This is denoted by the circular, square and inverted solid symbols on Figure 8(b). The small ore particles on Figure 8(d) attained a relatively higher momentum than the small coke particles as a direct consequence of differences in particle density. However, the momentum of these small ore particles was not sufficient to cause the embedding mechanism and hence break through the heap surface upon contact with the surface. Instead, the small ore particles of higher momentum induced the action of the trajectory mechanism. This resulted in the highest concentration of the small ore particles bouncing away from the fill point to a position either side of the vessel centre. This is denoted by the hollow circle, square, triangle and inverted triangle symbols on Figure 8(d). The small coke particles of lower particle density built up insufficient momentum due to the imposed free-fall height of the filling process and therefore did not have sufficient momentum to significantly bounce away upon contact with the heap surface. This is conspicuous by finding the highest concentration of small coke particles at the centre of the vessel at all vessel heights. Subsequently the mechanism of sieving-percolation within the heap segregation process influenced the final deposited position of the small coke particles.

3.7.3 Process Variables

The formulation of appropriate mixture constituent proportions in order to effect the correct action or reaction of a process can influence the priority of mechanisms of heap segregation. In addition, the speed of a process fixes the amount of mixture handled per unit of time. This could also significantly influence the type and extent of mechanisms that categorise heap segregation.

3.7.3.1 Batch Feeding

Johanson [20] documented the possibility of a mechanism of segregation resulting from constituents of the mixture having large differences in their natural angles of repose. The author postulates that these different repose angles can cause the final resting positions of constituents to be somewhat at odds with normal positions influenced by the mechanisms associated with heap segregation. It is clear that in this situation the resulting pattern of segregation is a direct result of the differences in angle of repose of the mixture constituents. Whilst this might be a behavioural facet that can be categorised according to particle characteristics, the process of batch or feeding a vessel or process operation can significantly exacerbate this behaviour, hence its categorisation as a process variable. Similar conclusions were drawn by Mosby et al. [16]. Both authors illustrate angle of repose segregation behaviour associated with vessel filling of a mixture in batches of separate constituents. The definition of the angle of repose mechanism was previously documented in Section 3.5.8 and will preferentially initiate segregation by angle of repose of the constituents and not by size.

3.7.3.2 Feedrate

Lawrence and Beddow [47] commented on the fact that if the time taken to fill their die under investigation was reduced, then the resulting segregation also significantly reduced. This view was complemented by Holmes [45] who undertook investigations into the influence feedrate had on the resulting segregation produced when charging a conical pile with a binary mixture of coal. Holmes concluded that rapid formation of the conical heap tends to inhibit segregation. This conclusion seems plausible since an increase in feedrate will reduce the time allowed for mechanisms of segregation to influence particle separation within the avalanching layer as it descends the heap surface.

3.7.3.3 Proportions of Mixture Constituents

As highlighted in Section 3.7.3, it is often a requirement of a process to feed in a stipulated proportion of one mixture constituent with others to achieve the desired reaction. This reaction may take the form of chemical reaction rate, colour or degree of flavour etc. This can influence the type of mechanism associated with heap segregation. Lawrence and Beddow [47] highlighted this affect by varying proportions of large to small particles for a 2.36:1 diameter ratio binary mixture subjected to heap segregation. The authors postulated the theory that the proportions of small particles in the charging mixture dictated the severity of mechanisms of segregation associated with heaping. An extensive testing program was undertaken to assess this affect by sampling both radial and vertical positions within a charged die.

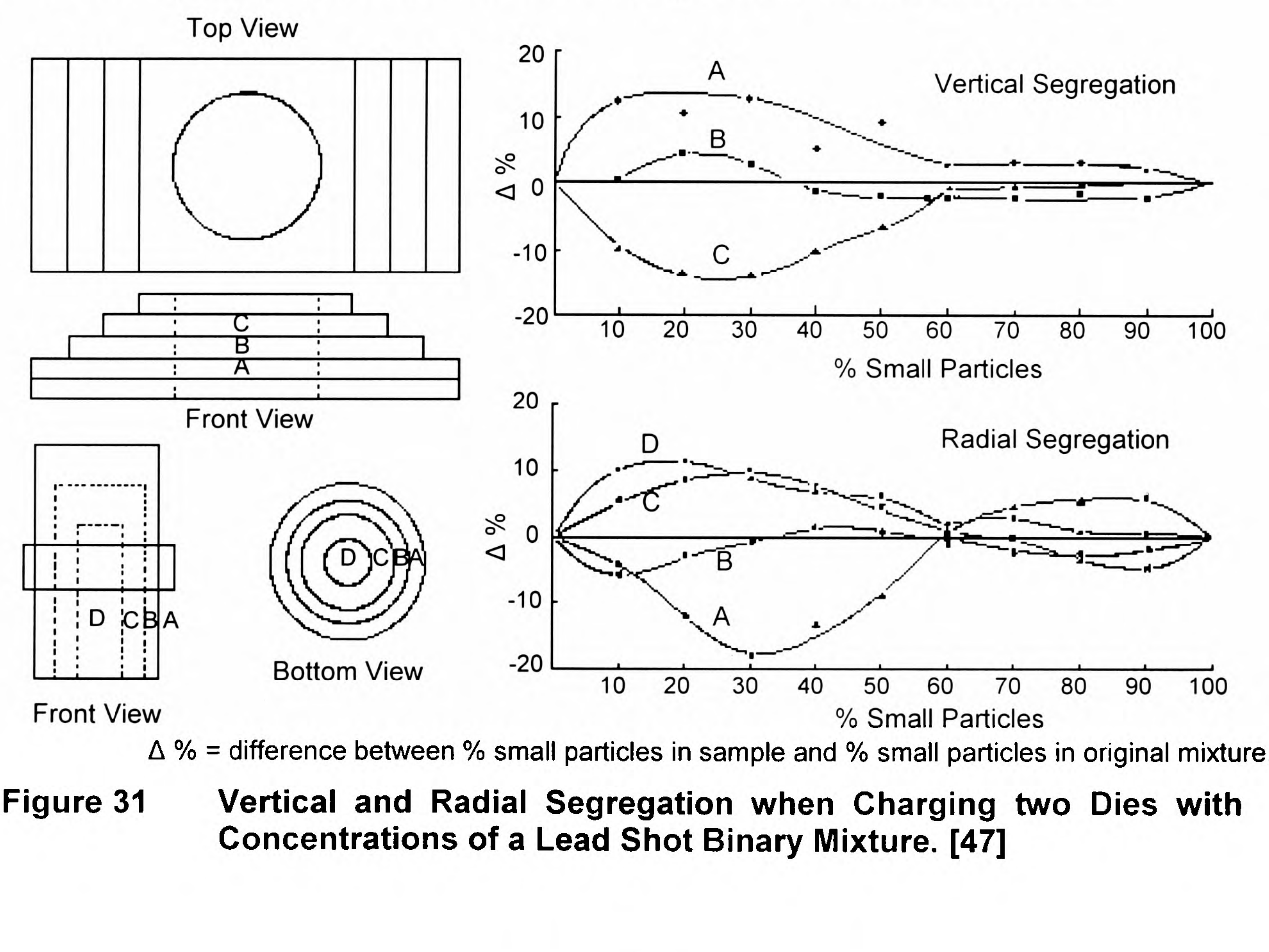


Figure 31 Vertical and Radial Segregation when Charging two Dies with Concentrations of a Lead Shot Binary Mixture. [47]

According to Lawrence and Beddow, as the proportion of small particles increases, > 60% on Figure 31 to give a highly saturated, predominantly small particulate mixture, the pattern of segregation will change. The pattern produced is akin to the 'inverse' segregation pattern when pneumatic central point charging a vessel i.e. Figure 25, Section 3.7.2.1.2. The authors speculated that for highly saturated small particle mixtures the large particles are unable to flow through a matrix of small particles and thus will settle out and accumulate under the vicinity of the feed point. For highly saturated large particle mixtures the pattern of segregation of the mixture resembles the normally observed segregation pattern of small and large particles as observed on Figure 8, Section 3.1.4.4. However, this speculation contradicts Drahun and Bridgwater [37] who provide evidence that for a binary mixture highly saturated with small particles, the large particles, influenced by the mechanism of migration, still find their way to the heap periphery. This is illustrated on Figure 13 in Section 3.7.1.1. This contradicting behaviour was discussed previously in Section 3.6. However, irrespective of the mechanisms or final deposited position of large and small particles of the mixture, all the documented literature that investigated the affect of mixture proportions indicated that constituent mixture proportions significantly determined mechanisms of segregation.

Bagster [54] [55] [56] undertook an investigation into the consequences of changing the concentration of large particles in a mixture. In all cases, mixtures differed only in size. The resulting segregation was quantified utilising an index of segregation as described in Section 3.9.1.4. The affect of large particle concentration in a binary sized sand mixture for a single diameter ratio can be seen on Figure 32(a). Figure 32(b) groups together all results of diameter ratios and concentrations assessed using an index of segregation derived in Section 3.9.1.4.

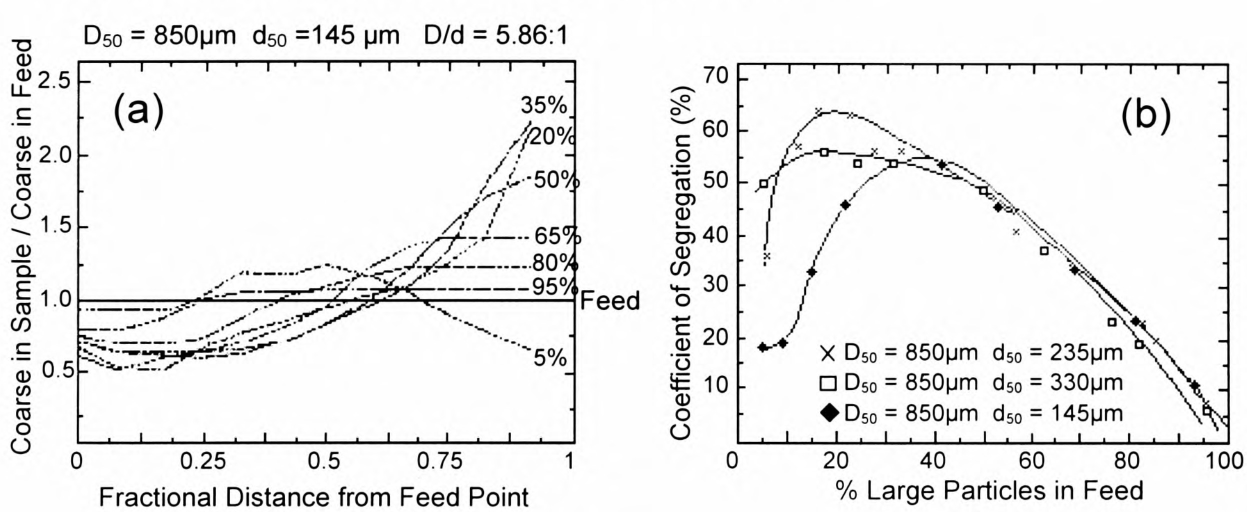


Figure 32 Pattern of Segregation for Various Concentrations of Large Particles in Binary Sized Mixtures. [54]

The majority of the results indicated a mixture whose behaviour was compatible with those defined and denoted as solid triangles on Figure 38, for mixtures whose differences in size were larger than density. Consequently, the large particles behaved as 'floaters'. An exception to this, where the large particles behaved like 'sinkers', was found for 1, 3 and 5% large particle concentration mixtures whose large and small particle diameter was 850µm and 145µm respectively. This differing behaviour was possible when the mean diameter of the mixture was taken into consideration. The 1, 3 and 5% mixtures had a mean diameter of 497µm, which, according to Figure 16, Section 3.7.1.1, on page 57 meant that this mean size could significantly influence the resulting pattern of segregation. For all other mixture conditions tested by Bagster, the mean diameter of the particles was far from a mean diameter value that was considered significant in influencing the resulting pattern of segregation. The 1, 3 and 5% test conditions were repeated for three different heap lengths but the resulting pattern of segregation remained unaltered.

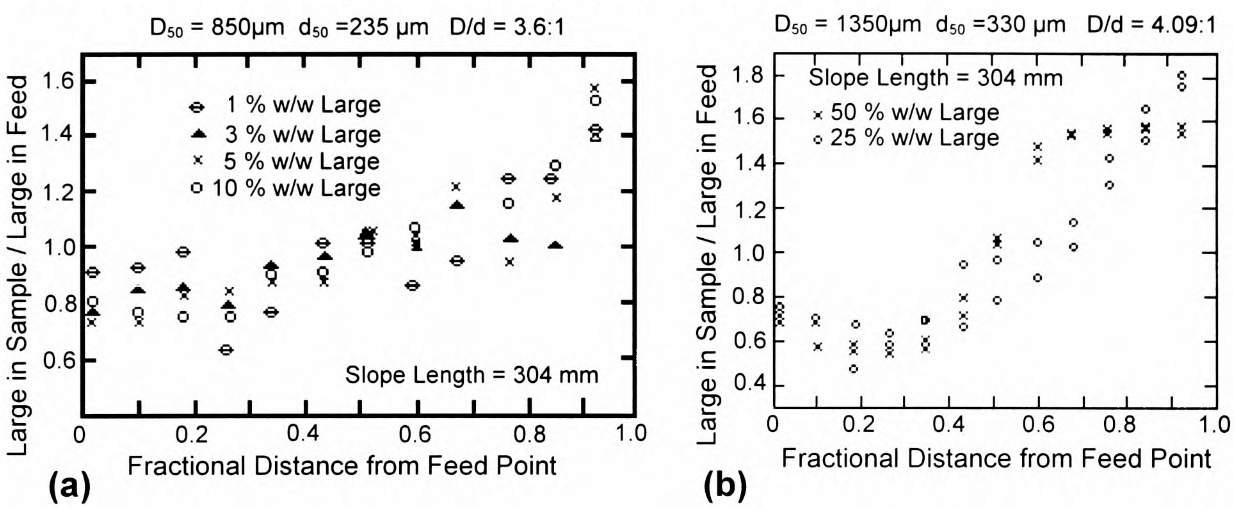


Figure 33 Various Patterns of Segregation for Increasing Large Particle Content of a Binary Sized Sand Mixture. [55]

As can be seen from Figure 33(a) for concentrations of large particles up to 10% by weight, the profile of segregation is reasonably consistent. This indicated that no significant influence was contributed by the proportion of large particles within this region. However, analysis of the profile for greater concentrations of large particles in the mixture indicates the spread of results is more scattered, Figure 33(b). This suggests that higher concentrations of large particles did have some significance in influencing the segregation pattern produced. The author suggested that the method of normalising the concentration values for the abscissa on his graphical illustrations, was at best an approximation for low concentrations. However, this method was not advised for representing graphical illustrations of the segregation patterns for higher concentration ratios of large particles. This point is further discussed in Chapter 7.

3.7.4 Interactions Between Particle, Process and Geometric Variables

It has been touched upon previously in Section 3.7.3.3 that the combination of process, and particle characteristics will allow certain segregation mechanisms to combine to produce a unique pattern of segregation. This is only one example of the numerous interactions between particle, process and geometric variables that conspire to induce differences in patterns of segregation for the heaping process.

3.7.4.1 Size and Density

Williams [17] concluded that vibrating a mixture of particles of different sizes caused the large particles to rise to the top, irrespective of whether they were denser than the small particles. In comparison, vibrating a mono-sized mixture differing only in density will cause the denser particles to fall. Williams postulated that it might be possible to formulate a mixture combination of density and size, which would not segregate when exposed to a vibration regime of flow as differences in particle density, would cancel out differences in size. Williams experimental work utilising vibration as the means of instigating particle movement, indicated that this is not attainable as the larger particles will always be made to rise, whatever their density. However, this does not take into account the concentration of large to small particles in the mixture and the regime of flow. As shown on Figure 38 it is possible to make a large particle sink which is denser than the small particles for a specific concentration ratio and in a heaping regime of flow. More information on interactions between size, density and concentration can be found in Section 3.7.4.5.

Drahun & Bridgwater [37] postulated that it might be possible to formulate a mixture where a certain size and density ratio would cancel out heap segregation, Figure 34. They illustrated that an even distribution of tracer particles was attainable throughout the bulk material over the heap length by using bulk particles that were approximately 2.5 times denser and approximately 1.3 times larger than the tracer particles.

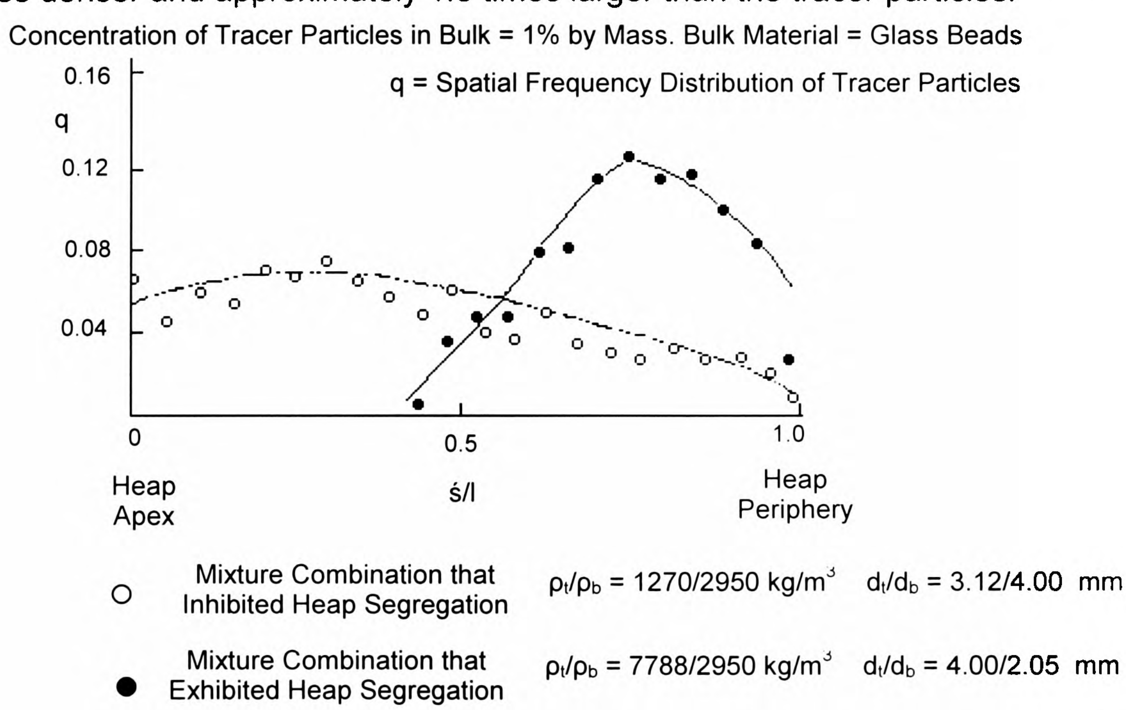
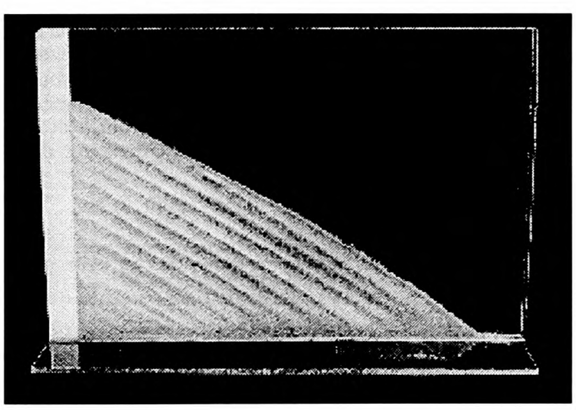


Figure 34 Illustration of Formulated Density and Size Binary Mixtures that Exhibit and Inhibit Heap Segregation. [37]

Further investigation into the relationship between size and density is required if the practical utilisation of this behaviour is to be employed to inhibit segregation in practice. Apart from concentration variations of large particles, the influence of other independent variables has not been quantified with respect to the interaction of size and density.

3.7.4.2 Size and Shape

Makse et al. [30] documented a unique perspective on shape and size interaction of constituents of a binary mixture that combine to produce visible stratification when forming a heap. In terms of size segregation, avalanching associated with heap segregation produced pairs of layers, with the small particles forming a sub-layer (darker in colour on Figure 35) underneath a layer of large particles (lighter in colour on Figure 35). Size segregation of constituents of the mixture was stated as being evident in all tests undertaken by the author, although not all results are documented in the literature. According to the author, the existence and degree of stratification was dependent on the large particles having a greater angle of repose than smaller particles. This difference in angle of repose was as a function of the mixture constituents having differences in shape.



Stratification and Segregation Produced from a Mixture of Three Different Constituents.

Spherical Glass Beads	d_{50} = 0.15 mm Angle of repose = 26^0
Blue Sand	d_{50} = 0.40 mm Angle of repose = 35^0
Red Sugar Crystals	d_{50} = 0.80 mm Angle of repose = 39^0

Figure 35 Proposed Size and Shape Interaction to Produce Visual Stratification and Segregation of a Mixture. [30]

A unique postulation has been presented by the author of the interaction of particle shape with size, where shape differences result in changes in angle of repose of the constituents and consequently induce stratification of the mixture.

- Segregation and the appearance of stratification were found to occur when using large cubic particles and smaller spherical particles. For this combination, the angle of repose of the large particles was greater than the small particles.
- Segregation with no visible stratification was achieved when the large particles were less faceted (more rounded) than the small particles i.e., the large particles had a smaller angle of repose than the small particles.

To confirm the authors philosophy irregularly shaped sand grains (angle of repose 35 degrees and mean particle size 300μm) were used as the base material. Firstly, two binary mixtures were composed by combining this base material with spherical glass beads of mean size 700µm and 1100µm. In both cases, the smaller particles being spherical had a smaller angle of repose and therefore the mixture resulted in stratification and segregation. However, when the base material was mixed firstly with spherical beads of 550µm and secondly with spherical beads 770µm so that the lager particles had a smaller angle of repose there was only segregation of the mixture. The appearance of stratification of the mixture was not observed. However, a graphical illustration of the absence of stratification from this test was not provided in the authors reviewed document. In addition, the influence and interaction of other particle, process and geometric variables may well have compounded the occurrence of this stratification phenomenon.

3.7.4.3 Size and Particle Attraction

Barbosa-Canovas et al. [9] provided comparative segregation results for two different regimes of flow when investigating the interaction of particle attraction with size for food powders that were susceptible to segregation. The two regimes of flow were classified as:

- Heap segregation when charging a two-dimensional plane flow vessel.
- Vibration tests using a split-cell container that enabled the determination of the concentration profile of small particles along its height.

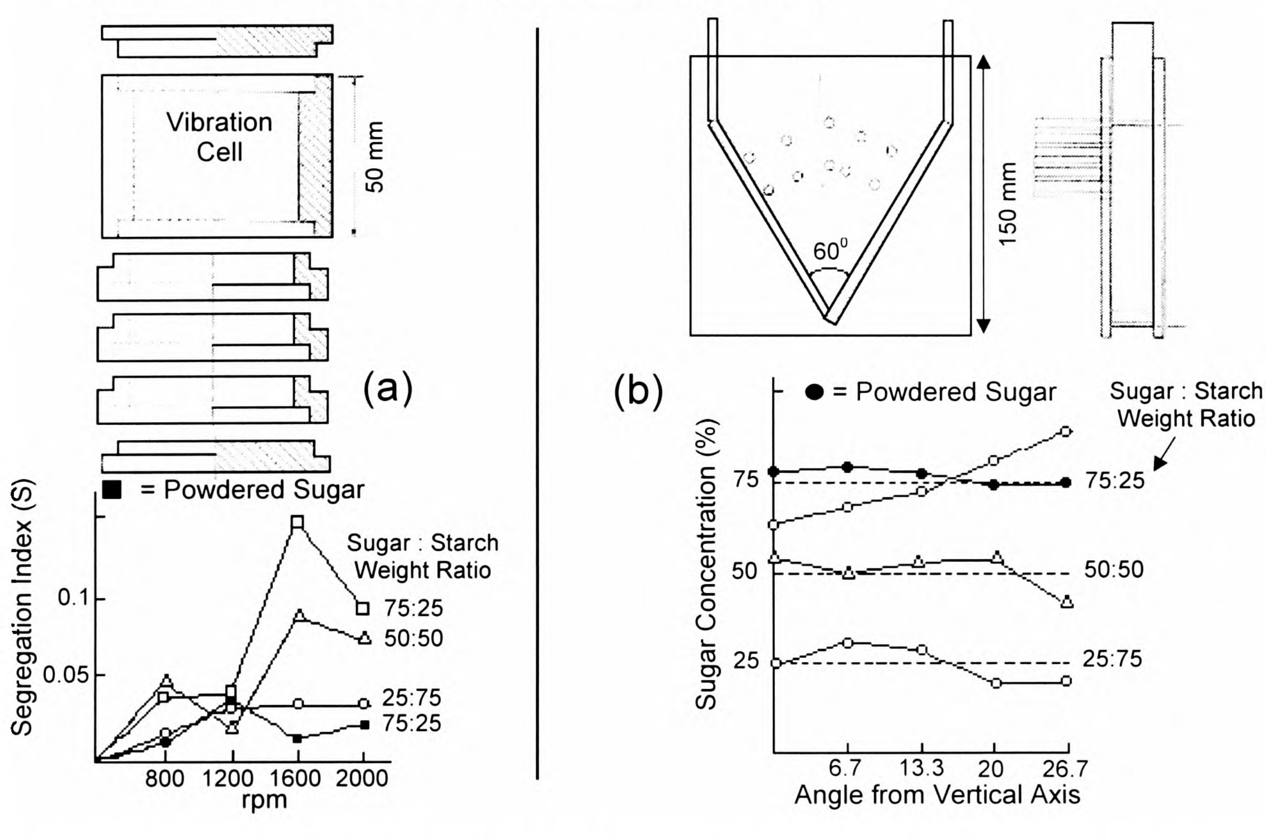


Figure 36 Segregation of Binary Sized Granular Sugar/Starch Mixtures Induced by Two Regimes of Flow. Segregation is Inhibited when Using a Sugar Mixture in Powdered Form. [9]

The cell design used to initiate and evaluate vibration-induced segregation is shown on Figure 36(a) together with a typical result. Also included on Figure 36(b) is an illustration of a heap inducing segregation test rig and an associated test result. Barbosa-Canovas et al. [9] used an index of segregation, as outlined in Section 3.9.1.3, to quantify the segregation in both types of testing facility.Figure 36 indicates particle attraction affects resulting from sugar/starch size segregation tests. Powdered sugar proved less likely to segregate than granular sugar. Figure 36(a) shows that when high vibration conditions are induced into the mixture, the measured degree of segregation was relatively small. The authors suggested that granular sucrose and starch powders could form, depending on concentration, various types of ordered/ adhesive mixtures whose segregation tendency was inhibited by the inherent moisture within the sugar and starch particles. Sugar and instant coffee mixtures of the same concentration and size order almost completely segregated under similar conditions. The maximum degree of mixedness associated with low vibration energies was attainable after only 10 minutes of mixing. Further duration of mixing resulted in overmixing of the material and hence deterioration in mixture quality. This overmixing was attributed to the magnitude of vibration induced into the material. For low vibrations, the measure of segregation progressed to an equilibrium position after a short time. For high vibrations, the classic fluctuating behaviour between extremes of high and low levels of mixedness occurred. This higher vibration increased the momentum and energy induced into the mixture. The higher shear and friction forces associated with increased agitation of the mixture caused particles to overcome the interparticle adhesive forces associated with ordered/adhesive mixtures, thus liberating a particles movement from its neighbour. However, the newly freed starch particle was almost immediately exposed to impact against a new receptive sugar particle, that formed, at least, momentarily, a new ordered mixture. This characteristic fluctuating behaviour associated with results produced from the split-cell vibration apparatus is similar in principle to some standard mixers where the fluctuating level of mixedness as a function of mixing time is of common occurrence to both. Evidence of the resulting fluctuation between mixing and segregation can be observed from Figure 36(a) above. The granular sugar was larger than the starch and hence size segregation occurred when mixed. The powdered sugar mixture was similar in size to the starch at approximately 100µm therefore segregation was inhibited due to increased mixture cohesivity. However, this form of powder, because of its strong tendencies to form aggregates may not be easy to mix.

The importance of this authors work must not be understated. This is one of only a few documented accounts of an investigation where an identical test material was subjected to two different forms of material movement. Comparison of results from both the flow tests and vibration tests indicated that similar conclusions could be drawn with reference to gauging the propensity that the material would segregate. The cell design used to initiate and evaluate vibration induced segregation as shown on Figure 36(a) was also utilised by Popplewell et al. [58] for conducting investigations into validating two segregation indices for binary powder mixtures. More information on this work can be found in Section 3.9.3.3 of this thesis.

3.7.4.4 Size and Concentration

Standish [32] investigated segregation of ternary sized iron-ore mixtures when charging a model vessel. The vessel was geometrically representative of a vessel used to feed a blast furnace used in the iron-making industry, Figure 8 page 37.

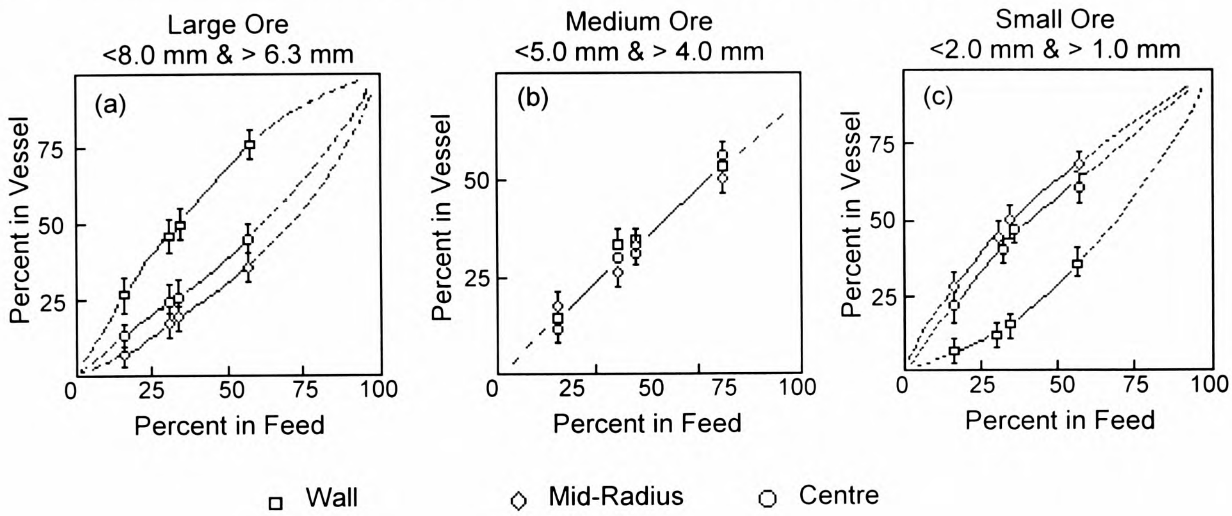
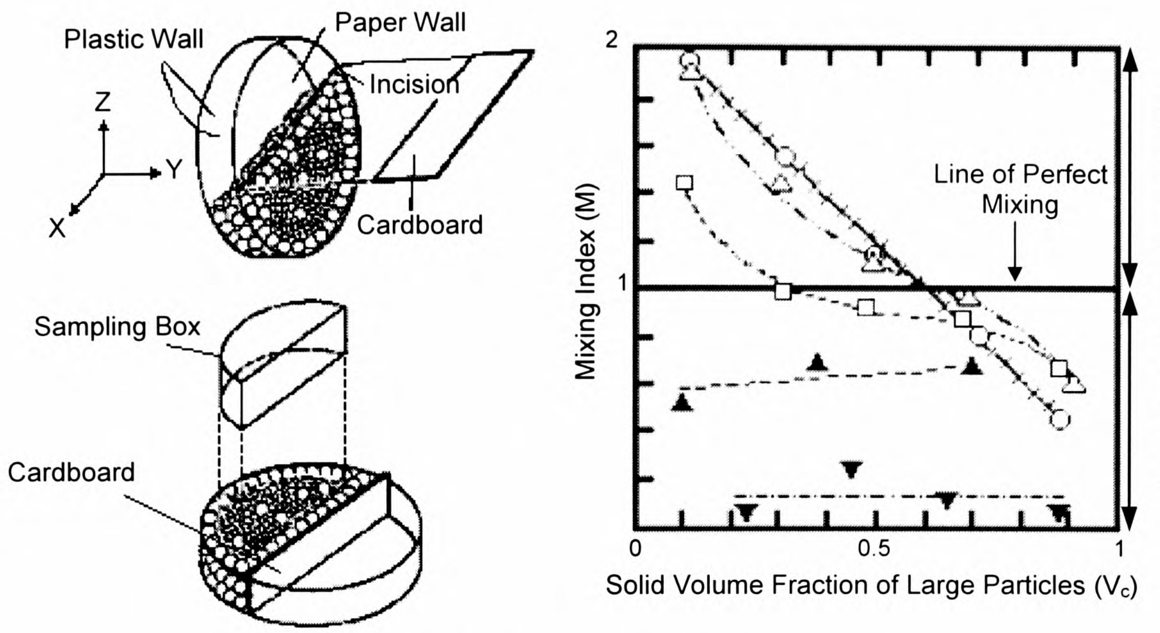


Figure 37 Non-Linear Segregation Relationship of a Ternary Mixture as a Function of its Feed Content. [32]

As can be seen from Figure 37 the function of feed composition of small particles on the resulting segregation in a vessel is not linear in relationship. Although the proportions of small particles in a mixture must start at 0% and terminate at 100%, the relationship in between is seen to be non-linear. Figure 37(a) indicates that the curve representing an increase in large particles at the periphery of the heap in the vessel for increasing concentration of large particles is convex in nature. Likewise, the trend of position of small particles located at the heap periphery for increasing concentration in the mixture is concave in nature, Figure 37(c). The position of the mid-range particles was unaffected by increasing concentration, Figure 37(b).

3.7.4.5 Size, Density and Concentration

Alonso et al. [59] focussed their investigation on attaining the optimum combination of three variables in order to reduce to a minimum the resulting segregation. The two-dimensional rotating cylinder used for their testing apparatus created a constant and moving inclined plane of flowing material. The regime of flow created is similar to that when forming a conical heap. The authors were careful to restrict the rotational speed of their equipment in order to eliminate high dynamic influences. The resulting segregated bed of material was separated into an inner core and outer annular ring of equal volume and the contents were screened in order to ascertain the proportions of the components in each core.



Mixture Combinations and Material Properties

○ 10 &12 ▼ 4 &13 △ 3 &12 □ 4 &10 ▲ 9 &11

3. Glass Beads ρ = 2490 kg/m^3 d_{50} = 1.30 mm
4. Glass Beads ρ = 2490 kg/m^3 d_{50} = 1.60 mm
9. Plastic Beads ρ = 1050 kg/m^3 d_{50} = 1.25 mm
10. Plastic Beads ρ = 1050 kg/m^3 d_{50} = 1.00 mm
11. Chocolate Balls ρ = 1420 kg/m^3 d_{50} = 4.00 mm
12. Steel Balls ρ = 7780 kg/m^3 d_{50} = 2.95 mm
13. ZrO2 Spheres ρ = 6040 kg/m^3 d_{50} = 1.12 mm

Figure 38 Test Facility and Graph showing Mixing Behaviour According to Concentration, Density and Size Ratio of Mixture. [59]

Figure 38 shows the affect of varying concentration of mixture constituents using an index of mixing similar to that used by Williams [44], details of which are documented in Section 3.9.1.5. Interpretation of the graphical representation of results in Figure 38 allowed the following qualitative statements to be made:

- Irrespective of the concentration of large to small particles in the mixture, when size differences are greater than density differences the large particles will always float at the surface of the flowing layer. (shaded triangles on Figure 38)
- At low concentrations of large to small particles, when density differences are greater than size differences the large particles will 'sink' down through the flowing medium and embed into the static layer beneath. (hollow markers on Figure 38 when V_c <0.65)
- At high concentrations of large to small particles, when density differences are greater than size differences the large particles will 'float' and remain at the surface of the flowing layer. (hollow markers on Figure 38 when V_c >0.65)

For very low concentrations of large to small particles in a mixture, mixing or segregation is controlled by the ability of the large particles to open voids in a layer below due to their specific weight. Small particle percolation does not play any role at this level of concentration and agrees with the findings of Arteaga and Tüzün [60] concerning heap segregation when charging silos. Arteaga and Tüzün suggest that at low concentrations of large particles, the formation of a matrix of large particles is not possible therefore making the mechanism of sieving-percolation inactive. Conversely, for high concentrations of large particles, segregation is controlled solely by the sieving-percolation mechanism. Therefore, the large particles will invariably behave as 'floaters' regardless of their density. The changing mechanisms of segregation associated with this flowing regime forms a substantial part of an investigation undertaken into the qualitative description of the heaping process, which is discussed in detail in Section 6.4.

3.7.5 Concluding Remarks on Factors that Affect Heap Segregation

Analysis of segregation literature exposes the establishment of a hierarchy of variables that affect segregation. It has been consistently observed that size differences of particulates of the solids dictated the extent of segregation of a mixture in a particular handling or processing operation [17] [37] [45] [48] [49]. However, there are conflicting views as to the influence of other variables in dictating patterns of segregation in a heaping environment. It is conceivable that each particle, geometrical or process variable, can, in its own right induce segregation tendencies of the mixture. When a flow regime is created that permits the sieving-percolation mechanism to induce the majority of segregation of the mixture, Bridgwater and co-workers [38] [39] concluded that particle size completely out-performed any other particle variable investigated. However, the influence of differences in particle size must be analysed in conjunction with the absolute size of the mixture. The affect of absolute particle size has been illustrated by Lawrence and Beddow [47] and Williams and Khan [49] on Figure 16, Section 3.7 1.1. According to Figure 16 there is a recognised absolute mean size of particle that can be classified as free-flowing enough to facilitate the recognised segregation mechanisms of the heaping process. Below this critical value, the pattern of segregation is inhibited by cohesive forces. Subsequently the recognised mechanisms associated with heap segregation are altered.

There have been numerous attempts to gauge how particle shape influences heap segregation e.g. Harris and Hildon [48], Lawrence and Beddow [47] and Drahun and Bridgwater [37]. The underlying conclusion drawn is that shape, unless the disparity is very large, does not significantly influence heap segregation when other differences in variables are present. When only large shape differences exist then shape induces the percolation mechanism of heap segregation to percolate angular particles in preference to spherical ones. It is difficult to relate the physical behaviour of particles to their mathematical shape definition. Particle shape is related to the size geometrically and frictional affects kinematically. Shape affects particle mobility within the flowing layer and across the static heap surface. Shape crosses the boundary of shape classification into the characteristic area describing the roughness of particles.

Drahun & Bridgwater [36] [37] concluded that the surface roughness of their particles was not important in significantly altering their distribution down the inclined segregated mixture slope. However, their mixtures comprised of tracer particles that were fed at very low concentrations, typically 1% of the total mass charged to a segregating two-dimensional half heap vessel. The frictional influence of such small quantities of rough particles can be ignored. If the concentration of tracer particles was increased significantly then the frictional characteristics associated with particle roughness would no doubt have an affect on the frequency of avalanching. In addition, roughness will affect the dynamic movement of the flowing layer and the ability of the flowing layer to drag along particles that were previously part of the stationary heap.

Shinohara [51] [52] [53] [63] gave some qualitative explanations of the movement of particles influenced by the heaping process of segregation according to a particles size, density or shape. Detailed analysis and subsequent theoretical modelling of this authors work can be found in Section 3.9.3.1. Separate segregation experiments were conducted to investigate particle characteristics such as density, size and shape. Shinohara concluded that small dense or angular particles produced a similar pattern of segregation, which was conspicuous by the accumulation of these particles under the feed point. However, Shinohara suggested that their mechanisms of segregation within the heaping process differed. Small particles filled voids present in the static layer, whereas the dense particles could only swap places with lighter particles of the same size in the static layer. Patterns of segregation of angular and lighter particles were different, however their mechanism of segregation was similar. As there was no size difference in density mixtures and shape mixtures, packing of the segregating component into voids of the static layer could not happen. These simplified stages of heap segregation philosophy suggested by the author did not incorporate any information as to the concentrations of particulate types. Furthermore, the segregation of a mixture whose constituents differed in all three of the particle characteristics was not discussed.

The importance of the interaction of size with density, especially concerning heap segregation was highlighted by several authors such as Williams [17] and Drahun and Bridgwater [37] in Section 3.7.4.2. There are ambiguous assumptions on the severity that density has on the resulting segregation pattern produced during heap segregation. This was often the result of different regimes of flow being created in test facilities used to investigate this characteristic. Some literature that investigated mixtures differing in size and density suggested that density had no influence whereas other documents stated that density does have a role to play in the segregation process. This anomaly can be resolved by understanding how the interaction of size and density is influenced by the concentrations of particulates of the mixture. This interaction was established quite categorically by Standish [32], Section 3.7.4.3 and also Alonso et al. [59], Section 3.7 4.5. They concluded that the disparity of each particle characteristic present and the concentrations of each in the mixture dictated the resulting pattern of segregation produced.

To cross-reference the interaction of the absolute mean size and proportions of mixture constituents a single test condition of used by Bagster [54] was selected and compared to those of Alonso et al. [59] and Drahun and Bridgwater [37]. Apart from one mixture formulated by Bagster, segregation of similar absolute size and concentration mixtures compared favourably with Alonso et al. and Drahun and Bridgwater. The size of mixtures formulated fell into a region far greater than the critical absolute mean size of approximately 550µm. Therefore all the mixtures could be classified as being free flowing in nature. Consequently the segregating behaviour of particles was unaffected by the mean absolute size of the mixtures formulated. Examples of results produced by Bagster can be seen on Figure 33 and are indicative of the majority of test conditions undertaken by the author. The behavioural movement of the particles fulfilled the criteria to comply with the philosophy proposed by Alonso for the concentration ratios employed and subsequently the majority of small particles 'sank' and accumulated under the feed point. In addition, the large particles behaved as 'floaters' and were subsequently deposited at the heap periphery. However, when Bagster formulated a mixture of 5% large particle concentration whose mean absolute size was less than 500µm, Figure 32(a), the resulting segregation behaviour was not commensurate with the philosophy proposed by Alonso. The large particles instead of acting like 'floaters' now behaved like 'sinkers'. Bagster attributed this change in segregation behaviour to the absolute size, concentration ratio and moisture content of the mixture tested. The absolute mean size of this mixture was approximately 450µm, which fell below the critical size shown on Figure 16, Section 3.7.1.1. Consequently, the mixture exhibited some cohesive behavioural tendencies. In addition, the particle size of the small component was approximately 135µm and therefore vulnerable to the affects of cohesion. Furthermore, the moisture content of this small particle fraction was deemed high enough to possibly allow certain adhesive mixtures to be formed. These are all suggested as reasons why the majority of large particles are not present at the heap periphery, which was a common place occurrence of these mixture types documented in the literature that comprised this review. These reasons are further validated by comparing the test rigs used by the three authors. These rigs excluded the majority of other process and geometrical variable affects that could have influenced segregation i.e. free-fall heights, lateral velocity, impact velocity and other kinematic influences synonymous with highly dynamic flow conditions.

Lawrence and Beddow [47] highlighted from their investigations that reducing the fill time could reduce the magnitude of segregation. They attributed this fact to the rapid motion of the material, which reduced exposure time to mechanisms of segregation.

However, Drahun and Bridgwater [36] [37] did not include the fill time of the heap as being significant to the resulting segregation suffered. This may be due to the authors' using low feedrates throughout their test work.

Lawrence and Beddow [47] state that the affect of free-fall height is significantly reduced when using small particle sizes around 250μm. Mixtures containing small particles that were larger than this critical size resulted in the free-fall height influencing the pattern of segregation. This was due to the influence of the coefficient of restitution characteristic. Research into free-fall height showed a general trend of behaviour. In most cases, increasing the free-fall height resulted in reduced segregation. Particles of more resilience, or of less density, having increased momentum as a direct result of the free-fall height scattered more widely over the heap surface due to increased bouncing. This is the reason given by Drahun and Bridgwater [37] of the opposite pattern of segregation of large particles for similar concentration small particulate mixtures used by Lawrence and Beddow [47].

It is evident that no single piece of literature provides all the necessary information on all aspects of heap segregation. All the relevant literature combines to produce an interlocking web of information on segregation. This provides a unique knowledge base on the interaction of particle, process and geometrical variables and their resulting influence on producing patterns of segregation for a heap segregation environment.

3.8 Measures Employed to Counteract Segregation

It is often a design requirement of a handling or processing operation to encourage free flowing material tendencies throughout the process whilst at the same time minimising any environment that will readily facilitate segregation, if segregation is considered to be a potential problem. In dealing with techniques for addressing segregation, the literature reviewed has primarily been concerned with the variability of the bulk solids that <u>discharge</u> from a handling or process operation. However, in many instances it is important to recognise and resolve the factors that cause segregation upon <u>charging</u> the vessel, as these will alleviate the majority of problems being experienced when the vessel contents are subsequently discharged. In general, the measures employed to counteract segregation can be categorised into three classifications:

3.8.1 Altering the Process.

The position of the unit or handling operation that initiates segregation of the mixture being handled should be moved to a position within the industrial process where any resulting segregation of the material is unimportant. A mixture that is comprised of constituents which are uniform in themselves but vary distinctly from one another should be mixed at a stage immediately prior to any processing step which is sensitive to any distribution of mixture constituents.

3.8.2 Retrofit Existing Process Plant

When charging vessels under the influence of gravity it is recommended to prevent the formation of a single heap, which instigates the mechanisms of segregation associated with the heaping process. Reisner and v. Eisenhart-Rothe [61] describe various examples of inserts that can be placed beneath the charging stream in order to prevent single heap formation. The authors also suggest multiple-point filling and claim that this is sufficient to alleviate the majority of single point gravity charged segregation problems. By achieving this, fractions of all components are charged to the centre of the vessel as well as to the vessel walls.

Retrofitting vessels to initiate a mass flow mode of discharge has long been suggested as a suitable means of counteracting the influences of mixture segregation resulting from vessel charging. This claim is made on the basis that discharge associated with this regime of flow results in total movement across the whole cross section of the vessel upon discharge. Therefore, any lateral separation of constituents of the mixture as a direct result of segregation when charging will be re-mixed and discharged in similar proportions to those charged. However, Arteaga and Tüzün [60] have shown that this is not the case. Constituents are not re-mixed upon discharge; they are simply discharged in similar proportions to those charged. The authors provide evidence that the motion of particulate constituents of the mixture as they progress to the discharge point of the vessel results in segregation. This is proved by measuring segregation upon discharge even when the mixture in the vessel suffered no segregation upon charging.

3.8.3 Alter Characteristics of Mixture Constituents

Barbosa-Canovas et al. [9], Williams [62] and Carson et al. [1] have provided a variety of guidelines for changing the constituents of the mixture in order to diminish the influence of segregation. In doing so, this acts to suppress and minimise the segregation phenomenon:

- Altering the size distributions of the constituents of the mixture, by grinding, for example, to the size of the finest ingredients in the mixture. However, for some foodstuffs this may result in a powder whose particulates are too small to be re-hydrated easily and are highly susceptible to caking. This technique was employed by Goodwill et al. [1] and Johanson [19] where the absolute mean size of the components was not a significant factor in altering the efficiency of the process. However, particulates of the mixture must be sufficiently small to avoid free flow but not initiate flow problems within the process or handling operation
- Reduce the mixtures physical mobility by geometrically eliminating headspace.

- Wet mixing and drying of the ingredients to guarantee uniform composition in each individual particle. Although this is the most effective way in eliminating segregation, it requires a considerable technical complication of the production process, adds drying costs, and may result in undesirable exposure of the mixture constituents to high temperatures or evaporation losses.
- The addition of a small amount of liquid to make particles cohesive may prevent segregation. However, one must be aware of hygroscopic materials that can exhibit detrimental characteristics of flow when subjected to contact with moisture. If excessive moisture is added, problems such as arching or rat holing may replace that of segregation and result in greater disruptions to the process.
- The formulation of adhesive mixtures. The definition of an adhesive mixture can be found in Section 2.1.5 on page 19 of this thesis. This method can result in a mixture where the small particles form a coating on the larger particles and will not be free to segregate. It may then be possible to obtain better than random mixing and the possibility of approaching an ordered mixture.

3.9 Quantification and Modelling Segregation

In order to develop predictive techniques that model segregation requires an initial means of quantifying segregation as a numerical value. However, this is a major difficulty in itself. The magnitude of material segregation is dictated by particle, geometrical and process variables. Quantification of segregation in terms of a numeric measurement for any one of these variables is compounded by the fact that any combination of these cause differing magnitudes of interaction. To help alleviate these problems, research into segregation has often been simplified by utilising binary mixtures, often differing only in size. Furthermore, quantification of these materials has often been investigated in small bench-scale test facilities with focus directed at a single segregation variable. Subsequent quantification of segregation utilising these methods can be broadly classified into two areas:

- Classifying the particle mixture into a large and small fraction, and measuring the change in proportion of these two fractions in parts of the segregated bed
- Monitoring the change in concentration of tracer particles in a material bulk.

Segregation was often quantified by an arbitrary degree of segregation unique to the author conducting the investigation. Therefore, these techniques are not universally applicable to all regimes of flow known to initiate segregation of a particulate material. Furthermore, in the majority of cases of reported segregation within industry, the materials handled are often free-flowing, multi-component in nature and have a continuous distribution of particle characteristics that segregate in differing regimes of material flow. As a consequence a technique that encompasses all these factors is not available at present.

There are no established standardised techniques for quantifying segregation for a given material and duty. One technique employed has been to scale simulated segregation produced from a small laboratory sized rig to an industrial scale that exhibits similar problems. However, to determine the segregation potential of any solids mixture, you must simulate the full-scale factors affecting the segregation mechanism being investigated. This point was confirmed by Johanson [20] and is often overlooked when trying to correlate small-scale segregation results to large scale segregating environments. Constructing a small-scale environment to simulate fluidisation, air current, and trajectory mechanisms on an industrial scale is extremely problematic in comparison to initiating a small-scale environment that induces vibration or heap segregation. Yet, these air-induced mechanisms are known to be significant contributory factors to the ensuing segregation pattern produced from such environments. When air is considered a contributory factor then any small-scale investigation of this phenomenon must simulate the quantity and velocity of air entrained within the falling solids relative to the industrial situation. False conclusions may be drawn on the influence of variables when simulating segregation in small-scale rigs. Provisions for scaling factors such as free fall heights, particle trajectories, quantities of air introduced by pneumatic conveying and the venting of displaced air are often not taken into consideration. Indeed any characteristic known to influence segregation, which cannot be scaled down from an industrially sized problem must be of the same order in a small-scale rig investigation.

It is therefore an extremely difficult task to develop a multi-faceted technique for predicting segregation which is sensitive to all the external influencing characteristics that can contribute to the resulting pattern of segregation in both small-scale and industrially relevant environments.

3.9.1 Quantification of Segregation

As outlined in the previous section, segregation is often be quantified in two ways. Firstly as a measurements of the change in proportion of a large and small binary size mixture within in a segregated bed or secondly monitoring the concentration or position of tracer particles in a segregated bed. This conclusion is substantiated by both Williams [44] and Drahun and Bridgwater [37] from their documented reviews of segregation literature. Some of the more relevant techniques used to quantify segregation are described as follows:

3.9.1.1 Williams et al.

The index used by Williams et al. [49] worked on the principle of dividing a segregated mixture into two halves and then measuring the proportion of small and large particles in each. The index was defined as

$$C_S = \frac{W_{CT} - W_{CB}}{W_{CT} + W_{CB}} \qquad \text{Equation 1}$$

where

C_S Coefficient of Segregation.
W_{CT} Proportion of large particles in the top half of segregated bed.
W_{CB} Proportion of large particles in the bottom half of segregatedbed.

This index was used to quantify the propensity that a mixture will segregate in a rotating mixing drum, which initiated a regime of flow that facilitated a low dynamic form of the heaping process. An index value of one denotes complete segregation with a value of zero representing complete mixing. Compared to statistical methods for determining mixture segregation, this technique has an advantage of its mathematical simplicity and the convenience of the experimental procedure for its determination. However, as the segregated bed is halved for analysis, the scale of scrutiny is limited to the size of each half.

3.9.1.2 Harris and Hildon

The total segregating component of four samples extracted from the segregated mixture in the test apparatus shown in Section 3.7.1.1 is taken as 100. An index of segregation is then defined as the sum of the differences of the segregating component in each sample from the average content of these samples. If the segregating component content of the four samples from a test is α_1 , α_2 , α_3 , α_4 where $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 100$, then by definition:

$$S = \sum_{n=1}^{n=4} \left| \alpha_n - 25 \right| \qquad \text{Equation 2}$$

where

S Degree of Segregation.
α_n Content of segregating component in sample n.

When all the samples have the same amount of segregating component, S is denoted as zero. When only one sample contains the segregating component then S becomes 150.

3.9.1.3 Barbosa-Canovas et al.

Barbosa-Canovas et al. [9] quantified measures of mixture quality or degree of segregation in the foodstuffs industry. Segregation can take the form of variations in either particle size distribution or in mixture composition. The quantitative determination of the composition can be by either physical means (e.g. reflected colour) or by chemical or physicochemical analysis. Examples of the two latter methods of analysis provided by the authors for the foodstuffs industry include:

- Index of refraction, or polarisation of the dissolved powder for sugars and the Biuret reaction [9]
- Spectrophotometric determination of proteins [9]
- Titration tests for an acid component (e.g. citric or malic acid)

In terms of size segregation, the authors employed the following index of segregation to quantify the segregation or mixedness of their binary mixture.

$$S = \frac{\sum_{i=1}^{n} W_i \left(X_i - \overline{X}\right)^2}{\sum_{i=1}^{n} W_i} \qquad \text{Equation 3}$$

where

W_i Weight of powder in each ring of tester.
X_i Concentration of given component.
$\overline{X}$ Mean (or total) concentration of this component in the mixture.

It is claimed that the index utilised by this author yields results that compare favourably to measures of segregation/mixedness produced when utilising the index derived by Williams & Khan [49].

3.9.1.4 Bagster

Bagster undertook investigation into the affects of concentration of large particles in a binary sized mixture of equal densities. Results of the testwork undertaken were processed utilising a coefficient of variation / degree of segregation index.

$$S = \frac{\sqrt{\dfrac{\sum_{i=1}^{N} \left(C_i - C_f\right)^2}{N-1}}}{C_f} \qquad \text{Equation 4}$$

where

S Degree of segregation or coefficient of variation.
N Number of samples.
C_i Large particle concentration of sample i
C_f Large particle concentration in the feed mixture.

A graphical description of the results when using this technique of quantification can be seen on Figure 36(b). Quantification of segregation by this measure indicates segregation to be worst for greater concentrations of large particles.

3.9.1.5 Alonso et al.

Alonso et al. [59] quantified the segregation/mixing results produced from an experimental apparatus as shown on Figure 38 by utilising an index of mixing. This index is similar in nature to that of Williams et al. [49].

$$M = 1 + \frac{V_c^i - V_c^o}{\Delta V_c} \qquad \text{Equation 5}$$

where

$$\Delta V_c = \left(V_c^i\right)_{max} - \left(V_c^o\right)_{min} = \begin{cases} 2Vc & \text{for } Vc \leq 0.5 \\ 2(1 - Vc) & \text{for } Vc \geq 0.5 \end{cases} \qquad \text{Equation 6}$$

where

Vc	Overall solid volume fraction of large particles in the mixture.
V^i_c	Solid volume fraction of large particles in inner core.
V^o_c	Solid volume fraction of large particles in outer annular region.
(V^i_c)max	Maximum possible value of V^i_c.
(V^o_c)min	Minimum possible value of V^o_c.

Values of 'M' between 0 and 1 describe situations where large particles float and accumulate at the outer annular region of the bulk. A value of 'M' between 1 and 2 corresponds to large particles that sink and concentrate at the inner core. A value of 'M' equal to either 0 or 2 indicates complete component segregation. For 'M' = 1, the tendency of floating equals that of sinking and the large particles (or the small ones) are distributed evenly within the bulk of the mixture.

3.9.2 Statistical Quantification of Mixture Segregation

As outlined in Section 2.3 the variance of a component in a number of samples is often used as a measure of the consistency or quality of the product in order to quantify mixture segregation. It is necessary to compare this value with the theoretical limiting variance values for a completely segregated and randomised mixture structure. However, statistical quantification of segregation is disadvantaged by problems of the predictive nature of segregation and problems relating to sample selection and procurement. The use of statistics has long been employed as a means of interpreting test data gathered from a mixing or segregating process. The generally accepted platform on which most statistical ideas are based for the interpretation of such test data has recently been questioned in a paper published by Rollins et al. [13]. Whilst the majority of the mixing related literature was concerned with the application of statistical methods to mixing studies the methods used to quantify mixture quality were applicable to segregation studies. The majority of established statistical indices are hybrids of a general index derived by both Lacey et al. [10], and Poole et al. [11]. Rollins et al. [13] provides theoretical evidence that these are unacceptable procedures for quantifying mixture quality. The author points to two intrinsic flaws in their derivation that are responsible for their inappropriate application to determining mixture segregation.

1) It is inevitable that measurements taken from samples taken from a powder mixture will inherently incorporate some sampling errors, which is especially indicative of sampling free flowing particulate bulk materials. It is imperative therefore that any derived statistical index should provide a measure of the mixedness of a material that is insensitive to the influence of any extenuating non-segregating factors. However, when the author derived and incorporated some sampling errors into measurements of a perfectly ordered mixture, the values of all the indices investigated by the author exhibited a change in their value of mixedness. This led to the conclusion that it was possible for current established indices under review in this investigation to fluctuate in their quantification of mixedness for factors other than segregation.
2) A statistical index is a random variable that attempts to estimate some fixed quantity from a number of samples taken. Consequently, the statistical index will seldom equal the quantity. It is therefore a requirement to combine a statistical mixing index with a measure of the confidence that its value is accurately representative of the true quantity being measured. The indices investigated by the author will yield their own unique value as to the quality of the mixture being analysed. Therefore, the comparative assessment of each index investigated without a measure of the confidence in the accuracy of each index value being produced is severely limited. Consequently, the comparative evaluation of the significance of the indices investigated cannot be undertaken.

Because of these two shortcomings, current statistical techniques used to assess mixedness of mixtures have been disregarded in favour of an ANOVA (analysis of variance) technique. Rollins et al. [13] provides theoretical evidence that this technique can be employed to isolate and represent a measure of the mixedness of the mixture that is not influenced by any external non-segregating factors. The author claims that the ANOVA technique provides information on the confidence of producing accurate results. This is based on established statistical theory, is insensitive to sample size and can be subjected to other inferential techniques. However, it is felt that the theoretical findings proposed require some form of experimental validation before an approach of this type can be adopted. As previously mentioned this work is tailored to mixing studies and is not truly representative of heap segregation associated with charging storage vessels. Consequently, an in-depth investigation within this area has not been pursued.

It is generally felt that statistical techniques developed thus far, which are based on an assumption of randomness, are misplaced in their suitability to predict segregation. This is because evidence documented thus far indicates segregation to be an ordering process dictated by varying interactions of process, geometrical and particle variables.

3.9.3 Modelling Heap Segregation

In general, modelling of segregation is usually presented in the form of the relationship between the selected segregation variable or index and the time of exposure to the segregating environment or location within an segregating environment. This selection of the appropriate segregation variable is dictated by the characteristic of the process that is deemed sensitive to the influences of segregation.

3.9.3.1 Shinohara et al.

Shinohara and co-workers have documented the continual development and application of a general theoretical 'screening-layer' model in a variety of papers pertaining to the heaping process of free flowing particulate solids. The rudimentary beginnings of their current theoretical screening layer model began in the form of a model used to predict segregation of a material discharging from hoppers. Using different forms of this model, theoretical analysis of size segregation in filling a hopper was undertaken by Shinohara et al. [51]. This was further adapted to accommodate the affect of shape segregation [53] and density segregation [52]. The model was also adapted to describe the size segregation process occurring during the formation of a conical heap in which analysis was undertaken irrespective of particle properties of the mixture such as size, density and shape [63]. This was possible due to the fact that the variables contained within the model that governed the prediction of segregation were dependent on the feedrate of the mixture and the initial volumetric mixing ratio of the segregating material. Quantification of differences in characteristic proportions of the mixture such as size, density and shape are not incorporated as input variables to the model equation.

The form of the screening-layer model that best described its applicability to the heaping process was documented by Shinohara et al. [63] and Mosby [64]. It is based upon the volumetric movements of particles within a flowing layer that descends the heap surface until it reaches the wall of a plane-flow geometry vessel. The mechanisms of heap segregation that the model represents are tailored to mechanisms relevant to the particle characteristic under investigation. This was achieved by categorising the flowing layer into differing segregating sub-layers and setting the segregation parameters of the model that dictate the pattern of segregation, depending on the application of the model. In terms of a binary mixture that differed only in particle shape, the pattern of segregation produced was similar to that for size. The same pattern of segregation can be obtained for a binary mixture differing only in density. Shinohara derived a separate theoretical model to predict the segregation pattern according to each of these three particle characteristics and the mechanisms that account for these characteristics were discussed previously in Section 3.7.5.

The most relevant form of the screening-layer model relates to size segregation and functions by categorising the heaping process into four sub-layers:

- The remaining sub-layer
- The segregating sub-layer
- The separated sub-layer
- The static under-layer upon which the flowing layer descends.

The schematic arrangement of the sub-layers within the flowing layer may be seen in Figure 39:

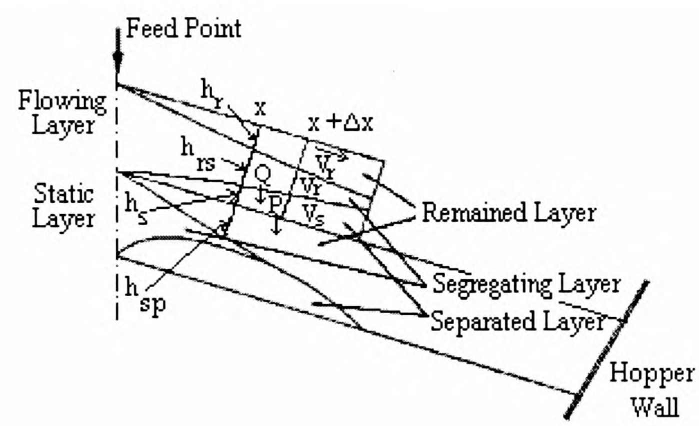


Figure 39 Screening-layer Model of Shinohara's Adapted for Size Segregation. [63]

where

Q	Penetration rate of segregating particles through mixture layer per unit area and time, cm/s.		
P	Packing rate of small particles into static under-layer per unit area and time, cm/s.		
x	Distance from feed point along heap surface, cm.		
h	Thickness of flowing layer or sub-layer, cm.	v	Velocity.
rs	Mixed or Segregating.	s	Separated.
sp	Packed after separation.	r	Remained.

The segregation process of the four sub-layers is described by four partial differential equations:

$$\frac{\partial h_r}{\partial t} = \frac{\partial (h_r v_r)}{\partial x} + \frac{Q \cos I}{1 - e_r} \frac{1 - M_i}{M_i}$$ *For the remaining layer.* Equation 7

$$\frac{\partial h_{rs}}{\partial t} = \frac{\partial (h_{rs} v_r)}{\partial x} + \frac{Q \cos I}{M_i (1 - e_{rs})}$$ *For the segregating layer* Equation 8

$$\frac{\partial h_s}{\partial t} = \frac{\partial (h_s v_s)}{\partial x} + \frac{Q - P}{1 - e_s} \cos I$$ *For the bottom separated layer.* Equation 9

$$\frac{\partial h_{sp}}{\partial t} = \frac{P \cos I}{1 - e_s}$$ *For the static underlayer.* Equation 10

The variables are defined as:

M_i Initial volumetric mixing ratio in the feed.
e Void fraction of particle sub-layer.
v Descending velocity of sub-layer along inclined heap surface, cm/s.
h Thickness of flowing layer or sub-layer, cm.
I Angle of repose of solids heap, radians.

The formulation of these differential equations has resulted in the generation of two factors of segregation Q and P. The force that drives these segregation factors is gravity induced and the factor values model the resulting pattern of segregation of the mixture. There is a third segregation factor, R that describes the velocity ratios of the sub-layers within the flowing layer of mixture. The equation that represents this relationship is given by

$$R = \frac{v_s (t,x)}{v_r (t,x)}$$ Equation 11

where

R Velocity ratio of separated sub-layer to upper flowing layer of mixture.
t Descending time, s.
x Distance from feed point along heap surface, cm.

Once the thickness and velocity of each sub-layer at a certain position and time are given those at differential distances can be estimated by using the above equations. As a direct result of the solution of equations 7-11, the pattern of segregation can be predicted for fractions of the mixture, as a function of position along the heap slope. Therefore, when the time taken for the flowing layer to reach the vessel wall is known, the volumetric mixing ratio versus distance down the heap length is given by:

$$M(x) = \frac{h_{rs} (T,x)(1 - e_{rs}) M_i + \lfloor h_s (T,x) + h_{sp} (T,x) \rfloor (1 - e_s)}{h_r (T,x)(1 - e_r) + h_{rs} (T,x)(1 - e_{rs}) + \left[h_{rs} (T,x) + h_{sp} (T,x) \right] (1 - e_s)}$$ Equation 12

The variables not previously defined are:

T Time required for a layer head to reach vessel wall, s.

A comparison of experimental profiles with the predictive capabilities derived by Shinohara can be seen in Figure 40. Both experiments were carried out using an initial mixing ratio of small particles on a net volume basis, and with heap lengths of 47 and 63 cm respectively.

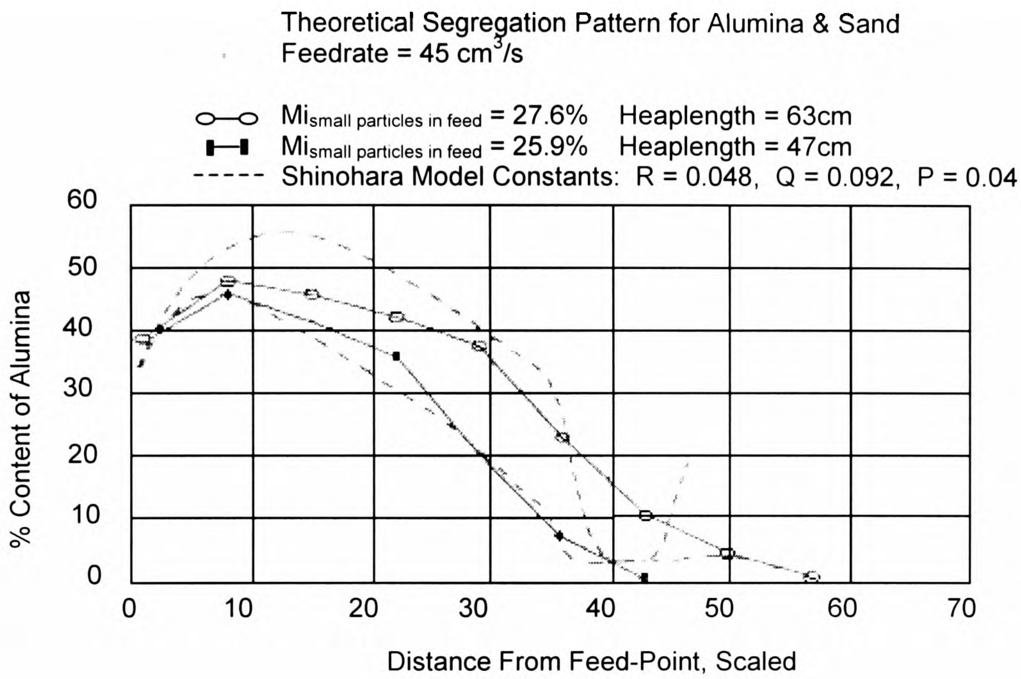


Figure 40 **Shinohara et al. Predicted Simulations Compared to Two Experimental Results [64].**

3.9.3.2 Savage & Lun

Savage & Lun [65] modelled the process of gravity separation of large and small particles during the shearing flow of a binary particulate mixture that flowed down an inclined chute. The authors attempted to correlate model predictions to the segregation mechanisms associated with steady two-dimensional inclined chute flow of a 1.7:1 diameter ratio spherical particulate mixture. They claimed that reasonable agreement was found between theoretical findings and experimental data. The authors postulate that the segregation transfer, or migration of particles across the shearing flowing layer under investigation, can be described by only two mechanisms of segregation. These are defined as the 'random fluctuating sieve mechanism' (the definition of which is analogous to that outlined in Section 3.5.1), and a unique 'squeeze expulsion mechanism'. These mechanisms are attributed to the slow, multi-particle layered, shearing flow that is of interest to the authors. Consequently, their resulting theoretical considerations have been tailored to accommodate this behaviour.

The 'squeeze expulsion mechanism' was derived as a result of analysing slow motion video footage of experimental testwork undertaken. This mechanism is defined due to the fluctuating contact forces that occur on an individual particle due to force imbalances. These forces are such that a particle is squeezed out of its own layer into an adjacent one if the opening is available or if the force imbalance is sufficiently large. This mechanism is not gravity driven, it is not size preferential and there is no inherent preferential direction for the layer transfer of a particle. This behaviour of particle movement is analogous to the two migration mechanisms defined in Sections 3.5.4 and 3.5.5. By combining these two proposed mechanisms, the net sieving velocities of both the small and large particles that comprised the binary mixture were obtained. This approach allowed the development of concentration profiles of large and small particles with respect to distance downstream from the feedpoint.

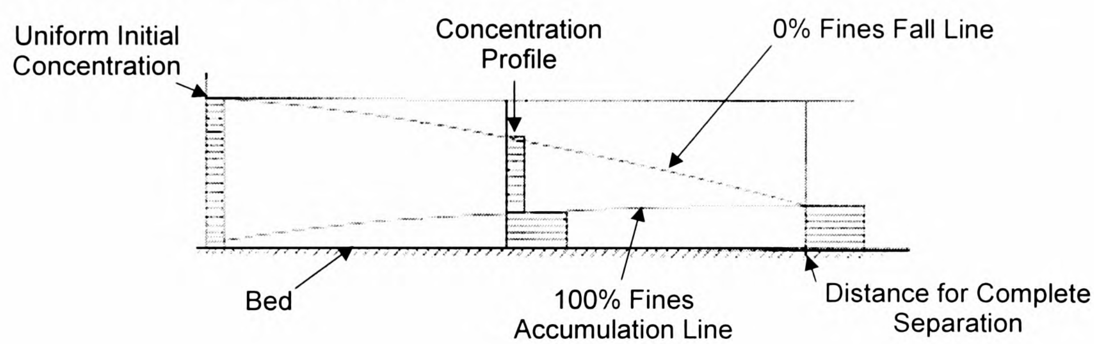


Figure 41 Profile of the Depletion Rate of Small Particles as the Binary Mixture Descends the Chute. [65]

Although the authors utilise only two mechanisms of segregation, they do give qualitative recognition to other mechanisms that are perceived to come into play in more general heap segregation. These other mechanisms are associated with the increased shear rates, which are sufficiently high that dominant contributions to the total stresses on particles within a flowing layer are due more to interparticle collisions than friction. Therefore, the affects of frictional contacts are considered negligible at high shear rates. They concluded that increased layer momentum of heap segregation enhances more kinetic characteristic mechanisms of segregation, which are not taken into account in their theoretical endeavours. Likewise, no consideration has been given to the behaviour of the feed material upon contact with the heap at the feed point where the affects of periodic avalanching akin to the natural gravity influenced heap formation are present. The requirement of numerous empirically defined constants coupled with its restricting applicability for low flowrates, indicated that substantial further development was required. This technique can only be considered a worthwhile inclusion in a general technique for predicting binary mixture segregation when the aforementioned problems have been resolved.

3.9.3.3 Popplewell, Campanella & Peleg

The authors have undertaken a theoretical comparison of a proposed segregation index to that of Williams & Khan [49], previously documented in Section 3.9.1.1. Both indices yield a value of one for complete segregation and zero for no segregation. The major difference between William's index, Cs, and Popplewells' et al. [58] is that the latter required only a knowledge of two variables.

1. The small particles weight fraction at the bottom of a vibrated segregation cell.
2. The initial proportion of small and large particles in the mixture.

This information allowed the index proposed by Popplewells to predict the pattern of segregation within a vibration cell of a design shown on Figure 36(a). In order to quantify a value of segregation using Williams' index there was a need to divide and analyse half of the bed of material. The index proposed by Popplewell only requires analysis of the mixture composition in the bottom near the base of the cell shown in Figure 36(a). The index, I_s can be defined as:

$$I_s = \frac{A - C_o}{1 - C_o} \qquad \text{Equation 13}$$

where

C_o weight of powder in each ring of tester
A The small particles weight fraction at the bottom of the segregation cell

It is claimed that this index is more representative of the concentration profile of large and small particles across the whole height of the bed compared to Williams index [49]. Graphical interpretation of this philosophy can be seen on Figure 42.

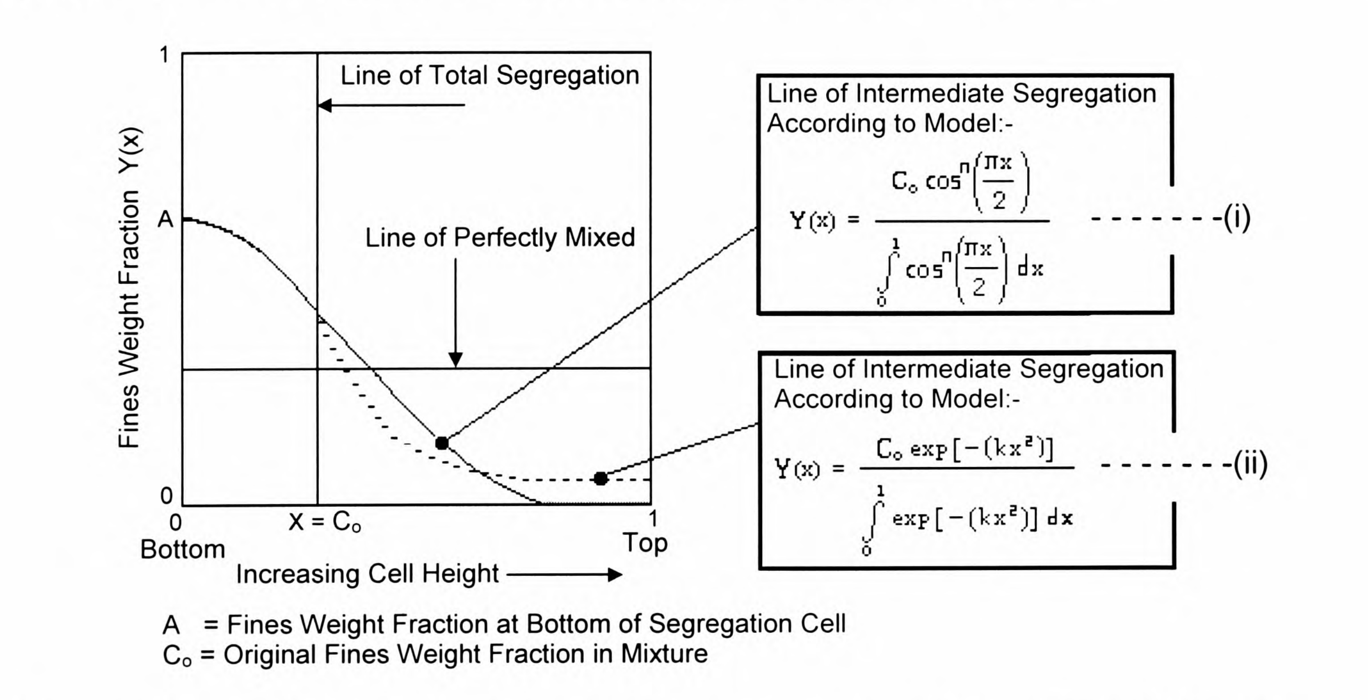


Figure 42 **Schematic Illustration of Two extremes of Segregation of Small Particles in a Segregation Cell along with Model Profile Equations. [58]**

The index is based on the assumption that the segregation behaviour of the binary mixture i.e. the concentration profile of small to large particles above the bed base follows one of two profiles, described by two theoretically derived models. These two model equations describe the concentration profiles between two extremes of a perfectly mixed and a totally segregated state. The authors claimed that if profiles produced by the two model equations can predict the behaviour of real mixtures, then the relationship between constants of the equations 'n' and 'k' serve to characterise the propensity that a material will segregate. To substantiate this claim the authors stated that the simulated profiles produced by the two equations shown in Figure 42 are not purely hypothetical, with similar segregation experimental profiles being identified in relevant published literature.

In order to make a fairer comparison between the indices proposed by Williams and Popplewell, the index of Williams (Cs) was restricted to quantifying segregation of binary mixtures whose concentration profiles followed the same model equation profiles upon which the index proposed by Popplewell (Is) is based. Comparison of the two indices under these conditions still showed that Is was more sensitive than Cs. This was particularly relevant for mixtures with low concentrations of small particles, or at advanced stages of segregation, when all or most of the small particles were already in the bottom half of the cell. For these situations, the continuing changes in concentration profile in the bottom half of the cell were still being accounted for by the index proposed by Popplewell but not by Williams.

Only a small amount of experimental evidence is provided to corroborate that the simulated profiles produced by these model equations fit to experimentally observed patterns of segregation. More comparisons of segregation data with profiles produced from these empirical models are required in order to increase confidence in the claims of this theory. Assumptions made in the theoretical derivation in terms of mixture incompressibility and possible changes in density profile as a direct result of the applied vibration require verification. However, the index and model profiles suggested in this work shows promise in its adaptability for modelling the segregation of binary mixtures associated with the flow regime that induces heap segregation.

3.9.3.4 Alonso et al.

Drahun and Bridgwater [37] postulated the behaviour of a segregating component as being characteristic of a 'floater' or a 'sinker' as it travelled within a flowing layer descending down a heap surface. The mechanisms of segregation for the heaping process induced into a particle were considered to be of two types:

- Migration of a particle
- Sieving-percolation of a particle

Detailed definitions of these mechanisms can be found in Sections 3.5.4 and 3.5.5. What is of relevance here is that based on 'floater' and 'sinker' terminology, Alonso et al. [59] has developed an index to predict segregation for a heap-inducing regime of flow. The index is sensitive to both size, density and concentration changes and simply requires a knowledge of certain characteristics of the constituents that comprise the mixture. A major advantage of this index when compared to others in the literature pertaining to segregation is that most other predictive models are empirically derived, where a fitting constant is incorporated into the modelling. The method by Alonso enables the index to predict the segregation of a mixture based on the understanding of the interaction of particle and process variables with the perceived mechanisms of segregation, that are active within heap segregation. This analysis resulted in,

$$S = \left\{\frac{\rho}{d}\right\}\left\{\frac{1+V_c(d-1)}{1+V_c(\rho-1)}\right\}\left\{\frac{1-\varepsilon\exp\left\{-\frac{1-\varepsilon}{\varepsilon}\left[\left(1+\frac{1}{1+V_c(d-1)}\right)^2-1\right]\right\}}{1-\varepsilon\exp\left(-3\frac{1-\varepsilon}{\varepsilon}\right)}\right\} \quad \text{Equation 14}$$

where

S	Index of Segregation
d	Large to small size ratio
ρ	Large to small density ratio
V_c	Overall solid volume fraction of large particles in the mixture
ε	Average porosity or void fraction of the bed of material

If their model yields a value of less than one, the large particles are deemed to behaved like 'floaters'. They will rise to the top of the avalanching layer and settle in the outer annular region of the mixture in the test facility shown on Figure 38. Conversely, if the model yields a value greater than one, the large particles tend to sink to the bottom of the flowing layer mixture and settle in the core of material in the testing facility. If the index yields a value approximately equal to one, then no segregation should take place and therefore large and small particles should be evenly distributed throughout the mixture.

The equation is derived according to the combination of two factors. These are the ability of large particles to sink in the flowing medium due to their specific weight (sinking migration mechanism) and the relative ability of the small particles being able to percolate through the interstices in the avalanching layer. There are some assumptions made in the derivation of this predictive technique:

- The energy available to a particle in order to sink its way down through the flowing bed is purely potential, therefore the influence of any kinetic tendencies of particles are not incorporated into the authors theoretical considerations.
- No frictional relationship between large and small particles of the mixture has been included in the theoretical considerations.

- The percolation ability of particles has been modelled on the assumption of a static bed of particles. In reality, particles will move relative to one another and the voidage through which a particle can percolate is probably larger than for a static bed scenario.
- The section parallel to the free surface (i.e. the surface which the avalanching layer descends over) of the bed is assumed to consist of particles of equal size.

Examples of the ability to predict the floating and sinking ability of large particles for mixtures differing in both size and density by using equation 14 can be found in Figure 46, page 111. Figure 46 shows that the majority of experimental results compare favourably to the predicted magnitudes of segregation produced by equation 14.

3.9.3.5 O'Dea and Waters

O'Dea and Waters [6] [25] provided documented accounts of modelling size segregation of sinter mixtures, which were promoted in order to improve the efficiency of sintering operations. The philosophy behind their approach has been previously mentioned in Section 3.1.4.2. The authors considered the segregation process to be a two-mechanism phenomenon that could be described by two first order processes:

- The sieving-percolation of small particles through a matrix of large particles.
- The rolling mechanism of a large particle down the heap surface.

The authors substantiate their claims that two first order hypotheses are capable of modelling the size segregation process by referencing several authors who have successfully modelled different particulate systems in this manner. Model constants produced from solving the sieving-percolation and rolling first order processes served to characterise the propensity to which the mixture under investigation will segregate. The authors found it difficult to differentiate between the value of the two constants and therefore they were combined into a single constant that described the segregation of the material as a whole. The changing size distribution of the material on the surface of the heap formed was expressed in size distribution terms as the cumulative mass fraction of particles passing through a chosen arbitrary sieve size. The final part of model derivation incorporated a material balance where the size distribution of the feed was approximated to the average size distribution on the entire segregated surface. The size distribution at any distance down the heap surface could be predicted by the following equation:

$$P_i = \frac{1}{\left(1 + \left(\left(\dfrac{1 - e^{-kL}}{1 - e^{-kLP_i^f}}\right) - 1\right) e^{ky}\right)} \qquad \text{Equation 15}$$

where

P_i	Cumulative mass fraction of particles passing through chosen sieve size x_i.
L	Length of slope.
P_i^f	Fractional proportion of particles in feed which pass chosen sieve size x_i.
y	Fractional distance down heap surface.
k	Constant of segregation.

For the purposes of comparing model predictions with experimental data provided by the small-scale sinter-strand segregation experiments, a statistical non-linear regression procedure was utilised. This evaluated the value of the segregation constant that fitted the model most precisely to the experimental data. An example of the modelling potential represented by equation 15 can be seen on Figure 43. The authors provided evidence to suggest that the model predictions compared favourably to the experimental data they provided in their literature. A schematic layout of the experimental testing facility that produced the comparative segregation test data can be found on Figure 5(b) in Section 3.1.4.2.

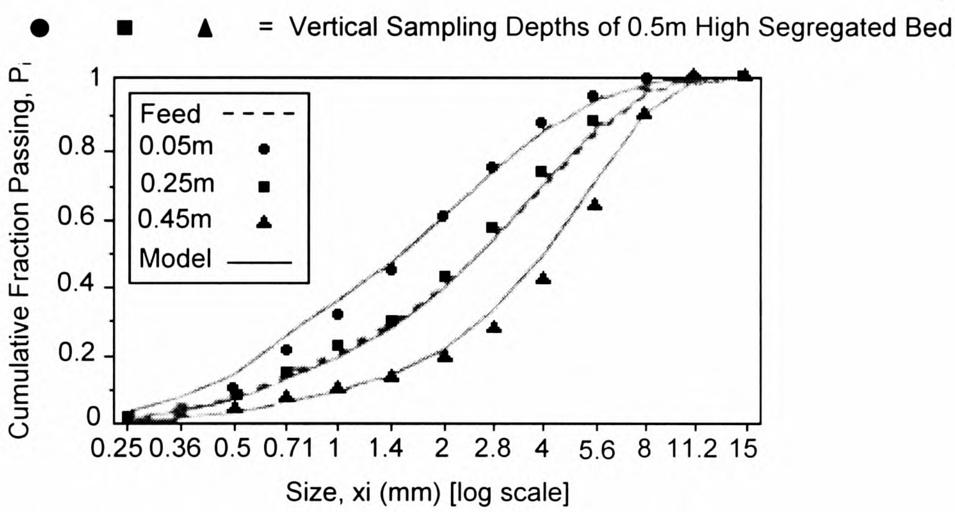


Figure 43 Comparison of Model Predictions with Size Distributions Measured at Various Vertical Depths of a Segregated Bed. [6]

For steady state conditions, O'Dea and Waters stated that the segregation occurring in their vertical bed experimental system was easily equated to free surface segregation measurements resulting from heap formation. The claims of this model are different to those that characterise mixtures into large and small size fractions. This model has the potential of being able to estimate particle size distributions at any position within a free standing pile of material or a storage vessel.

3.9.3.6 Dolgunin and Ukolov

Dolgunin and Ukolov [66] developed a dynamic segregation model to describe size and density separation of particulate materials based on an equivalent mass transfer equation of particles moving between shearing sub-layers of an avalanching layer. The avalanching layer descended an inclined surface, whose angle was commensurate with the angle of repose of the material. The model was based on a general equation of particle transfer, taking into account mechanisms of mixing and segregation. These included convection transfer, quasi-diffusional mixing (which impedes particle separation) and particle segregation (which impedes ideal mixing). The parameters for dictating segregation kinetics are expressed as the degree of non-uniformity of the segregating particles and the bulk medium. The driving force behind segregation is dependent on two aspects of uniformity

(1) non-uniformity of the segregating particles (size, shape, roughness, elasticity etc)

(2) non-uniformity of the bulk medium by the addition of the segregating component.

The magnitude of non-uniformity dictates the velocity and direction of segregating particle displacement within the flowing layer and is a function of the concentration of the segregating particle in the bulk medium. The analysis of non-uniform particle interaction was carried out with respect to impact momentum, frictional and gravity affects. These dictated the forces acting on the segregating test particle and hence determined the velocity and direction of the particle within the flowing layer. Non-uniform particle interaction was also considered a function of the most important particle, process and geometrical characteristics of the flow i.e. particle size density, friction, and restitution coefficients, the layer shear rate and its specific free volume. (The specific free volume is defined as the ratio of the void volume to the sub-layer volume).

The general equation presented by the authors for the segregated component distribution in a two-dimensional steady state flow is presented below:

$$\frac{\partial c}{\partial t} = - \frac{\partial (U_c)}{\partial x} + \frac{\partial}{\partial y}\left[D_{dif} \cdot \frac{\partial c}{\partial y} - K_s \, . c \, . \, (1-c) \right] \qquad \text{Equation 16}$$

where

D_{dif} Coefficient of particle diffusional mixing.

K_s Coefficient of segregation.

U Velocity distribution.

c Test component concentration.

t Time.

x Position down inclined surface.

y Perpendicular position within flowing layer.

Good comparison between experimental results and modelling predictions were found. Calculation of the quasi-diffusional mixing and segregating coefficients of the general equation were determined by assuming particles were spherical in shape. In a general case, segregation would be affected by not only size, but also density, surface roughness, adhesion properties, shape and elasticity differences as well as flow structural and kinematic characteristics. It is not possible at present to produce a definitive value of segregation and quasi-diffusive coefficient for such a mixture. The solution of the general equation also requires knowledge of the velocity distribution of the flowing layer and the segregating particles concentration in the mixture. There are some reservations as to the suitability of this model to the heaping process when charging storage vessels. The quasi-diffusion coefficient is expressed by an analogy with gas molecular diffusion coefficient, the modelling is restricted to a two-dimensional steady state gravity flow and the unknown significance of particle rotation inertia is ignored.

3.9.4 Computer Simulation Techniques

The increase in processing power of modern computers has seen the appearance of some recent publications where computer simulations of parts of the heaping process have been attempted.

3.9.4.1 Meakin and Jullien

Meakin and Jullien, [67] assumed size to be the most important particle characteristic variable that influenced heap segregation and subsequently undertook computer simulation of spherical particle binary sized mixture segregation. They modelled the heaping process using a hybrid of the rolling mechanism that was previously defined in Section 3.5.3. Computer simulations of heap formation were undertaken using various sizes of large to small particles and the proportions of these particles added to the heap. Attempts to model the journey of a particle descending the heap surface according to its proposed mechanism of segregation is schematically shown in Figure 44(b).

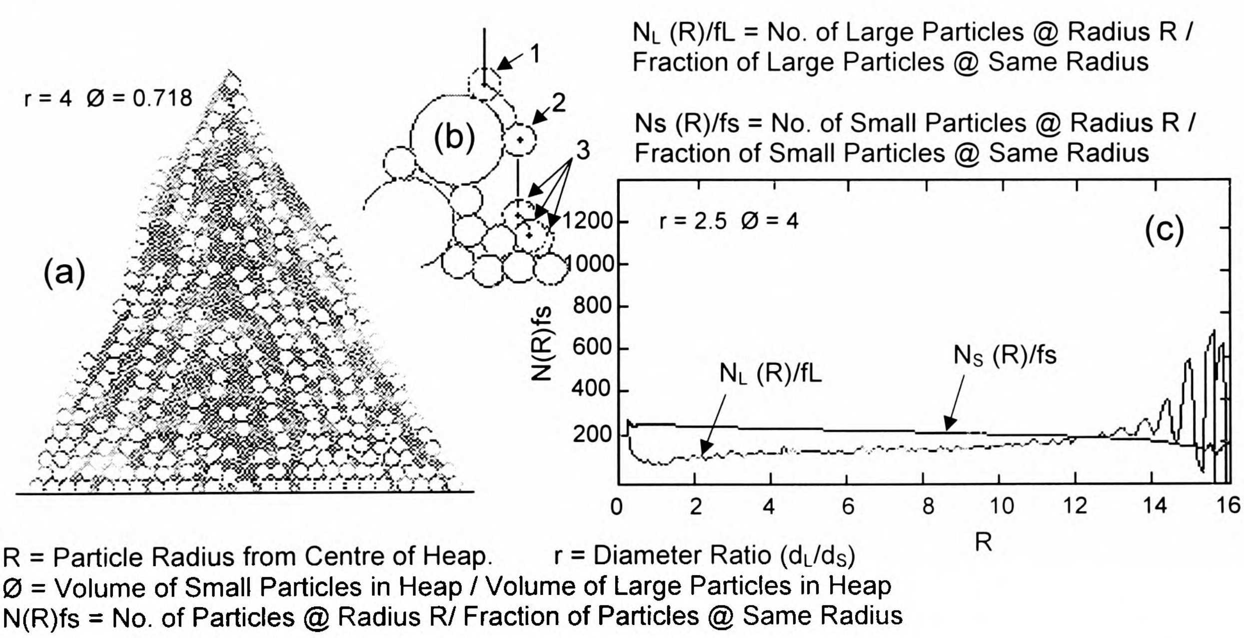


Figure 44 (a) Predicted Heap Formation. (b) Mechanism of Segregation. (c) Depletion rate of Large and Small Particles as a Function of Position Away from Heap Periphery. [67]

A single small or large particle, selected at random, was added to the heap in the same lateral starting position and followed a path of steepest descent, point 1 on Figure 44(b). The particle was constrained to remain in contact with the heap unless a situation occurred as in point 2 on Figure 44(b) where the particle underwent vertical free-fall until contact was again made with the heap surface. A particle fluctuated between these two types of movement as it descended the heap surface until it came to rest at either a local minimum, point 3 Figure 44(b) or at the heap base. When stationary, the particle became part of the heap and could not be further moved, irrespective of any external forces applied to it. Once the particle was stationary, a new one was deposited at the top of the heap. This process was repeated until the defined number of small and large particles had been deposited. These definitions of particle movement and assumptions of the mechanism of heap formation was processed using a computer algorithm that yielded a two dimensional simulation of a heap as shown on Figure 44(a). As shown of Figure 44(c) the diameter ratio, 'r' between the large and small components and the concentration ratio of these, 'Φ' is stipulated. It is claimed that the computer simulation can successfully be adapted from two to three dimensional heaps. The prediction of the distribution of large and small particles as a function of horizontal radius from the centre of the heap can be seen in Figure 44(c). The diameter of the vessel for the three-dimensional simulation shown in Figure 44(c) was restricted to thirty two times the largest particle diameter. This was due to limitations in computer power. As is typical of size segregation results from other documented literature, the computer simulation indicates a depletion of large particles around the vicinity of the feed point and a depletion of small particles at the vessel walls.

Any heap segregation patterns produced will be formed according to the rolling mechanism of segregation. Therefore, there are some reservations of the computer algorithm used for simulating heap formation in its current format. There is a complete absence of any particle-particle interaction commensurate with an avalanching layer descending the heap surface. There are no direct comparisons with any experimental data to corroborate the accuracy of its predictions. Some of the diameter ratios selected for heap simulation encroached on sizes that could induce the spontaneous percolation mechanism, which was not incorporated as an integral part of the computer algorithm. Avalanching of layers down the heap surface, synonymous with the heaping process could cause some movement of particles already positioned on the heap surface. Furthermore, the kinetic impact behaviour of the feed upon contact with the heap surface may also initiate some movement of particles already positioned on the heap surface. In addition, the embedding mechanism dictated by the feedrate of the charging mixture would influence the resulting pattern of segregation. The computing simulation of heap formation presented in an algorithm of this form is still in its infancy and does not include any of the aforementioned characteristics of heap segregation. This computer simulation shows the promise of utilising computer processing to model the individual movement of particles of the segregating material. In its current format, the computer model is more suited to modelling flow regimes where kinetic behaviour of particles is deemed insignificant in influencing the resulting pattern of segregation.

3.9.4.2 Makse et al.

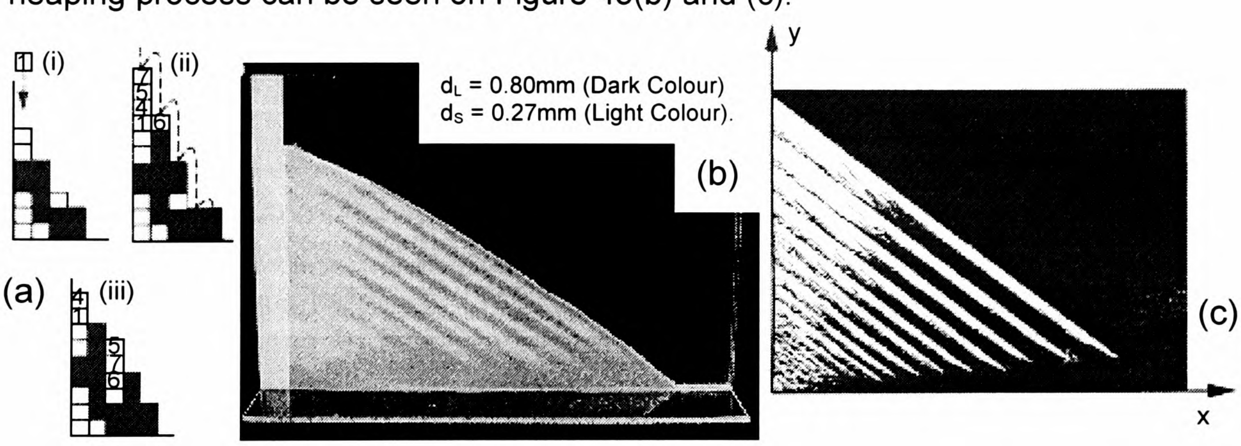
An attempt at computer modelling of the stratification (layering) of constituents, conspicuous during the heaping process, has been undertaken by Makse et al. [30]. The stratification is related to the separation of the mixture constituents into two layers formed in the course of each avalanche. An in depth discussion on segregation and the appearance of stratification according to the interaction of size and shape is documented in Section 3.7.4.2. The computer simulation of heap formation was based on:

- The velocity of the particles as they descended the heap
- The stopping of layer movement upon reaching the heap periphery
- The thickness of the sub-layers throughout the duration of each avalanche.

The computer simulation considered a mixture comprised of small and large particles one pixel in width but differing in height. Individual particle motion was accommodated into the model along with the angle of the pile being created. This angle fluctuated between the angle of stability and the angle at which an avalanche is instigated, Figure 5(a) in Section 3.1.4.2. Heap building was considered a three-stage process as shown on Figure 45(a).

I. An individual particle added to heap in sequence.
II. Heap process continues until a particle reaches the substrate at furthest right column of pile. The heap at this point becomes unstable.
III. Pile avalanches to a position of stability and process reverts to step (i).

The potential of the model in describing the segregation and stratification of the heaping process can be seen on Figure 45(b) and (c).



(a) Model Mechanisms of Heap building.
(b) = Segregation and Visual Stratification of a 50:50 Binary Sand mixture.
(c) = Model Prediction of Stratification and Segregation based on Model Mechanisms Defined in (a).

Figure 45 Modelling the Experimentally Produced Segregation and Stratification Behaviour as a Direct Result of Avalanching during Heap Segregation. [30]

The two layered structure consists of a sub-layer of small particles and a top layer of large particles. The mechanism of segregation upon which the model has been based is a hybrid version of the rolling mechanism. The author states that it is easier for large particles to roll down upon a surface of smaller particles than small particles to roll on top of large particles. Figure 45 indicates that there was good correlation of model predictions to the experimental pattern of segregation produced. Whether stratification and segregation behaviour is still valid for different feed proportions of constituents has not been ascertained.

3.9.5 Concluding Remarks on Modelling Heap Segregation

It is clear from the review that a general, universally applicable solution for modelling heap segregation is still far from a reality. As an example to illustrate this, Makse et al. [30] and Meakin and Jullien [67] modelled segregation based predominantly on the rolling mechanism, whereas Shinohara and co workers modelled the heaping process based on the sieving-percolation mechanism. It is evident that heap segregation is significantly affected by the diversity and interaction of particle, process and geometrical variables where different mechanisms of segregation are omnipresent in avalanching flow during heap formation.

Makse et al. [30] modelled heap formation, in terms of rolling and avalanching, and provides graphical evidence of stratification and segregation when large particles have a greater angle of repose than small particles. However, their literature does not provide any graphical evidence to substantiate their claim that segregation exists without stratification when larger particles have a smaller angle of repose than small particles. The validation of the degree of segregation for both scenarios must be undertaken, as the stratification phenomenon might well influence the resulting degree of segregation undertaken in the heaping process. It would be unwise to assume that building a heap by adding one particle at a time would ultimately represent the entire heaping process present in most industrial handling or process operations.

Shinohara and co workers, Section 3.9.3.1, suggested that their screening layer model could be adapted to predict segregation for difficult quantifiable variables such as shape, and roughness, etc. This was because the segregation parameters within the model (Q, P and R) that fit the model predictions to the segregation test results are based on non-particle characteristics. The parameters concerned measure non-particle, process or geometric variable parts of the heaping process. Subsequently, there is an inherent disadvantage of formulating segregation parameters of this type in terms of the applicability of the model.

- Shinohara's theoretical model incorporates only the sieving-percolation mechanism of segregation associated with heap segregation. The author has studied in detail the movement of particles within sub-layers of the flowing layer under the influence of this mechanism. It is evident that this literature review has highlighted numerous other significant mechanisms of segregation thriving within heap segregation that will have some significant contributory influence on the segregation during heap formation. Consequently, to base the entire heaping process on the sieving-percolation mechanism is underestimating the full extent of the segregation behaviour akin to the avalanching regime of flow. This view is further enhanced by the discovery of the significant rolling of particles throughout the avalanching process, which is not taken into account by the model.

- One undesirable consequence of theoretically modelling the sieving-percolation mechanism in such complex detail is the formulation of a number of segregation parameters (Q, R, and P) which, by their nature, are difficult to quantify for practical purposes. In addition, the parameters are dependent on feedrate and the initial volumetric mixing fraction of the segregating component. Subsequently, the screening layer model cannot be utilised to investigate how the segregation pattern is affected by these two variables. Consequently, in order to gauge their affect an independent quantification or modelling technique is required.
- The assumption that the avalanching layer will descend across the entire static layer to reach the vessel wall is not commensurate with real segregation scenarios. It is often found that sporadic and chaotic avalanching occurs which can send a flowing layer only part way down the heap surface.

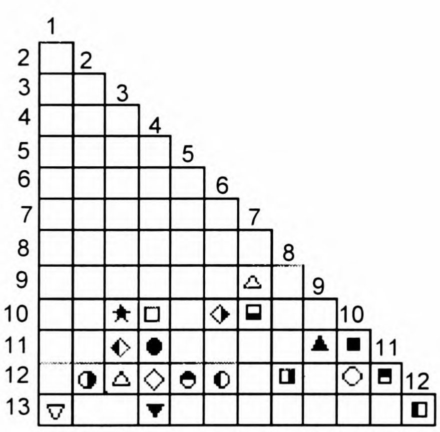
Mosby [64] undertook an extensive examination of the screening layer model proposed by Shinohara and its suitability to modelling heap segregation. An attempt to refine and simplify the existing computer code that described the screening layer model was undertaken by Mosby. This was a necessary requirement as Mosby found some anomalies in the original modelling:

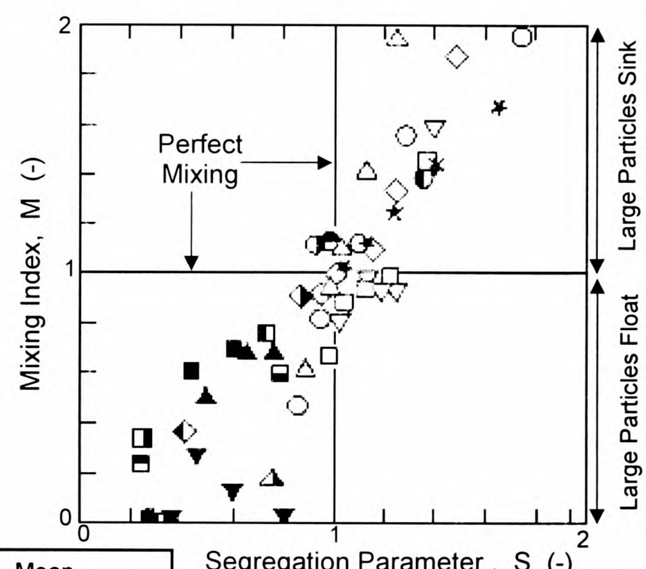
- Shinohara's computer model managed to generate small particles and produced patterns of segregation of small particles in a vessel that were in excess of those in the original mixture feed.
- Shinohara's model produced an uncharacteristic increase in small particle content at the end of the heap length. This characteristic was not in keeping with what was to be expected for patterns of segregation produced as a result of the sieving-percolation mechanism.

The new computer code generated by Mosby managed to rectify the problem of Shinohara's model in producing an increase of small particles at the end of the heap although the problems of mass balance could not be rectified. This problem was in addition to the already difficult quantification of the segregation parameters (Q, P and R) and the model being representative of only one mechanism of the heaping process. Mosby therefore considered it inappropriate to continue further investigation into a general predictive technique of modelling.

A potentially more representative modelling technique was suggested by O'Dea and Waters [25]. This model was derived according to the sieving-percolation and rolling mechanisms of segregation. It also had the inherent advantage of being able to predict the segregation of a material comprised of a wide size distribution rather than a simple binary mixture of two sizes. However, the approach requires the determination of an empirical segregation constant in order to fit model predictions to observed segregation test results. The relationship of this constant with differences in particle, process and geometrical variables of the segregating mixture has yet to be substantiated in enough detail to make any conclusive statements as to the credentials of the approach.

Alonso et al. [59] suggested an approach to segregation modelling that required a knowledge of easily quantifiable particle and process variables to be input directly into a model. The models derivation does not require fitting constants in order to match model predictions to experimental results. The model will predict the potential for the mixture to segregate within the heap segregation environment. It is also in a form that suggests it to be a universally applicable predictive tool for predicting whether a large particle will float or sink in a heap segregation environment.





No. Material	Mean Density (kg/m^3)	Mean Diameter (mm)
1 = Glass Beads	2490	0.70
2 = Glass Beads	2490	1.00
3 = Glass Beads	2490	1.30
4 = Glass Beads	2490	1.60
5 = $CaCO_3$ Granules	2730	1.30
6 = Al-Coated Cocoa Balls	1570	1.90
7 = Al-Coated Cocoa Balls	1540	2.55
8 = Al-Coated Cocoa Balls	1460	5.00
9 = Plastic Beads	1050	1.25
10 = Plastic Beads	1050	1.00
11 = Chocolate Balls	1420	4.00
12 = Steel Balls	7780	2.95
13 = ZrO_2 Spheres	6040	1.12

Figure 46 Comparison Between Test Results (M) and Model Predictions (S) that Determined a Large Particles 'Sinker' or 'Floater' Behaviour for a Variety of Particulate Materials. [59]

The predictive index provides quantitative information of segregation based on the interaction of size ratio, density ratio and concentration ratio. However, the model was derived based on the assumption that only sieving-percolation and migration mechanisms induce heap segregation.

As can be seen from Figure 46, the experimental results provided in the form of the mixing index (M) are compared with predictive capabilities of the segregation model (S) for various particulate mixture combinations. It appears that the results of both 'M' and 'S' compliment each other across the majority of tests undertaken. When the mixing index produced a value less than one for a particular mixture combination tested, Figure 46 indicates that the large particles will act like 'floaters' For the same mixture combination, the predictive segregation index also indicates a value less than one. The predictive power of 'S' also compares favourably to mixture combinations that yield a mixing index, 'M' greater than one, corresponding to large particle sinking behaviour. The experimental evidence provided on Figure 46 corroborates the predictive ability of the model in describing the 'floating', 'sinking' potential of a large particle.

It should be possible to utilise the model proposed by Alonso to predict the segregation behaviour of results produced in other segregation literature that initiated segregation for a similar regime of material flow. The test facility utilised by Alonso et al. employed a slowly rotating drum in order to initiate a cascading layer of flowing material down across the heap surface, Figure 38 page 83. Drahun and Bridgwater [37] used a half heap test facility that initiated a similar regime of flow. Both authors adhered to a testing methodology that was conscious of avoiding a highly dynamic flowing regime of material that would have induced kinetic affects such as the trajectory mechanism. Subsequently, any experimental segregation measured could be attributed solely to non-kinematic mechanisms of heap segregation.

Appraisal of the theory proposed by Alonso: example one

The combination of particle and process characteristics formulated by Drahun and Bridgwater [37] that resulted in inhibiting segregation was indicated by the 'hollow' dotted mixture line on Figure 34, page 78 Section 3.7 4.1. These same particle characteristics were used as input variables to the theoretical predictive model proposed by Alonso and documented in Section 3.9.3.4. The model yielded a value of 0.95, thus indicating that the large particles are just as likely to behave as floaters than as sinkers. In fact, a value of 0.95 could be construed as the large particles having a slight floating tendency. This slight floating tendency compares favourably with the trend of the 'hollow dotted' line show on Figure 34. Here the large particles are seen to float, ever so slightly to the edge of the heap and are conspicuous by their slight increase in proportion within this region. However, in general the mixture can be stated as inhibiting segregation when subjected to a gravity induced heaping regime of flow and further verifies the modelling potential of Alonso.

Appraisal of the theory proposed by Alonso: example two

The combination of particle characteristics formulated by Drahun and Bridgwater [37] that resulted in severe segregation was indicated by the 'solid' dotted mixture on Figure 34, page 78, Section 3.7 4.1. The values of these particle characteristics were used as input variables to the theoretical predictive model proposed by Alonso. The model yielded a value of 1.35, thus indicating that the large particles should behave as sinkers. Consequently, this combination of size ratio, density ratio and concentration induces segregation of this mixture, which is conspicuous by large particles accumulating under the fill point. The experimental result provided by Drahun and Bridgwater, solid circles on Figure 34, corroborate this behaviour and thus further substantiates the modelling potential proposed by Alonso.

For both of the aforementioned examples, Drahun and Bridgwater used a 1% concentration ratio of large particles in the mixture. According to the theory of Alonso, increasing the concentration ratio of large particles from 1% to 99% should alter the behaviour of the large particles when the density difference is greater than the size difference. This change in behaviour is indicated by the i.e. hollow dots, squares and triangle mixture symbols on Figure 38, page 83. Re-processing both example mixtures through the model of Alonso with this altered high concentration of large particles produced model predictions that complemented this change in large particle behaviour. However, Drahun and Bridgwater do not provide experimental evidence to allow a further possible verification of this affect.

These two examples of appraisal highlight the major advantage of the index proposed by Alonso. The model requires only a knowledge of easily quantifiable particle characteristics of the constituents that comprise the mixture. The model required no empirically derived fitting constant, which is considered a favourable model trait in comparison to other empirically derived predictive models. The pursuit of predictive techniques of this type based on quantifiable characteristics of a mixture (i.e. size ratios, density ratios, mixture proportions, etc) rather than empirically derived fitting constants should be the ultimate aim of research conducted into segregation. However, the model does not predict profiles or patterns of segregation but simply classifies the segregating potential of a particulate material based on readily quantifiable particle characteristic properties. Furthermore, there are still some assumptions made in the predictive model proposed by Alonso where it is confined to predicting segregation in a less dynamic regime of flow. Excluding trajectory and embedding mechanisms questions its universal applicability to all industrial segregating environments in its current format.

3.10 Conclusions from Undertaking Literature Study

Scrutinising the literature relating to the various studies of heap segregation revealed that it does not integrate to give a coherent physical picture of the mechanisms that contribute to segregation during the heaping process. Of the different forms of segregation, many have been influenced by the method of introducing material into the vessel or the possible preconditioned segregation of material prior to this stage. Drahun and Bridgwater [36] confirmed this view when they reported that it is sometimes stated that smaller particles congregate beneath the feed point, whereas at other times they are stated as accumulating at the heap periphery. Anomalies of the heap segregation phenomenon are documented widely and are attributed to segregation being highly sensitive to externally imposed factors, unique to the segregating scenario under investigation. Segregation crosses all boundaries of subject disciplines from engineering, pharmaceuticals, agriculture, geophysics, materials science, foodstuffs etc. Much of the literature results from investigation into the affects and causes of segregation in a specific area of interest to the author. This has led to the accumulation of an immense variety of segregation literature that have utilised diverse materials for investigating the phenomenon. A significant proportion of this work has been included in this review. This is necessary however as to understand the global implications of segregation, requires piecing together the segregation 'jigsaw' in terms of the variety and interaction of all the influencing variables known to have an affect. At present, there does not exist one author who has amalgamated every possible contributory influence into a general technique for predicting segregation that crosses the boundaries of all flow regimes discussed in this chapter. However, by understanding the ramifications to industry for all prevailing conditions a better understanding of the phenomenon can be established. This has resulted in a more considered opinion on the best means by which to address the problem.

As a direct result of undertaking the literature survey, the following conclusions as to influencing factors that initiate mixture segregation can be suggested.

- Segregation is ultimately influenced by differences in size of constituents or fractions of a single material. Other characteristics order themselves into a hierarchy of influential importance. However, any individual particle, process or geometrical variable, can, in isolation, induce segregation.
- For the normal gravity induced segregation phenomenon categorised by heap segregation, the segregating component of lower flowability, such as smaller, denser, more angular, more frictional, more cohesive or less resilient particles will accumulate under the fill point. Conversely, their characteristic opposites are deposited at the heap periphery. However, it has been established that concentrations of the characteristics of the mixture can significantly alter this behaviour. This may be further compounded with other factors such as the absolute mean size of the mixture, moisture, and resilience of particles induced

as a result of incorporating free-fall height affects into the material handling or process operation.

- Bridgwater et al. [39] indicated that when spontaneous percolation is acting within mixture segregation then a small particle will percolate slower in a moving bed than it does in a stationary one. The author also suggested that denser particles will percolate faster as will particles that have low elastic modulus such as rubber and PTFE.
- Methods used to charge vessels that utilise conveying means other than gravity i.e. pneumatic conveying could introduce a unique pattern of segregation. If the prevailing conditions are commensurate with the conditions required, then it is possible to achieve a complete reverse pattern of segregation resulting from the interaction of the bulk with the air used as the conveying medium.
- The feedrate can influence the time allowed for the segregation mechanisms to dictate the resulting pattern of segregation occurring as can the geometry of the vessel.

Attempts at modelling heap segregation have had to address the immense complexity and interchanging mechanisms at different points in the vessel filling cycle. This has dictated that theory developed has essentially been confined to focussing on only a small part of the heap segregation process. Segregation has such an enormous scope and diversity that literature published has often only been able to focus on one behavioural facet of the phenomenon utilising few materials. This has resulted in mechanistic theories being developed which can model certain mechanisms of the process in isolation, whereas a general solution, which incorporates all aspects of the process has yet to appear. This is not a surprise as the separate parts of the process are still to be understood more fully before attempts can be made to arrive at a more general solution to the problem.

Different approaches were undertaken to quantify segregation utilising various experimental test facility designs or different methods to initiate movement of mixtures. However, irrespective of these differences, similar indications of a materials propensity to segregate was found. Barbosa-Canovas et al. [9] clearly observed that the type of mixture that exhibited strong segregation tendencies in a vibration regime of flow also exhibited similar behaviour in a gravity induced regime of flow. The author suggests that although segregation strongly depends on externally applied regimes of flow, the relative tendency of powders to segregate is an inherent property that largely depends on differences in mixture constituent properties.

To compound the investigation of segregation still further, literature has often been published where results from small-scale rigs have been used in an attempt to model the flow regime commensurate with an industrial application. However, factors such as fluidisation, air current, and trajectory mechanisms on an industrial scale are difficult to scale down to laboratory type rigs. Techniques of quantification have been essentially empirical in nature, or mechanistic, which have often been limited to the inclusion of one or two mechanisms of segregation. A new hybrid of segregation literature is appearing, as outlined in Sections 3.9.3 and 3.9.4, that attempts to take the first tentative steps in incorporating all known characteristics into a mechanistic equation. These equations are still in their embryonic stages of development but are seen as an appropriate progressive step to formulating a general predictive technique applicable to all segregation scenarios.

Overall, undertaking a literature review of this magnitude has been necessary in order to piece together various disparate segregation articles into a coherent form that provides a clearer picture of the global applicability of segregation. This review has shown that it is not surprising that segregation is perceived as a complex and confusing phenomenon, with authors using or inventing different terminology and/or mechanisms that sometimes represent the same facet of segregation behaviour. This mass of non-standardised segregation literature is a manifestation of why industry is confused and is a justification for undertaking such an extensive review.

Approaches into understanding and resolving segregation have been approached from experimental standpoints, modelling from experimental laboratory-scale approaches and purely theoretical. Theoretical approaches have not currently progressed to a stage that incorporates all known contributory factors that are known to influence segregation. Experimental approaches have produced engineering solutions in terms of methods that can reduce segregation but at the expense of attaining any fundamental understanding of the mechanisms the induce segregation. An approach, which has seen more productive progress of understanding heap segregation, has been that of empirical modelling. Experimental results taken from industrially relevant segregating environments that incorporate a variety of known variables that influence the magnitude of heap segregation have been used to develop empirical models. Empirical approaches have been the most productive in terms of deriving industrially relevant applicable tools that can be utilised to quantify segregation. This strategy has therefore been adopted as the most appropriate means by which to investigate segregation pertaining to heap formation. An experimental testing facility that incorporates industrially scaled factors that significantly induce segregation, such as free-fall height, will be developed. Results taken from such a rig design will be used to develop empirically based techniques that can be used to quantify heap segregation.

CHAPTER 4

TESTING METHODOLOGY

4 Testing Methodology

As discussed in the conclusions of Chapter 3 the literature review highlighted the fact that more than one mechanism of segregation was functioning within the heap segregation process. In addition, the contribution of each mechanism was influenced by combinations of various particle, process and geometric variables, characteristic of the segregating environment. It was therefore necessary to establish the hierarchical priority and required testing range of particle, process and geometrical variables to be investigated within the gravity induced heap segregation environment. An empirical approach could then be applied to the most significant variables that are considered to influence heap segregation.

4.1 Hierarchical Structure of Segregation Variables

The literature reviewed in Chapter 3 revealed that similar particle, process and geometrical variables were being held accountable for the resulting segregation of a mixture under investigation. These variables were found to interact to varying degrees to produce unique patterns of segregation when charging a storage vessel. Consequently, any proposed testing facility designed to analyse this form of segregation should have sufficient flexibility to investigate these variables individually or in combination. However, there are many other segregation related variables, and whilst it would have been beneficial to incorporate them all into a segregation testing facility, a feasibility study into this possibility suggested that this was not a viable option. As segregation is only one facet of material behaviour within storage vessels, it was necessary to establish the inter-relationship between those variables that caused segregation and those associated with other aspects of particulate material flow. Particle size, size distribution, shape, density, flowability, angle of repose, resistance to agglomeration, surface characteristics, geometry of vessel, material height in vessel, wall friction, method of feeding etc must all be assessed for possible inclusion in any proposed investigation. A test facility design should ideally be able to quantify their influence on dictating segregation. Not all of these variables are independent and some, such as bulk density and angle of repose, are convenient measurements representing composite affects of variables. To simplify the process a variable flow diagram of heap segregation was formulated upon the basis of the authors experience and of the literature reviewed. This allowed the separation of the major factors from those believed to be of less significance. The variable flow diagram of influential particle, process and geometrical variables from the evidence provided in the literature review can be found in Appendix A.1. The hierarchical structure of the most significant primary variables, gleaned from the variable flow diagram and incorporated into the design of the segregation testing facility, is shown schematically on Figure 47. A test facility design should allow independent control of factors such as vessel geometry, free-fall height, and the position and method of feeding. Incorporating these variables would allow their influence on primary segregation variables to be controlled and eliminated when necessary.

As indicated on Figure 47 the most influential factor in dictating the propensity of a material to segregate when exposed to gravity-induced heap segregation is particle size. Although in the extreme, any difference in particle characteristic could initiate segregation in its own right, all the available evidence suggested that differences in constituent size had the most influence in contributing to the resulting pattern of segregation. This characteristic was deemed the most appropriate around which to base any ensuing investigation into segregation when charging storage vessels. Particle size alone was not the sole particle characteristic of interest. Particle density could interact significantly with size to influence the resulting pattern of segregation. In reality, the likelihood of a mixture having no difference in constituent density in any given application was unlikely. Consequently, any conclusions drawn from size only investigations must be made with respect to the interaction that density will also make in a given segregating scenario. All other particle characteristics and interactions could be considered of secondary importance compared to the interaction of size and density. Significant process variables were deemed constituent concentrations and feedrate. The concentration of constituents of a mixture dictated the types and extent of mechanisms within heap segregation, whilst the feedrate influenced the time available for these mechanisms to act. Geometric variables such as vessel geometry dictated the size of heap formed. Any free-fall height that is intrinsic of certain vessel geometrys induced kinetic influences of segregation into the charging mixture.

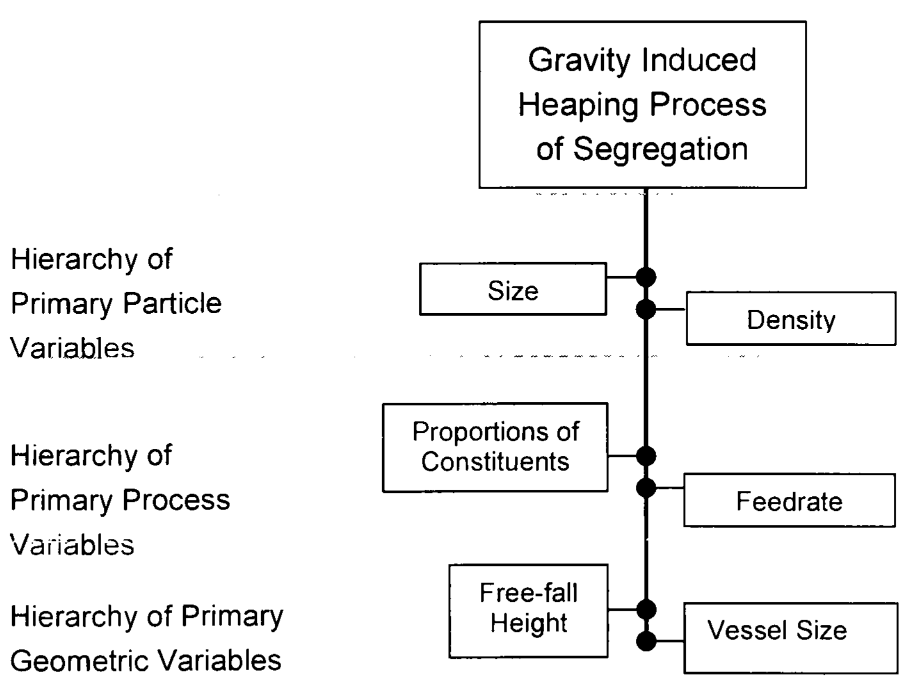


Figure 47 Primary Particle, Process and Geometric Variables that Influence Gravity Induced Heap Segregation

4.2 Requirements of Segregation Test Facility

As documented in Section 4.1 material segregation was deemed sensitive to the interaction of particle, process and geometrical variables initiated by the environment in which the system is operating. The forms of segregation test facility utilised to investigate segregation as outlined in Chapter 3 could be categorised according to the type of segregation investigated. Some documented research relating to gravity induced heap segregation that did not incorporate any kinetic influences that are known to affect the resulting pattern of segregation. Conversely, some authors, who recognised the influence of kinetic affects designed and utilised a testing facility that incorporated and compensated for this factor. For comparative and correlation purposes of this research, it was felt that any proposed investigation into segregation should produce results that are comparable with either a high or low energy segregating environment. Consequently, any proposed testing facility should have the facility to be able to create both types of segregating environment.

If any meaningful conclusions are to be drawn from undertaking a proposed plan of work investigating segregation, it was imperative to assess any formulated mixture quality prior to its exposure to segregating conditions. Quantification of mixture quality prior to segregation is absent from the majority of segregation literature reviewed. Therefore, any proposed method of mixing the diverse types of mixture combinations required for such an investigative undertaking must produce a consistent quality of mixture, irrespective of the propensity of the mixture to segregate.

A segregating environment created by the design of a test facility should be geometrically similar to that found in storage vessel environments. With respect to investigating a centrally charged plane flow two-dimensional environment, only one half of a two-dimensional heap needs to be formed in order to extract the necessary segregation information. This is possible since the segregating regime of flow for both sides of a two-dimensional heap is the same and the pattern of segregation is mirrored around the vertical centre axis of the heap, Figure 7

With respect to investigating gravity induced heap segregation of stockpiles or charging conical vessels, it is important to match and simulate the actual physical segregating environment to that being generated within the testing facility. Geometric variables such as free fall height are difficult to scale down successfully from the original size to a test scale dimension. Consequently, any pilot-scale test facility should incorporate the exact scale of variables so that it can accurately mimic conditions that prevail in an industrial environment that exhibits segregation.

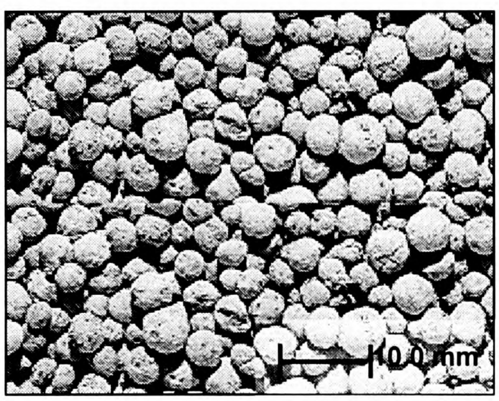
4.3 Selection and Characterisation of Appropriate Test Material

Particle size was prioritised as the most influential particle characteristic necessary for investigation and as such the selection of a suitable test material should comply with the following criteria:

- The material should not degrade. Degradation of the particles would cause an undesirable change in mixture size distribution as a direct consequence of being exposed to the mixing and material handling stages of the testing facility.
- The material should have a sufficient difference in sizes in order to formulate appropriate size fractions that induce the desired magnitude of segregation.
- Quantification of the size of an individual particle or the relationship between size fractions of a mixture is compounded when the particle is non-uniform in shape and surface texture. Therefore, as a starting point a free-flowing particulate material should be selected whose particle shape is largely spherical in nature.
- The material should be absent of inherent or surface moisture that can disguise or restrict the real significance of the variable under investigation
- Particle sizes below a critical value (generally 100μm) or absolute mixture sizes (generally less than 500μm, Figure 16) should not be used as cohesive properties of such particles can repress free-flowing and hence segregating tendencies of the mixture.

A search was conducted into the applicability of particulate materials that would fulfil the above mentioned criteria. This ultimately resulted in the selection of a lightweight aggregate named 'Lytag' as the base material for subsequent investigations. The lytag aggregate material is produced from a large scale sintering process and is composed of pulverised fuel ash, a by-product produced from the coal-fired electricity generation process. The pulverised fuel ash is pelletised and sintered at 1300°C to produce hard, lightweight rounded granules that have found widespread application in building, civil engineering and horticultural industries. For the purposes of investigating segregation, the particles could be considered spherical enough in nature, tough enough to inhibit degradation and available in a variety of sizes and colours to allow a visual indications and quantifiable measurement of segregation. Standard procedures were employed to characterise the principle properties of the aggregate. The results of these procedures are listed below and shown in Figure 48 together with references to the procedures used in determining characteristics of the particulates.

Bulk Density Poured (ρ_{bP}) = 900 kg/m^3 [68] Bulk Density Tapped (ρ_{bT}) = 950 kg/m^3 [68]
Particle Density (ρ_p) = 1660 kg/m^3 [69] Poured Angle of Repose = 35° [68]
Void Ratio (%) = 40 Median Particle Size (d_{50}) = 4 mm, Figure 46.
PSD obtained using Standard Sieving Technique [57]



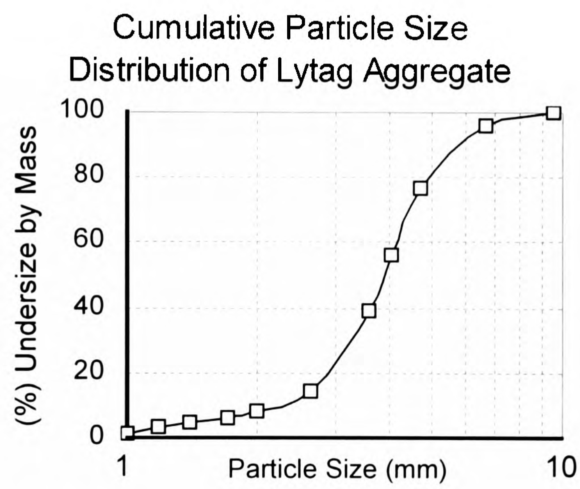


Figure 48 Photograph and PSD for Lytag Aggregate Material.

4.3.1 Quantifying Test Material Size Fractions

When selecting the required size fractions of lytag aggregate it was important to establish two limiting boundary conditions. According to Williams and Khan [49], the mean diameter of a mixture, or particles of a formulated size fraction, will not influence segregation of the material if the mean diameter exceeds approximately 500μm, Figure 16. Below this value, the affect mean particle size can have a profound influence on the resulting degree of segregation that the mixture undergoes. In addition, as highlighted in Section 4.3.2, binary mixtures whose diameter ratios exceed approximately 5:1 incur segregation that is greatly influenced by the mechanism of spontaneous percolation. Therefore, in terms of investigating size segregation of free-flowing materials, it is a requirement to separate a sufficient quantity of material into various size fractions that fit within these two limiting extremes. The required spread of sizes of lytag aggregate should therefore fulfil the following criteria:

- Size fractions must be formulated whose mean diameter is greater than 500μm to negate the affects documented by Williams and Khan [49].
- Size fractions should be narrow enough to allow a fraction to be quantified by the median diameter (d_{50}) of the size fraction.
- There should be a sufficient disparity of size fractions that can be combined, if necessary, to produce a binary sized mixture that encroaches on critical sizes that initiate spontaneous percolation.

The bulk lytag aggregate was separated according to the fourth root of two ratio relationship (4√2 = 1.189). This relationship is used to graduate sieve aperture sizes in compliance with B.S. 1796: Part1 1989 or ISO 2591-1: 1988(E) regulations. This technique of grading the lytag aggregate allowed a closer sizing of material fractions than the normally adopted square root of two ratio ($\sqrt{2}$ = 1.414). Narrow grading of lytag aggregate was necessary as only minute differences in size between two fractions is sufficient to incur significant size segregation, Figure 16(a).

Using the mean diameter to quantify a size fraction produced by the $4\sqrt{2}$ relationship does not incorporate any knowledge of the spread of particle sizes bounded within the limits of the fraction. By formulating size fractions according to the $4\sqrt{2}$ relationship a size fraction was produced that was sufficiently narrow in terms of spread of particle sizes. Subsequently, the median size of the fraction (d_{50}) could then be employed to give an accurate quantifiable measure of the size fraction. Some of the fractions formulated had an increased range of sizes. Fractions containing a wider range of sizes were formulated, as it was necessary to amass enough quantity of material of a particular size fraction in order to meet the volumetric requirements of the segregation vessel. However, the range of sizes that were used to formulate these particular size fractions were still sufficiently narrow and did not negate the median particle size being used to measure a size fraction.

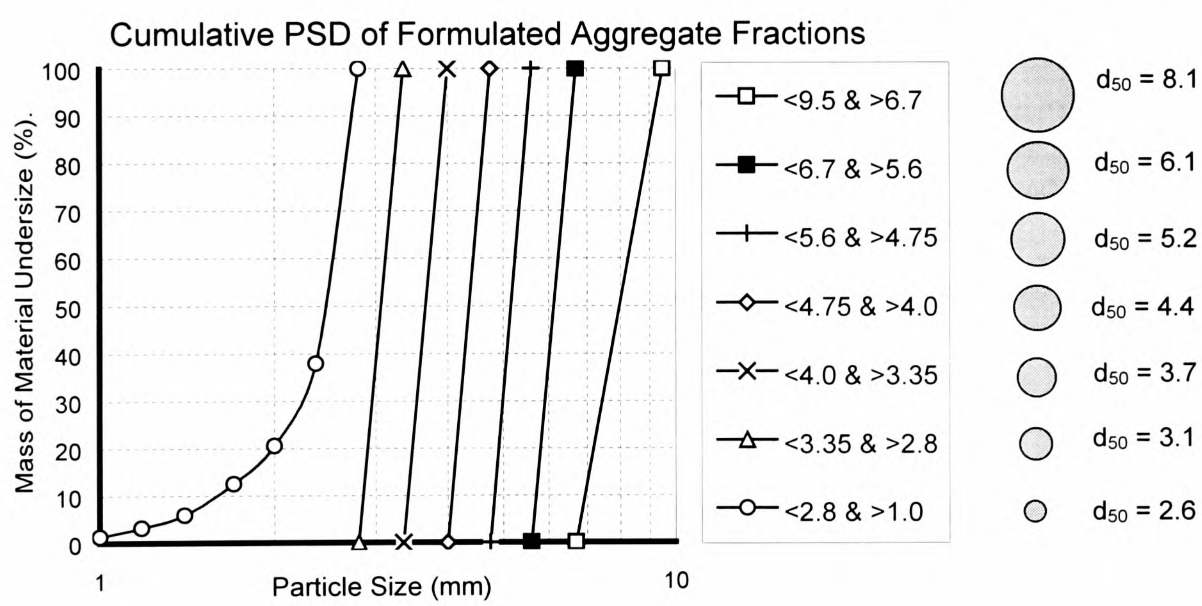


Figure 49 Particle Size Distributions of Formulated Size Fractions

The bulk material was separated into appropriate size fractions by using screening equipment that was re-engineered in order to process efficiently the lytag aggregate and other particulate materials for investigation, Figure 54. Bulk aggregate size fractions were repeatedly screened until an 'end-point' of sieving was reached. This point, according to B.S. 1796: Part1 1989 or ISO 2591-1: 1988(E) was reached when the quantity of small particles passing through the screen in 1 minute was less than 0.1% of the total mass charged to the screen. Screening the entire bulk material was conducted in accordance to the stipulated requirements set out in B.S. 1796: Part1 1989 or ISO 2591-1: 1988(E) in order to separate the bulk aggregate into appropriate size fractions as shown on Figure 49.

4.3.2 Ascertaining the Required Difference of Particle Sizes

The degree of disparity of particle sizes necessary to induce the required magnitude of size segregation is governed by the particle packing arrangement of the mixture. However, there is more than one type of packing arrangement that can exist within a gravity induced heaping environment. Furthermore, the types of packing arrangements formed remain unstable and alter continuously. Consequently, the factors that influence the type and duration of packing arrangement formed are:

- The degree of disparity between particle sizes.
- The proportion of constituent sizes that comprise the segregating mixture.
- The rate of material flow.

Rudimentary investigations of packing structures for mono-sized spherical particles are documented in Appendix A.2. This evidence indicates that various packing structures can exist at any one time within a heap segregating environment and compounds the search for a single critical diameter ratio that induces spontaneous percolation. A compromise was reached in an effort to determine a value. It was assumed that a general packing structure was formed for the segregating flowing bed. This then allowed an indication of the limiting diameter ratios required of a mixture. According to the documented evidence provided by Williams and Khan [49], Figure 16, the maximum degree of segregation occurred for a diameter ratio of approximately 5:1. Any further increase in the diameter ratio of the mixture components caused no increased rate of segregation with segregating behaviour tending to be asymptotic in nature. This would suggest that testing mixtures of greater diameter ratio than this value would not be a necessary requirement of this program of work. With reference to the various packing structures shown on Figure A.2.1, spontaneous percolation can range from a diameter ratio as low as 2.4:1 (square pore cubic packing structure) up to approximately 6.5:1 (triangular rhombic packing structure). Evidence was provided by Arteaga and Tüzün regarding the influence on the shape of voidage, the increased packing structure for flowing beds, and the generalisation that gravity induced heap segregation produces a mixture that assumes an orthorhombic structure. This suggested that the spontaneous percolation diameter ratio resided somewhere between 2.4:1 and 6.5:1. A diameter ratio of approximately 4.45:1 determined from the packing arrangement of four touching spheres as shown in Figure A.2.1, together with the suggestions proposed by Williams and Khan [49] indicate that the value should be approximately 5:1. This value was therefore selected as a ceiling for the magnitude of sizes to be used in this research. The largest difference of particle sizes for any formulated lytag mixture is approximately 3.1:1, which does not exceed the size that induces spontaneous percolation of a mixture that forms an orthorhombic structure. However, it is generally accepted that the magnitude of segregation is known to be most severe for mixtures having a diameter ratio between approximately 1.3:1 and 1.4:1, Figure 16(a). Consequently, the maximum difference of particle size formulated using the lytag aggregate material should yield the appropriate magnitude of segregation.

CHAPTER 5

DEVELOPMENT OF TEST FACILITY

5 Development of Test Facility

When designing the test facility it was important to realise the type of segregating environment being sought. It was not possible to accommodate all the contributory factors known to exist within heap segregation into a test facility. Consequently, the hierarchical list of factors, documented in Sections 4.1 and 4.2, was used to select factors for inclusion in an experimentally driven investigation into segregation. Investigations into segregation documented in the literature and the type of segregation results being sought indicated that the proposed investigation would be predominantly empirical in nature. There was a need for the facility to simulate, in a highly controlled and repeatable environment, high and low energy segregating conditions. The literature review highlighted that affects of variables such as free-fall height were difficult to scale down from an industrial scale to a pilot scale test facility. This therefore necessitated the design and construction of a relatively large test facility in order to correctly simulate these conditions in order that segregation results produced were representative of an industrial application. The design of test vessel that evolved from these requirements created an environment in which half of a two-dimensional heap was formed. This was sufficient to yield the appropriate amount of information on the propensity of a test material to segregate when exposed to the gravity induced heaping process of segregation.

5.1 Component Parts of Test Facility

A test facility was designed that was sufficiently flexible to incorporate the essential primary variables of concern. Primary variables included particle size, size distribution, angle of repose, flowability, and surface characteristics as well as geometric variables such as shape and size of vessel, height of material in bin, and the position and method of charging the mixture. Investigation was simplified still further by maintaining some of the secondary factors constant. The shape of the vessel remained constant, as did the method of feeding and the facility of maintaining a constant free fall height of charged material.

The test facility is shown in pictorial and schematic fashion in Figure 50. The facility can best be described by analysing, in sequence, the component parts that the test material under investigation is subjected to as it travels through stages of material formulation, segregation and spent material re-processing.

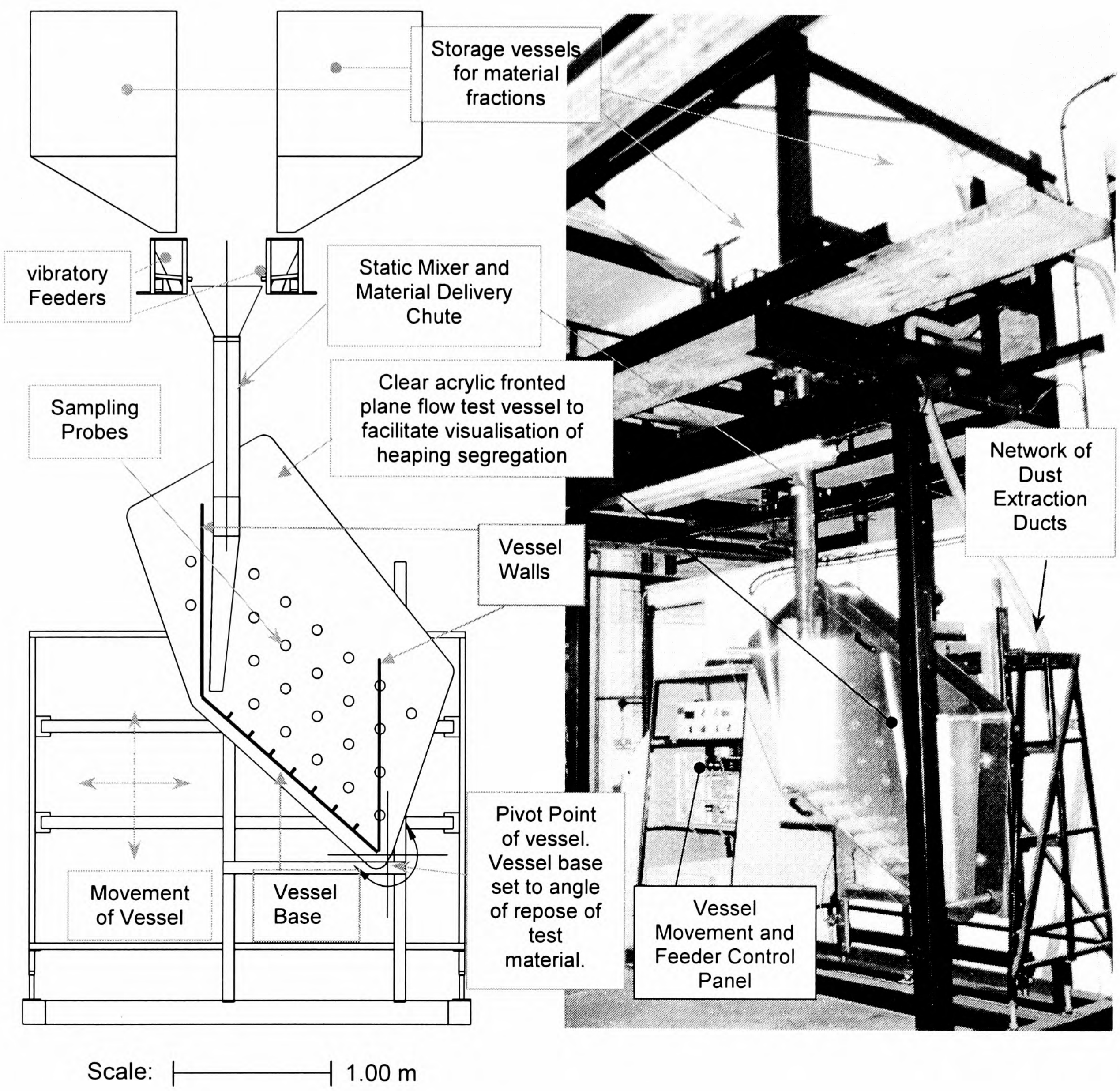


Figure 50 Photograph of Testing Facility with Schematic Diagram of System Components

5.1.1 Material Fraction Storage and Feeding

As shown on Figure 51, five hoppers provided a consistent head of material to the feeders via intermediate feed hoppers. It was conceivable, depending on the specifications of the test, that five variations of a single particle characteristic such as size, shape, or density etc. could be formulated. Similarly, a multi-component mixture could be formulated that differed in constituents. The specified mixture for investigation was fed via five, independently governed, amplitude control vibratory feeders. The feeders were manufactured based on a prototype design proposed by Barnes [70] that required a major re-design. The feeders proved flexible enough to formulate and feed simple binary mixtures up to industrially representative mixture compositions and/or characteristic distributions. Variation of constituent proportions and the overall consistent control of mixture feedrate were easily obtained using this design of feeder.

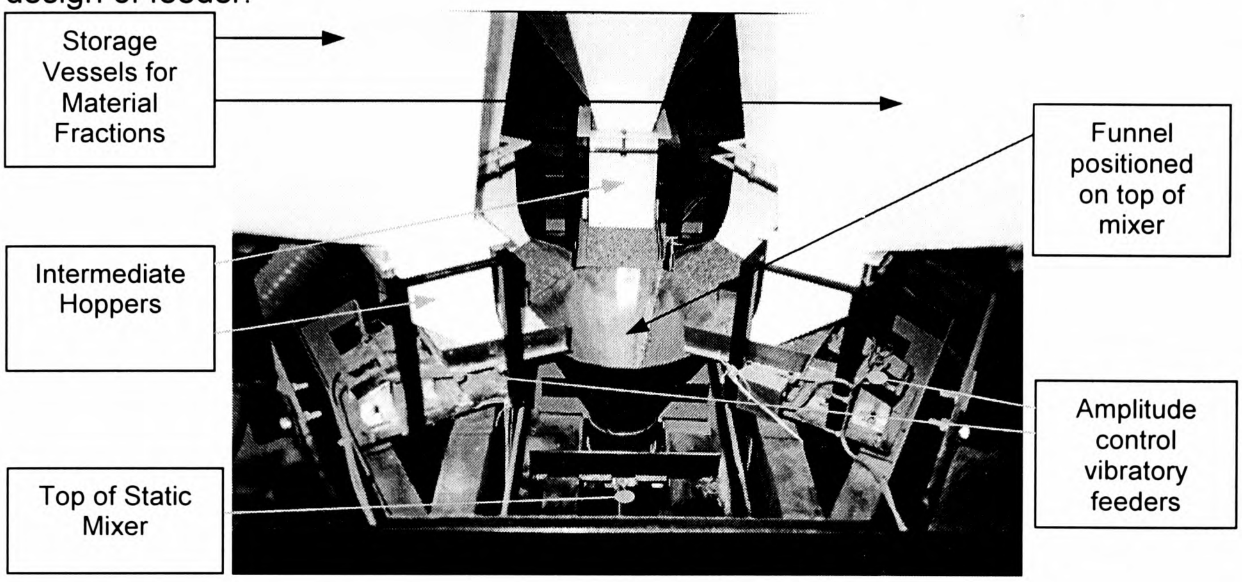
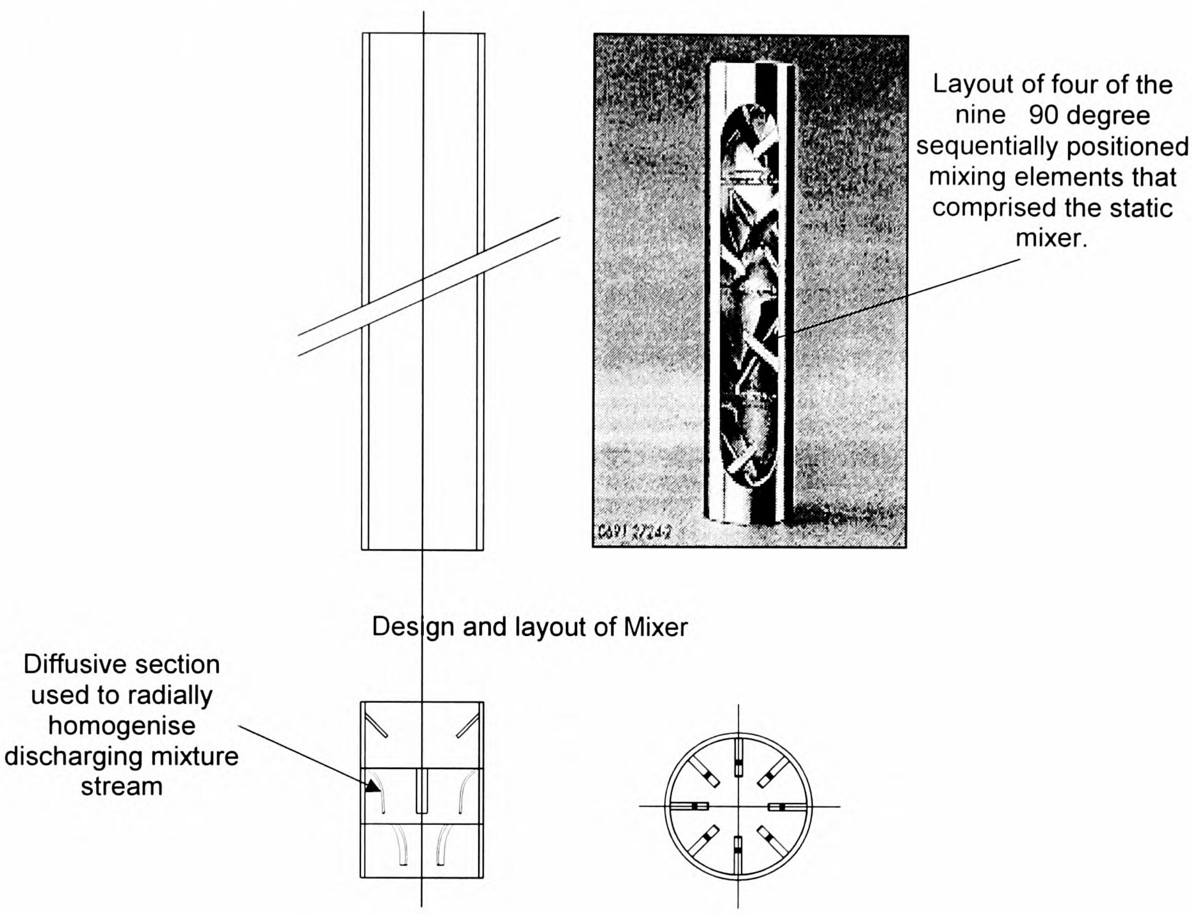


Figure 51 Storage and Feeding Parts of the Segregation Test Facility

5.1.2 Mixing and Delivery of Material Fractions

A considerable amount of investigative work went into the selection of an appropriate mixer, detailed results of which are listed in Appendix A.3. and A.4. Summary details of this work were also presented in a published article [71] which is included as Appendix A.3. Analysis of the results obtained from conducting a feasibility study revealed that a static in-line mixer was able to attain a sufficiently high degree of mixedness across the spectrum of particle sizes that were to be used in this investigation. The mixer was able to achieve this without incurring any significant change in particle size due to degradation. As shown on Figure 51 up to five separate size fractions could be fed into a funnel attached to the top of the mixer. This in-line mixer served to combine the incoming constituent streams using natural gravity influences in conjunction with the momentum induced into the material via the vibratory feeders. The internal construction of mixing elements is shown on Figure 52.

One component part of the mixer feasibility study concerned the discharged radial mixture quality as this was deemed essential if consistent segregation on each side of a centrally charged conical heap was to be achieved. It was found that the radial positioning of the vibratory feeders around the mixer in conjunction with the rotational geometry of the mixing elements dictated some preferential radial flow upon discharge [71]. To counteract this behaviour a diffusive section was attached to the bottom of the mixer, the design of which can be seen in Figure 52. This helped to radially homogenise and centralise the discharging flow. The mixed material was then allowed to pass through a flow converging section. This served to condense and shape the discharging mixture stream into an appropriate form for charging the test vessel. The converging section subsequently delivered the mixed material to the designated point of charging the heap in the test vessel.



Side and Plan View of Diffusive Section

Figure 52 Design of Static Mixer and Diffusive Section Elements

5.1.3 Test Vessel to Facilitate Segregation

The storage vessel used to create a segregating environment commensurate with a plane-flow storage vessel consisted of a hopper half section with sampling probes positioned at various locations along its length. The front wall of the vessel was transparent allowing visual inspection of segregation patterns. The vessel could be rotated via an adjustable pivot point to allow the alignment of probes to match the natural poured angle of repose of the mixture being investigated. The test vessel was mounted on a vertical traverse mechanism operated by a closed loop control system. This allowed control of the vertical movement of the test vessel and in doing so allowed the height between the heap surface being formed and discharge point of the charging mixture to be controlled at a fixed value. This could be achieved, irrespective of height of charged material and changing mass of the test vessel during filling. The free-fall height of the charging mixture stream could be fixed at a predetermined height or maintained constant at a predetermined distance in order to assess the influence that free-fall height had on influencing the heap segregation process. The control system used to control the vertical movement of the vessel together with the vibratory feeder controls can be seen on Figure 50.

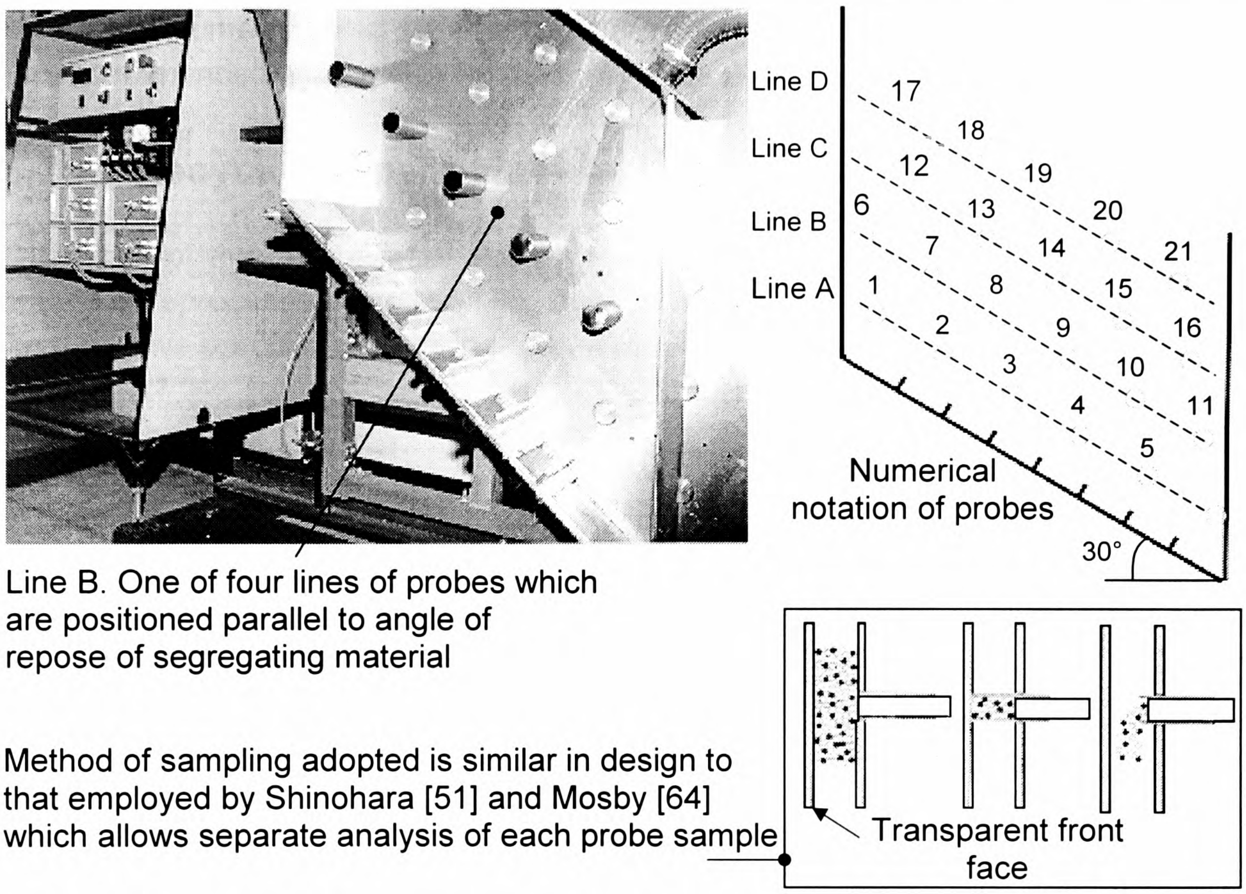


Figure 53 Positional Arrangement of Probes and Method of Sampling Segregated Mixture.

Williams [29] emphasised the importance of obtaining a required number of samples extracted from a bulk in order to determine a representative state of segregation. It was important therefore to establish the required dimension of sampling probe, which fixed the scale of scrutiny as well as the required probe sample volume necessary to provide an accurate description of mixture quality. As may be seen from Figure 53, the vessel set at an angle of 30 degrees to the horizontal allowed 21 samples to be extracted from a fully charged segregated bed of material. This equated to a sampling volume that was approximately 5% of the total volume of segregated material and was deemed sufficient in providing a representative measurement of segregation. In addition, Allen [57] suggests that the mass of material required to form a sample for a sieve analysis should normally lie between 25 and 50 grams. However this is dependent on characteristics of the material being sampled i.e. sample mass is dictated by particle size and density. The segregated material extracted from a single probe had a material mass of approximately 150 grams, which was felt not to be an excessive amount for sieving when considering the density of the aggregate used. A 150 gram probe sample converts to a bulk volume of approximately $0.158x10^{-3}$ m^3. The probe samples were to be processed utilising a series of 200mm diameter round sieves. B.S. 1796: Part1 1989 or ISO 2591-1: 1988(E) recommended that the maximum volume of material to be charged into a single 200mm diameter round sieve should not exceed approximately $0.35x10^{-3}$ m^3. Therefore the volume of material extracted from a probe sample exceeded the minimum volume required for charging a sieve and the mass did not exceed that of the recommended charge size for the test sieves used.

5.2 Recycling Spent Material

Quantities of the test material available were restricted, hence this necessitated a means of reprocessing and recycling spent material back into required size fractions. An extensive retrofit of an existing screen machine was undertaken to fulfil this task.

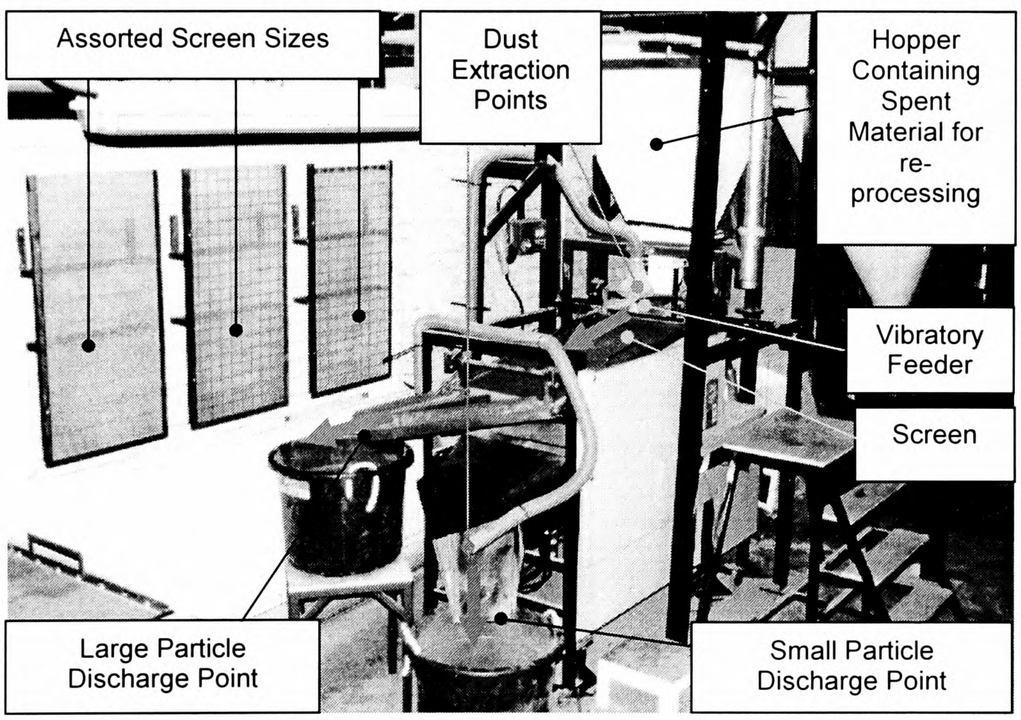


Figure 54 Photograph Showing Layout of Screening Station with Salient Parts

A vibratory feeder was used to feed spent material across the width of the screen. The screen was periodically oscillated between two pivots positioned along its length in order to induce particulate movement of the material on the screen. This was further intensified by a set of vibration pads that were used to agitate the screen and hence control the magnitude of particle movement as it descended over the screen surface. The combination of these two types of screen agitation produced an efficient means of separating sizes of the spent mixture back into their base fractions.

CHAPTER 6

ANALYSIS OF HEAP SEGREGATION

6 Analysis of Heap Segregation

Segregation tests were initially undertaken with the purpose of fulfilling three objectives:

- Familiarisation and commissioning of test rig performance.
- Ascertaining integrity of segregation data.
- Analysing heap segregation behaviour within the environment created.

A test program was implemented to assess these three objectives and gauge the significance of primary segregation variables established in Section 4.1. A test program was also constructed in order to fulfil the requirements of a statistical analysis that was derived from an understanding of factorial design [72]. Factorial design allows the undertaking of a minimal number of tests in order to ascertain the maximum amount of information pertaining to the significance and interaction of selected segregation variables.

6.1 Integrity of Data

As part of the initial familiarisation and commissioning stages of the test work, a series of tests were conducted to assess the repeatability and integrity of data being produced. These tests were performed in order to gauge the ability of the test apparatus in producing repeatable test results for one test condition and also to assess the accuracy of the method used to extract samples for analysis. Undertaking a series of repeats ensured that any measured variation of samples extracted for analysis could be attributed to experimental sampling error. It is therefore reasonable to assume that repeated sampling would yield a normal distribution statistical relationship commensurate with sampling error. Consequently, Figure 55 shows the repeatability of the results taken for a series of identical test runs with 95% confidence limits that all extracted sample results would reside within the regions shown.

Initially all test runs undertaken utilised the ability of the test facility to control the descent of the vessel whilst filling. This was implemented in order to maintain a constant height between the heap surface and the mixer discharge point as the vessel was filled. This ensured a constant free fall height was maintained throughout the duration of vessel filling. As a direct result of conducting tests in this manner, vertical segregation induced by variations in free-fall height during vessel filling was eliminated. Figure 56 shows the variation in vertical segregation for the four series of probes that run parallel to the heap being created. The notation and layout of probes in the vessel were shown previously on Figure 53, Section 5.1.3.

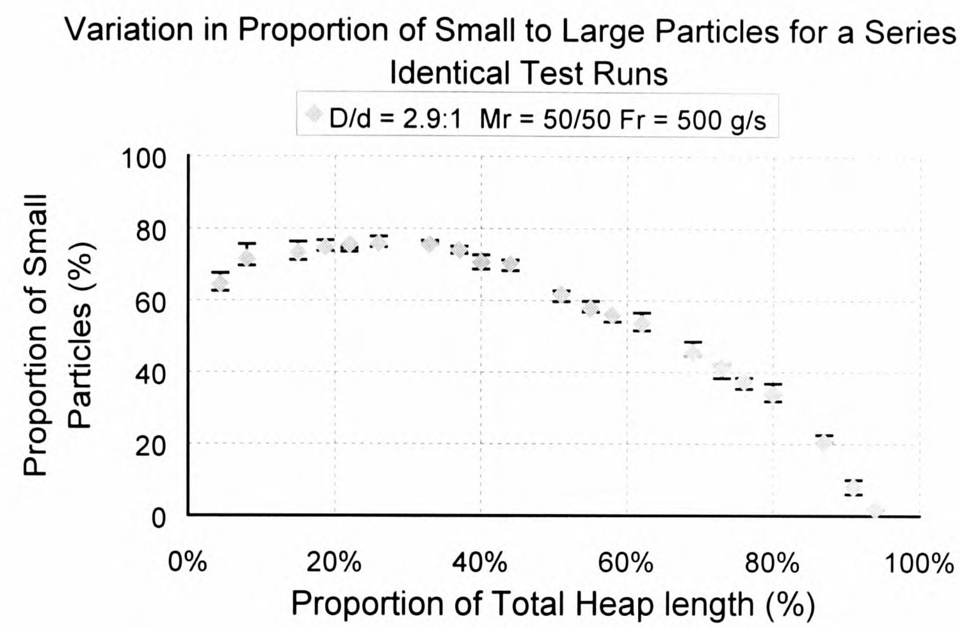


Figure 55 Variation in Measured Sample Compositions Extracted for a Series of Repeated Test Runs for One Test Condition.

It is clear that even at extremes of sampling error, utilising the adopted method of sampling produces patterns of segregation that would not significantly detract from that shown in Figure 55.

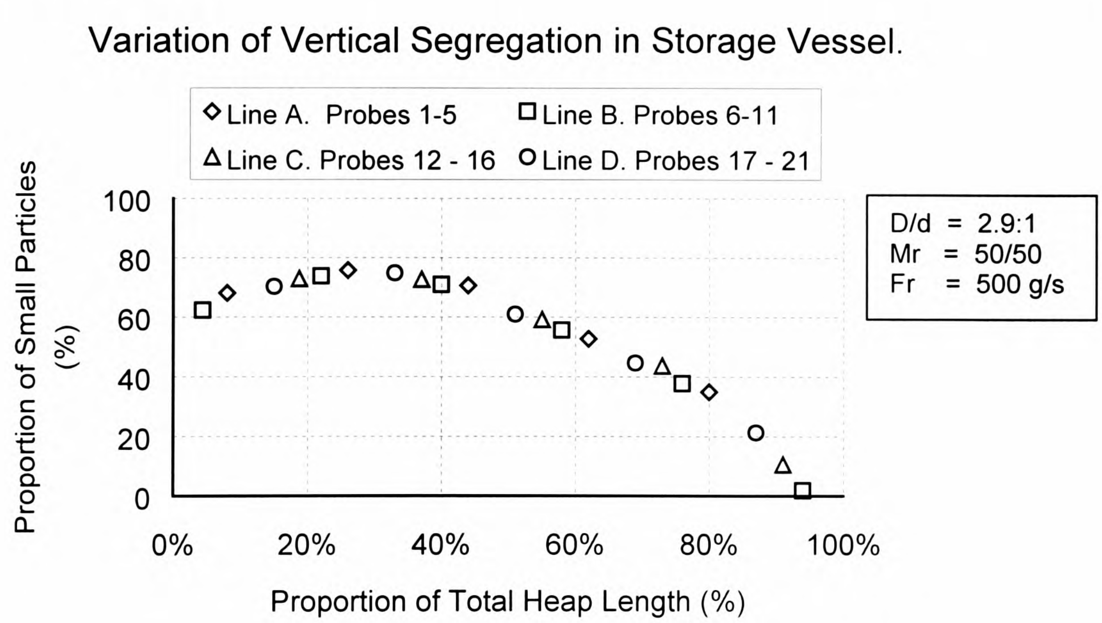


Figure 56 Variation in Vertical Segregation for an Arbitrary Test Condition.

The pattern produced by maintaining a constant free fall height was indicative of the majority of results analysed, thus indicating no significant vertical segregation.

6.2 Analysing Segregation Profiles of Large and Small Particles

Both visual and quantifiable evidence produced from analysing samples extracted at various locations within the material bed indicated that segregation had significantly influenced the resulting distribution of sizes within the vessel. Figure 57 indicates that charging the vessel in such a fashion as to create a heap induces fine particles to accumulate around the vicinity of the charge point with large particles congregating towards the periphery of the heap. Figure 57 shows a visual demarcation between these two zones. The pattern of segregation produced is comparable to established patterns of segregation documented in literature for vessels of this geometry.

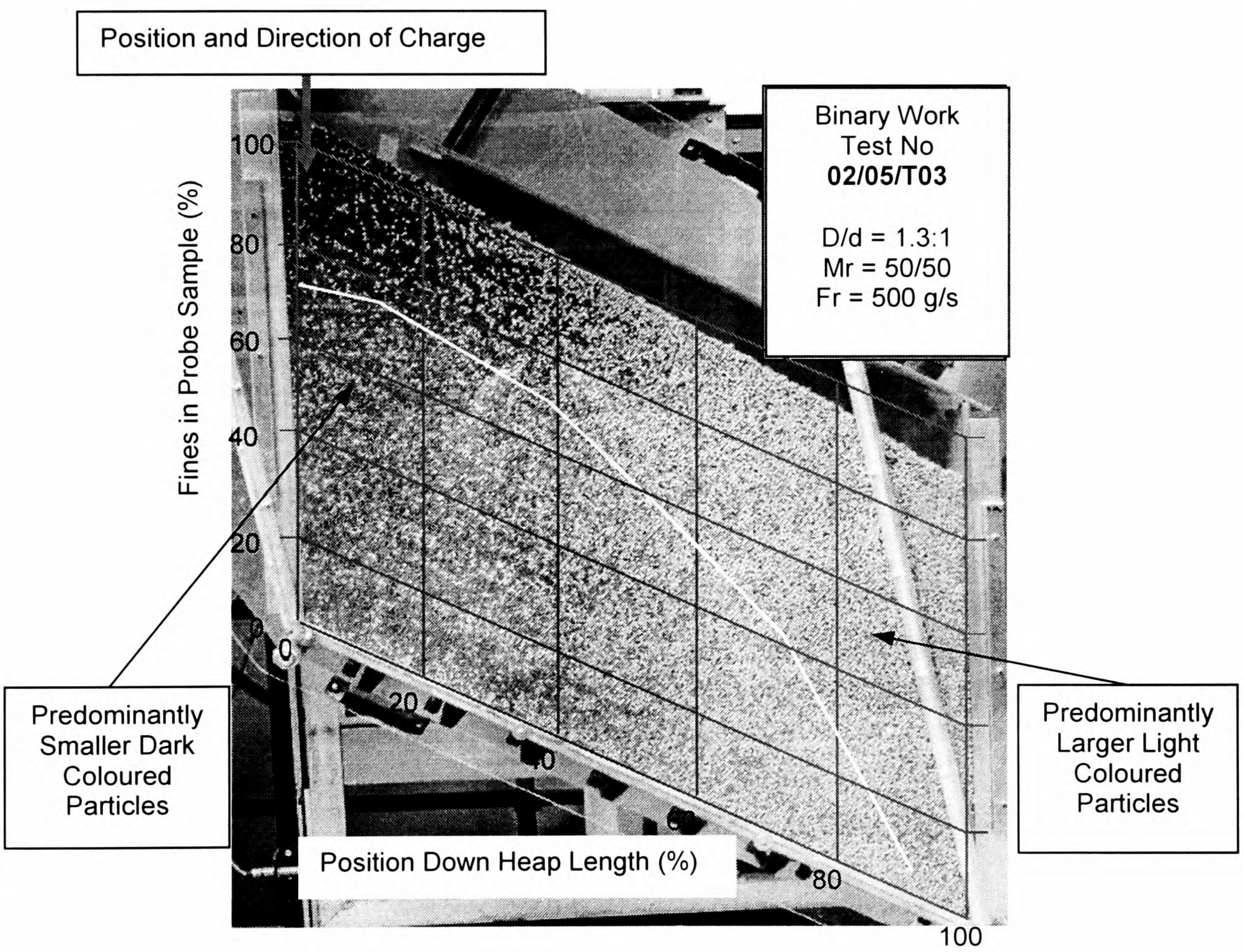


Figure 57 Significant Visual and Quantifiable Segregation of a Binary Sized Mixture after Charging Test Vessel

When sample measurements of proportions of small to large particles at locations in the vessel are superimposed over the visual picture of segregation, an unusual pattern of segregation around the vicinity of the charging point is revealed. This characteristic facet of segregation was conspicuous throughout the majority of tests undertaken and is recognisable by the initial increase in small particles immediately adjacent to the feed point. Thereafter the proportion of small particles decreases as shown, which is characteristic of size segregation resulting from heaping. Few documented accounts in the literature reviewed indicate the existence of this phenomenon. One such piece of evidence was provided by Lawrence and Beddow [47] who analysed film footage of the filling of a die. They recognised that the incoming stream of particles buried itself into the powder mass already in the die, in effect swelling up this mass during the filling process. This caused the top surface of the powder to bulge and flow outwards, thus producing a unique pattern of segregation around the vicinity of the fill point.

The majority of heap segregation models assume that the sieving-percolation mechanism of segregation actively engages in segregating the material as soon as the charged material is deposited onto the surface of the heap. It was evident from the initial tests undertaken that the avalanching/segregating layer progressed a certain distance down the heap surface before this mechanism participated in segregating the flowing mixture layer. Consequently, the majority of current modelling techniques based solely on the sieving-percolation mechanism cannot predict precisely the profile of segregation produced directly beneath the feed point.

The appearance of this initial 'hump' pattern under the feed point is a combined affect of two facets of the segregating environment:

- The momentum and direction of the charging material when contacting the heap surface.
- The particular mechanisms of segregation predominating within the heaping process around the vicinity of the fill point.

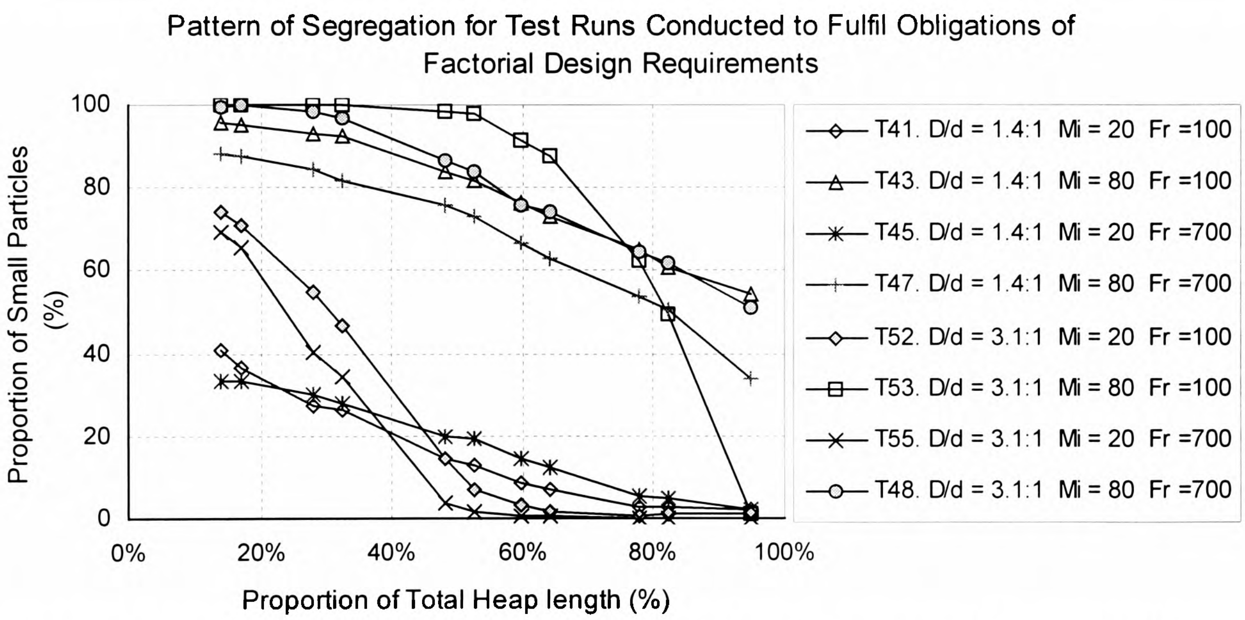
Analysis of video footage of the heaping process has resulted in the identification of different mechanisms of segregation, which dominate the segregation process at different stages of the avalanching layer descending the heap surface. A detailed qualitative description of these phenomena is documented in Section 6.4.

6.3 The Significance and Interaction of Factors that Cause Heap Segregation

An experimental investigation into segregation was conducted using a well-defined statistical sequence of operations in order to test for the significance and interaction of variables that caused segregation when forming a heap. A proven, reliable, statistically valid experimental design and data analysis technique [72] was used to undertake this investigation. The technique is a derivative of factorial design and utilises an orthogonal array to quantify the significance of factors and interactions based on the analysis of variance of a number of experimental observations. The variables selected as factors were chosen according to their frequency of occurrence throughout documented segregation literature that described them as being influential in dictating patterns of segregation produced by the heaping process.

Sixteen segregation tests were conducted in order to satisfy eight test conditions that were duplicated in order to fulfil the requirements of the orthogonal array. This provided the necessary information that was used to estimate an independent calculation of a single variables role on influencing the resulting pattern of segregation produced. Segregation variables, limits of investigation used and subsequent patterns of segregation for the eight test conditions conducted are shown on Figure 58.

Variable or Factor	Low Level (1)	High Level (2)
Median Diameter Ratio (D/d)	1.4:1	3.1:1
Initial Mixing Ratio of Small Particles. (Mi) %mass	20	80
Feedrate (Fr) g/s	100	700



Test No 41.	Mi in Original Feed = 20%	Average of Small Particles in all Samples = 16.5%
Test No 43.	Mi in Original Feed = 80%	Average of Small Particles in all Samples = 79.2%
Test No 45.	Mi in Original Feed = 20%	Average of Small Particles in all Samples = 18.4%
Test No 50.	Mi in Original Feed = 80%	Average of Small Particles in all Samples = 76.2%
Test No 52.	Mi in Original Feed = 20%	Average of Small Particles in all Samples = 25%
Test No 53.	Mi in Original Feed = 80%	Average of Small Particles in all Samples = 80.8%
Test No 55.	Mi in Original Feed = 20%	Average of Small Particles in all Samples = 19.7%
Test No 48.	Mi in Original Feed = 80%	Average of Small Particles in all Samples = 81.4%

Figure 58 Patterns of Segregation for Designated Test Conditions.

In order to apply the statistical technique it was necessary to quantify the pattern of segregation of the mixture into a single unit of measurement. As documented in Section 3.9.1, there exists a variety of indices used to quantify segregation, each of which has its own unique method of quantifying segregation. The underlying disadvantage of these indices is their inability to accommodate all the factors that influence segregation. However, the majority of these indices were readily available established means of quantifying segregation that required minimal manipulation of raw test data into a form required for processing through an index. To obtain greater confidence of the information produced by the statistical technique, the pattern of segregation produced was quantified using five different indices. Segregation was quantified by using Equations 1, 3, and 4. In addition, Figure 58 shows that it was possible to approximate the pattern of segregation to a straight-line. Therefore, the slope and intercept values of the straight-line law equation were also used to quantify the pattern of segregation. All the indices selected were used to describe the depletion rate of small particles per unit distance away from the fill point.

Irrespective of the index used to quantify the pattern of segregation, the values when processed through the statistical technique yielded similar results. The same variables and interactions were continuously being highlighted as proving influential in producing the resulting pattern of segregation.

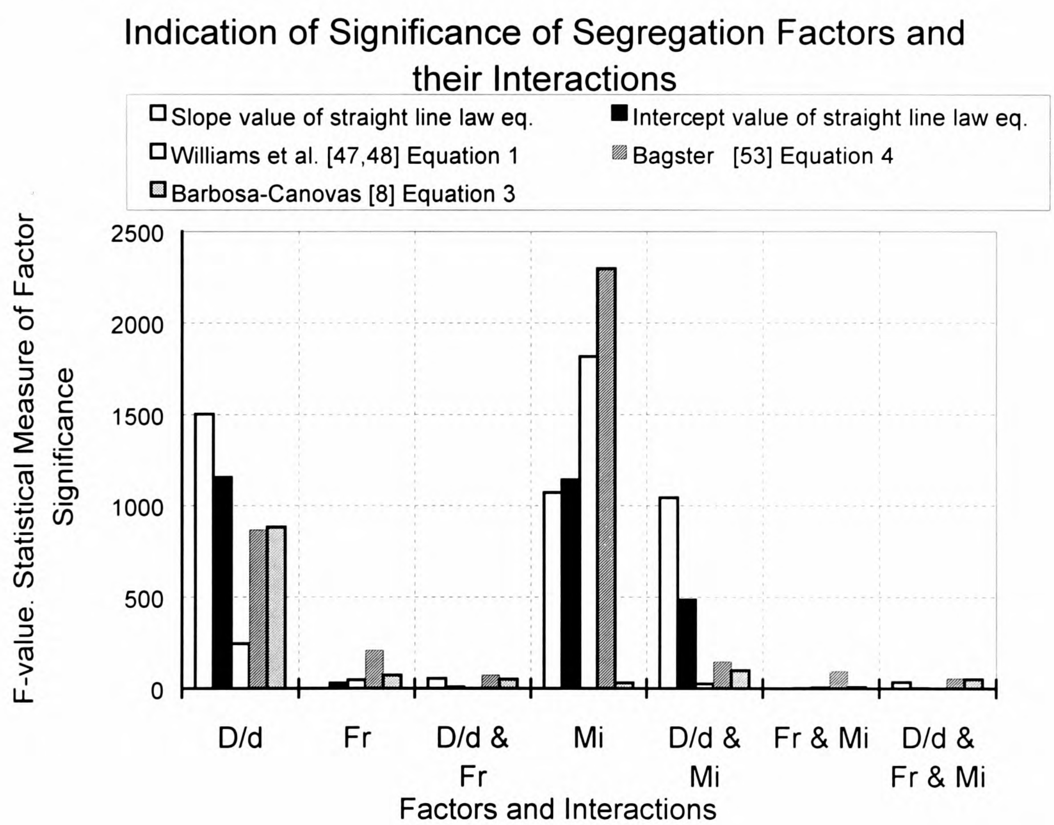


Figure 59 Indication of Significance of Factors and Interactions that Influenced Heap Segregation

An F-value was used to categorise whether a factor or interaction is significant. The F-value appropriate to this particular experiment can be found in F-tables published in statistical reference books and is an inherent part of this statistical technique. An F-value must be greater than 5 to stipulate a factor as being significant. As can be seen from Figure 59 the magnitude and relative differences between F-values produced is dictated by the segregation index used to quantify the pattern of segregation. The insignificance of feedrate within the range tested and the apparent significance and interaction of size differences and proportions of constituents are common to all results produced.

The statistical technique employed produced results of a factors influence within the range of tests undertaken. The technique provided an indication that the significance of a factor or interaction in producing different patterns of segregation is unlikely to have occurred by chance alone. However, any conclusive statements at this stage of the investigation must be stated alongside the fact that the internal model calculations are based on a linear regression technique. This infers that the relationship of factors used in the model calculations between the two boundary limits shown in Figure 58 is linear in nature. Nevertheless, with that said, the results produced from this work compare favourably with those documented in established segregation literature. Furthermore, the results indicate that the segregating environment being created in the test vessel is successfully simulating appropriate heap segregation behaviour being sought for further investigation.

6.4 Qualitative Description of Heap Segregation

Evidence of heap segregation behaviour has been gained from studying video footage of vessel charging and also analysing patterns of segregation produced when utilising the plane flow test vessel shown in Figure 53 page 130. It is evident that the behaviour of the heaping process is influenced by particle, process and geometric variables which all contribute to the number and extent of active segregation mechanisms at work. To simplify the qualitative description of heap segregation, size was selected as the only differing particle characteristic. The particle characteristic of size was therefore the only driving force behind the resulting mechanisms of segregation. Consequently, the following qualitative description serves to illustrate the segregation process driven by mechanisms activated by differences in particle size. However, where appropriate the qualitative description references significant differences in segregation behaviour to be expected when handling materials that have differences in particle characteristics other than size. Section 6.5 documents the contribution of other particle characteristics such as density that can greatly influence the mechanisms of segregation and subsequently the positional behaviour of constituents of the charging mixture.

The momentum of the feed mixture and contact characteristics of the heap surface determined whether the feed material as it is deposited into the vessel remained near the heap apex or avalanched down the surface. Either action prompts a change in the angle of the heap surface thus influencing the potential flowability of the subsequent charged material. Figure 5(a), page 33 schematically verifies the variation in angle of heap surface during heap formation. As a result of this behaviour the heaping process can be categorised into three different phases of material flow that are observed to occur during heap formation:

1. Avalanching of a layer across the heap surface
2. Retardation of the avalanching layer
3. No significant layer movement

6.4.1 Phase One: Avalanching Across the Heap Surface

This phase of heap segregation comes into effect when the material directly beneath the feed/charge point has attained enough energy to initiate the movement of a group of particles down across the stationary heap surface. This phase is initiated when either one of two facets of heap geometry are satisfied

I. The angle of the static heap exceeds the natural angle of repose of the material

II. The momentum of the charging stream is sufficient to displace the material at the heap apex and convert the potential energy of material at the static surface beneath the feed point into an avalanching/flowing kinetic energy surface.

The velocity, momentum and duration of an avalanche are influenced by the following factors: -

- The feedrate of the charging mixture.
- The protuberances on the surface of the static heap.
- The frictional relationship between particles within the avalanching layer.
- The frictional relationship between the avalanching layer and the static surface.
- The geometrical constraints of the storage vessel.

Throughout the duration of an avalanche progressing to the vessel wall, the type and priority of mechanisms that contribute to heap segregation change according to the particle, process and geometrical variables present. Phase one of the heaping process is therefore further subdivided into three regions of segregation behaviour.

6.4.1.1 Region One

Region one refers to the part of the avalanching layer directly under and within the vicinity of the feed point. The geometrical length of region one is a function of the geometrical, process and material characteristics present for the given segregation application. When an avalanche commences, the subsequent charging stream contacts a dynamic surface whose direction of movement is away from the feed point. This results in reducing the trajectory mechanism of segregation that induces the rebounding of particles when the feed stream contacts the moving surface. The contribution that the trajectory mechanism makes to the overall pattern of segregation produced is determined by the charging stream momentum, vessel geometry constraints and particle characteristics of the mixture.

For a binary sized mixture, the diameter difference between large and small particles is linear in relationship. However, their differences in volume is cubic, thus their mass will dictate a significant momentum difference that the large particles have in relation to the small particles. This in turn dictates the influence and extent of the trajectory and embedding mechanisms during region one for size only segregation. For mixtures containing differences in both size and density, the influence of momentum is greatly increased which subsequently increases the influence of the sinking-migration mechanism.

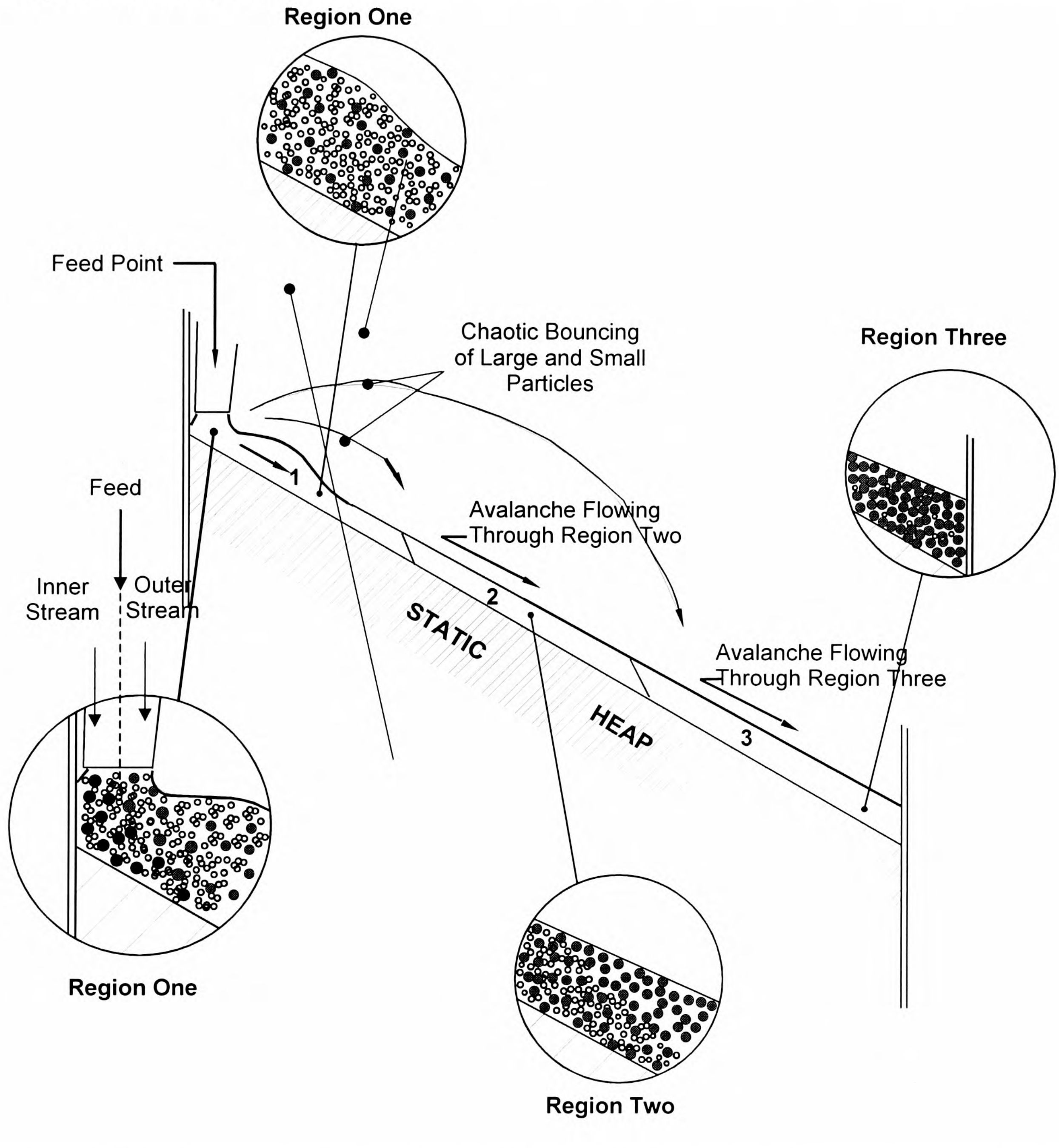


Figure 60 Phase One of Heap Segregation Process: Three Regions of Avalanching across the Heap Surface.

Describing the freedom of movement of individual particles within the feed stream upon contacting the avalanching layer is best illustrated by categorising the feed material into an inner and outer stream as shown on Figure 60.

- The outer part of the feed, i.e. the part of the feed furthest from the adjacent vessel wall essentially provides the bulk of the material that feeds and maintains the avalanching layer. This outer flowing stream amalgamates with the now moving bulbous region of material resulting from phase three of the heaping process, Section 6.4.3, to form the bulk of the avalanching material layer. The momentum of the outer flowing charging stream provides continued impetus to the avalanching layer as it descends the heap surface. There will be some degree of bouncing of particles of the outer feed stream on contact with the surface, and as such, these particles will distribute themselves over all three regions shown on Figure 60.
- The inner part of the feed material that is adjacent to the vessel wall does not have the same freedom of movement to flow and integrate into the avalanching layer. This inner feed stream is restrained from moving away from the feed point by the outer stream and hence part of it is compelled to remain embedded underneath the feed point. The embedding mechanism is conspicuous in its actions by producing the starting position for the 'hump' pattern of segregation as indicated by the patterns shown on Figure 55 and Figure 56. For all the size only segregation results conducted for this project, the amount of large particles measured directly under the feed point never exceeded the proportion in the feed mixture. However for mixtures differing in size and density, prevailing conditions can instigate proportions of large particles being measured directly under the feed point that are greater than those present in the feed.

For low feedrates the avalanching layer tends to be small hence the rolling mechanism of segregation can influence the pattern of segregation produced in region one. For higher feedrates where the avalanching layer tends to be several particles thick the more recognised sieving-percolation mechanism dominates. However, the feedrate of the mixture is not as influential in dictating mechanisms of segregation in comparison to size differences and proportions of small to large particles in the feed mixture. Visual observation of the segregation behaviour in region one indicates the existence of different states of particle arrangement that are dictated by the size ratio of small and large particles and the feed proportions of each size. When the concentration of small particles in the original feed mixture is low, the avalanching layer will be dominated by a large particle lattice where the sieving-percolation mechanism initiates the rapid segregation of small particles. This manifests itself as the rapid increase in population of small particles within the vicinity of the heap adjacent to the fill point. Consequently, a hump pattern of segregation was produced as shown in Figure 55 and Figure 56, where increases in the size differences between small and large particles dictated a more pronounced 'hump' shape.

When the proportion of small particles in the original feed mixture is high, the avalanching layer will be dominated by small particles that prevent a large particle matrix from forming. The sieving-percolation mechanism of segregation is thus not the primary mechanism of segregation and is superseded by mechanisms of rolling and migration. This is conspicuous by a reduction in the 'hump' pattern around the vicinity of the feed point. However, there still exists a slight 'hump' directly under the feed point. The starting position of this hump is attributable to the embedding mechanism. As the large particles do not create an interlocking matrix, they are influenced by the floating migration mechanism, which induces the large particles to move towards regions of highest shear that occur at the heap surface. This reasoning suggests that small particle segregation suffered due to sieving-percolation in region one is comparable to large particle segregation influenced by the floating migration and rolling mechanisms. The influence and interaction of each of these two mechanisms is difficult to quantify. However, they are perceived to play the dominating roles in heap segregation within region one when the proportion of small particles in the original feed mixture is high.

6.4.1.2 Region Two

Irrespective of the proportion of small particles in the initial feed mixture, a point is reached along the heap surface where there will be a sufficient number of large particles within the avalanching layer to form an interlocking matrix. Subsequently the sieving-percolation mechanism predominates to influence the resulting hump pattern of segregation. This constitutes an increase in depletion rate of small particles per unit length, conspicuous by the levelling off and downturn in the pattern of segregation as shown by Figure 55 and Figure 57. The characteristic segregation behaviour and environment that the material has experienced in region one dictates the presence and magnitude of segregation mechanisms in region two.

The flowing layers thickness in region two has thinned due to the removal of small particles in region one. The proportion of small and large particles of the avalanching layer entering region two changes the priority of the segregation mechanism to that of sieving-percolation. Its influence is a function of the velocity profile within the flowing layer and the speed and momentum of the whole avalanching layer as it descends across the heap surface. The frictional relationship between particles in the avalanching layer dictates the amount of rolling and hence the degree that the rolling mechanism influences the resulting pattern of segregation. In addition, the base of the avalanching layer is in contact with the stationary heap surface. The velocity profile therefore will be restricted to the ability of the particles of the bottom sub-layer of the avalanching layer being able to traverse the protuberances on the static layer. Furthermore, the velocity profile is further restricted to the ability of particles of the sub-layers within the avalanching layer being able to traverse across each other.

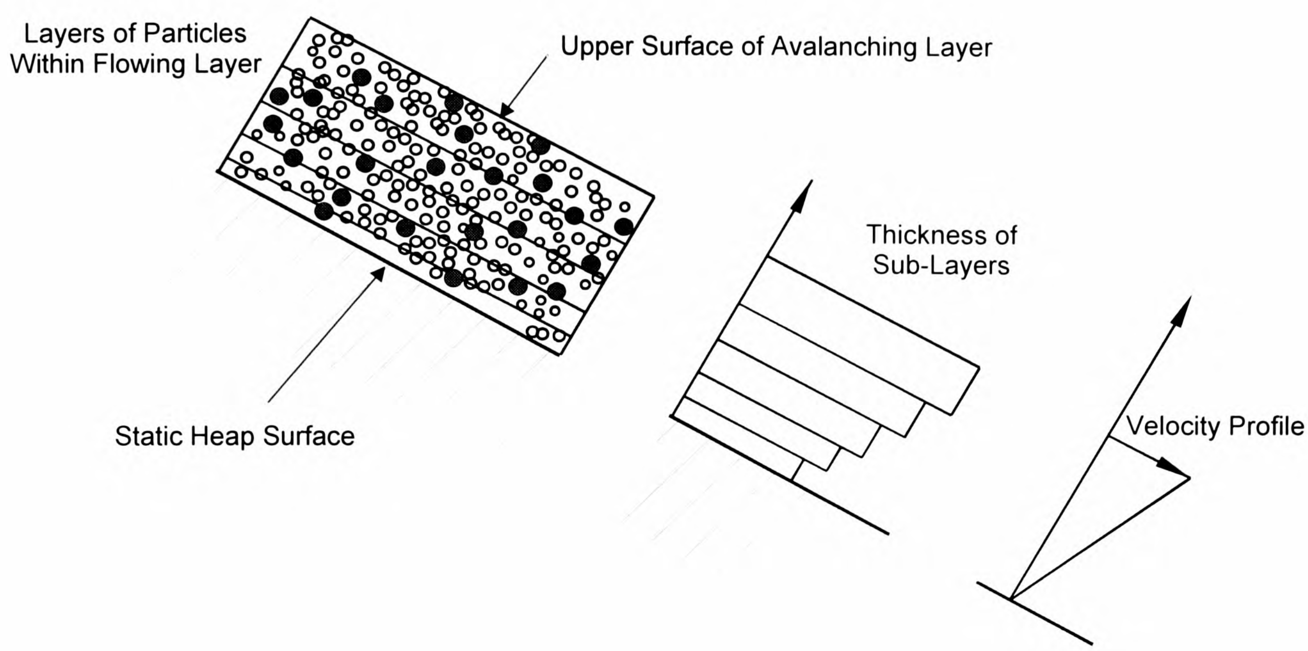


Figure 61 Flow of Sub-Layers within an Avalanching Layer and Associated Velocity Profile.

The frictional characteristics between particles within the avalanching layer and the static under-layer dictates whether any particles both small and large on the surface of the static layer are dragged along between the static and flowing layer. Video analysis of the majority of tests undertaken indicate that there is some visible disturbance and displacement of particles of the static layer as the flowing layer descends across its surface.

There are also some additional small particles positioned on the top surface of the avalanching layer as it progresses through region two as a function of the trajectory mechanism active in region one. The significance of this affect and subsequent pattern of segregation produced is dependent on the following factors:

- The geometrical distance region two is from the feed point.
- The momentum of the feed stream which provides the energy for the trajectory mechanism to act.

Subsequently the addition of small particles to the avalanching layer within region two resulting from the trajectory mechanism active in region one compensates to a degree for the loss of small particles segregating out of the avalanching layer.

As there is an increase in large particles in this region from preceding avalanches, the protuberances on the terrain of the static layer also increases. This in turn encourages the rolling mechanism of larger particles of greater momentum to take precedence in contributing to the segregation and hence final resting positions of the large particles. The greater the protuberances on the heap surface the more likely a small particle will be halted in its movement. This is particularly relevant towards the end of region two where the rolling mechanisms influence will come to the fore to that of the sieving-percolation mechanism. This is conspicuous by an increase in rate of depletion of small particles per unit heap length as shown on Figure 55 and Figure 57 The influence of the sieving-percolation mechanism is continually diminishing due to the lack of small particles left in the avalanching layer.

6.4.1.3 Region Three

The rolling mechanism prioritises itself in region three. A minimal amount of small particles are present within this region as a result of the trajectory mechanism active in region one together with any remaining small particles left within the avalanching layer exiting region two. The avalanching layers thickness and momentum has decreased still further due to: -

- The continued depletion of the segregated small particles and some large particles in the previous two regions.
- The presence of stationary large particles which formulate the terrain of the static heap upon which the flowing layer is descending.

The following factors all ultimately dictate the presence of any small particles on both the top surface and inside the avalanching layer as it enters region three.

- The degree of bouncing (trajectory mechanism) in region one.
- The length of the heap.
- The momentum of the flowing layer, thus determining the time permitted to separate the sieving of the remaining small particles.

What differentiates region three from region two is that this region incorporates the influence of the containing outer wall of the vessel. As the flowing layer progresses through region three it meets resistance to flow offered by the containing storage vessel wall and so initiates the transitional stage of heap segregation from phase one to phase two. The momentum remaining in the flowing layer will dictate whether some large particles have enough energy to roll directly over their preceding neighbours which have been previously brought to a stop by the vessel wall. This affect has been observed to occur and can influence the final angle of repose of the avalanching layer at the heap periphery when brought to a halt, Figure 62(a).

Upon completion of phase one, the geometric angle that the heap makes to the horizontal is a direct result of the mechanisms that have acted in the three regions. The angle of the heap is now at its most shallow for the three phases of heap segregation. The momentum of the flowing layer in region three for the majority of feedrates employed in the test program would have permitted the avalanching layer to progress further than the constraints imposed upon it by the vessel wall. Hence, the segregation pattern across the heap length for a particular mixture charged to a constrained plane-flow test vessel would be characteristically different to charging an unconstrained stockpile. This was a point well made by Yu et al. [28]. Upon reaching the vessel wall, the heap segregation process has taken full effect for phase one and subsequently progresses to phase two.

6.4.2 Phase Two: Retardation of the avalanching layer

When the avalanching layer reaches the outer wall of the test vessel it is brought to rest. This change is not instantaneous and a finite time exists before the entire avalanching layer is brought to a stop. This arresting of movement transmits itself back up the avalanching layer through regions one and two and depending on the feedrate of charging mixture can even halt layer movement directly underneath the charging point.

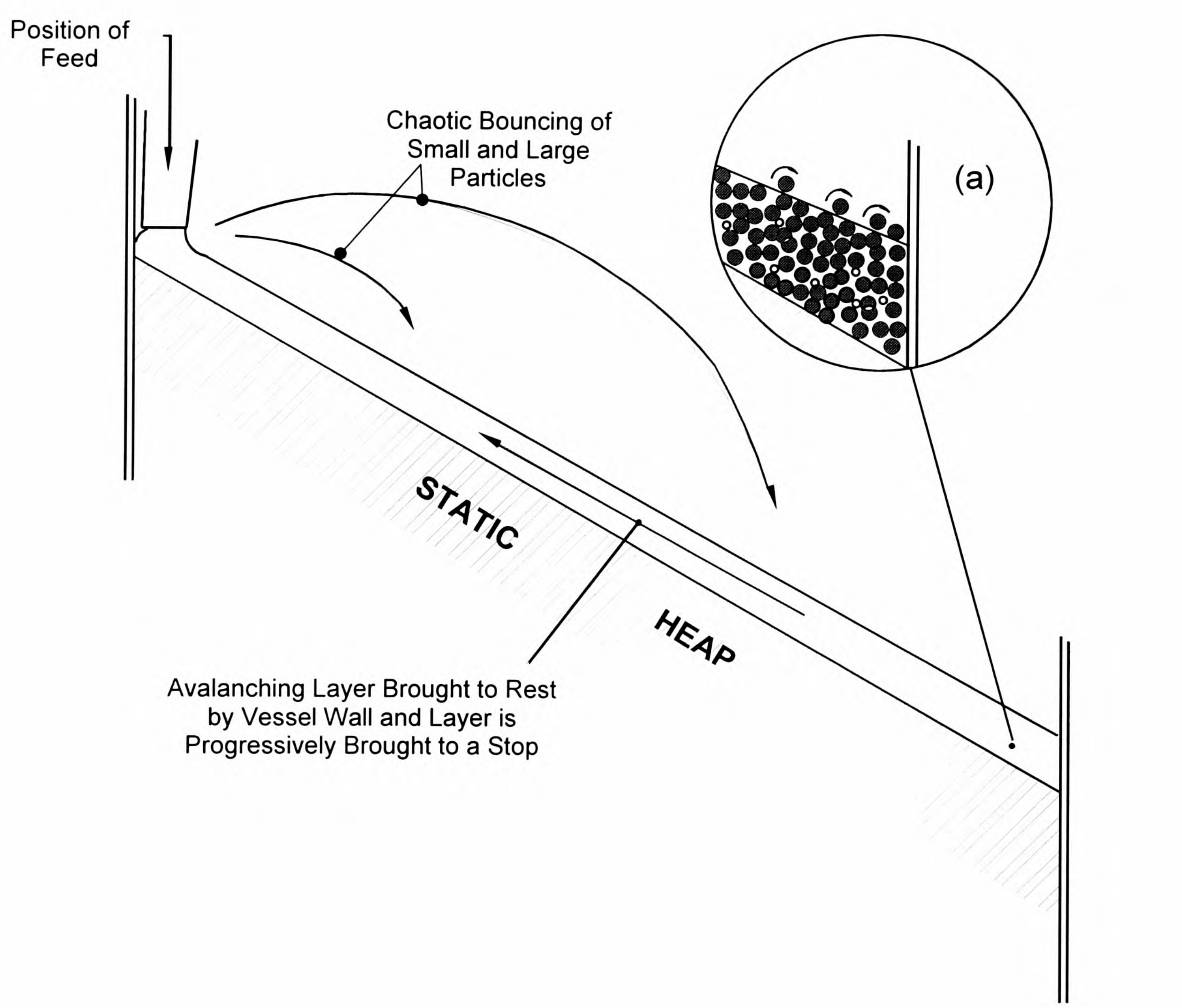


Figure 62 Phase Two of Heap Segregation Process: Arrestment of Moving Avalanching Layer upon Contact with Vessel Wall

As the avalanching layer is being stopped the resulting mechanisms of segregation in each of the three regions defined in phase one are also halted. It is possible for some spontaneous percolation to exist throughout phase two when size differences between constituents of the mixture dictate such a possible scenario. The avalanching layer when brought to a stop now becomes the new static layer and forms the base upon which the next avalanching layer descends. The characteristics of the segregating mixture and environment dictates the time period between successive avalanches. This period is defined as phase three of the heaping process.

6.4.3 Phase Three: No Significant Layer Movement

It is possible for the charging feed stream to sustain an immediate avalanche once the preceding one has finished if the feedrate is sufficiently high enough. This may be further enhanced if the angle of internal friction of particles in the charging mixture and on the static heap surface is relatively low. However, information on avalanching behaviour gleaned from a review of literature together with observations of tests undertaken indicate that successive instantaneous avalanching does not always occur. This is due to the surface geometry that the charging stream encounters after an avalanche has finished.

The proportion of large particles in a segregated mixture increases significantly towards the edge of the heap and occupies a larger packing volume than smaller particles. Consequently, a heap surface angle of repose is produced that is less than a heap formed with non-segregated feed constituents. In addition, as outlined in region one of phase one, an avalanche takes with it some of the static layer upon which it descends. This may be only several particles deep, and is dependent on the frictional relationship between particles. However, this removal of some of the static layer makes the angle of the heap surface under the feed point even shallower than the normally poured material angle of repose. Subsequently any feed material that is charged to the heap surface throughout the duration of phase three is less prone to avalanche across the static layer and more likely to congregate around the fill point. Some proportion of the feed embeds itself into the surface of the static layer due to the embedding mechanism and a minimal amount of the feed progresses down the heap surface under the influence of the rolling mechanism. The remainder is momentarily displaced to an area adjacent to the fill point, conspicuous as a bulbous shaped lump, Figure 63. The presence of this accumulated charged material during phase three together with previously segregated small particles contributes to an increased proportion of small particles at the heap apex. This increases the shear strength of the material under the fill point resulting from decreased voidage and subsequently increases surface contacts between particles. These all contribute to a stationary heap that increases in slope angle at the heap apex prior to the onset of another avalanche. A percentage of particles in the feed, both small and large, are exposed to the trajectory mechanism upon making impact with the inclined static surface and are deposited to positions away from the fill point.

After a finite time, a stage is reached where the space adjacent to the feed point that accommodates most of the feed material becomes exhausted. This state of criticality together with the momentum of the incoming feed material causes the bulbous shaped lump to attain sufficient energy to overcome the shallow angle of repose of the static heap and resistance to flow from particle friction. At this point, just before the onset of another avalanche, the angle the heap makes to the horizontal is no longer linear. The angle of the heap at its periphery will be similar to the heap found in phase two. However, the angle of the heap at its apex is now relatively steep due to the presence of the feed material deposited to the top of the heap during phase three.

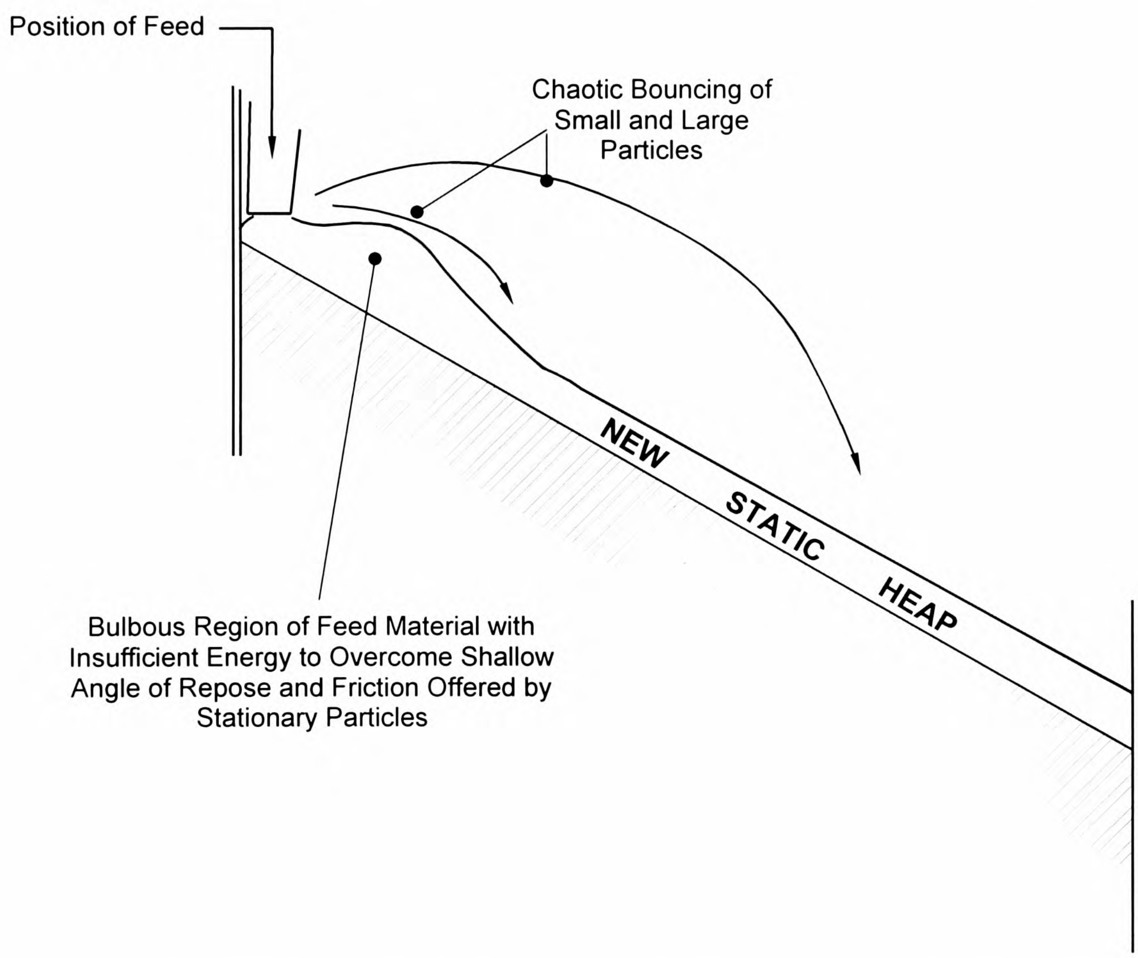
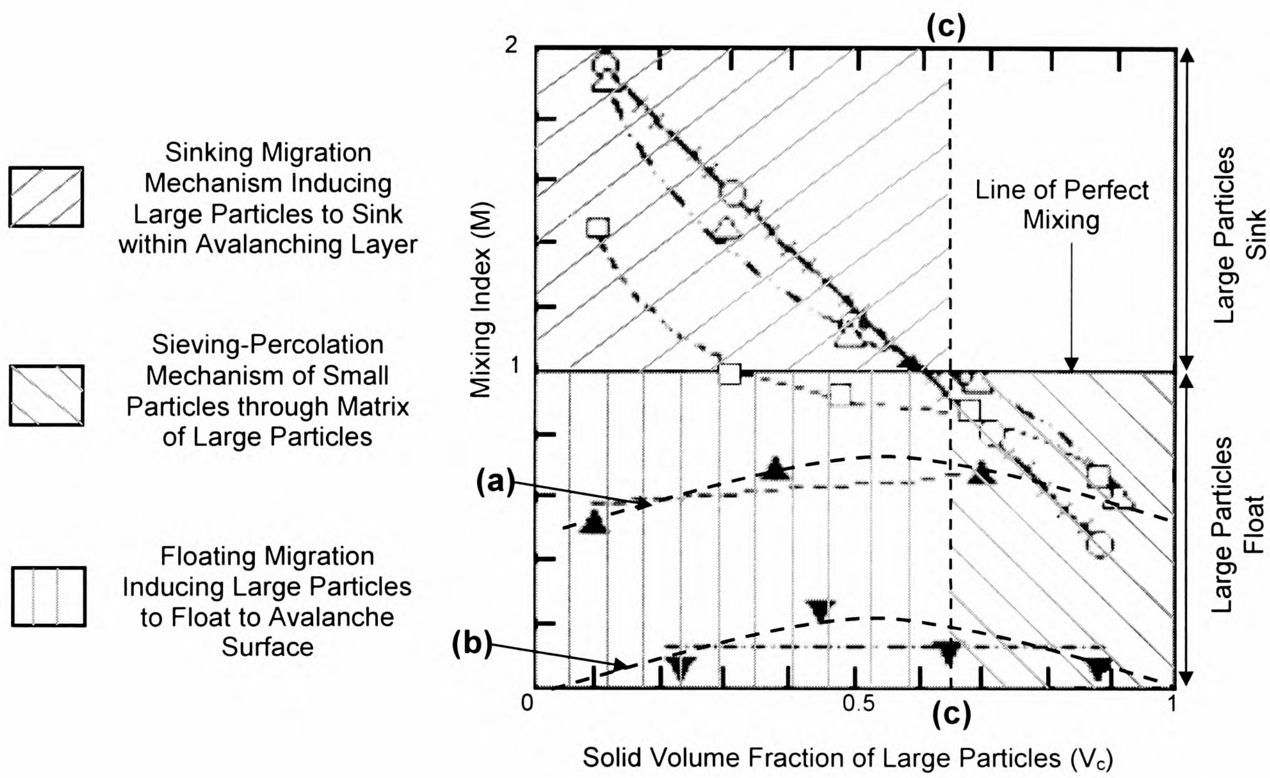


Figure 63 Phase Three of Heap Segregation Process: No Significant Layer Movement

When the energy in the charging stream has attained enough influence on moving the bulbous store of material directly under the feed point the heaping process reverts back to phase one.

6.5 Causes of Mechanism Change in Heap Segregation

The qualitative description of the heaping process described in Section 6.4 was confined to describing size only segregation with some emphasis placed on the influence of the proportions of small and large particles. However, evidence has been provided by Alonso et al. [59] that particle density can greatly influence heap segregation, as shown previously in Section 3.7.4.5. Alonso et al. [59] have shown that different combinations of density, size and concentration of small particles will dictate different patterns of segregation under the influence of heap segregation. These changes in mechanism can be identified by overlaying the change in mechanism information on the 'sinking', 'floating' ability of large particles, Figure 38 shown previously in Section 3.7.4.5.



Mixture Combinations and Material Properties

○ 10 &12 ▼ 4 &13 △ 3 &12 □ 4 &10 ▲ 9 &11

3. Glass Beads ρ = 2490 kg/m^3 d_{50} = 1.30 mm
4. Glass Beads ρ = 2490 kg/m^3 d_{50} = 1.60 mm
9. Plastic Beads ρ = 1050 kg/m^3 d_{50} = 1.25 mm
10. Plastic Beads ρ = 1050 kg/m^3 d_{50} = 1.00 mm
11. Chocolate Balls ρ = 1420 kg/m^3 d_{50} = 4.00 mm
12. Steel Balls ρ = 7780 kg/m^3 d_{50} = 2.95 mm
13. Z_rO_2 Spheres ρ = 6040 kg/m^3 d_{50} = 1.12 mm

Figure 64 Change of Segregation Mechanism as a Function of Particle Size, Density and Concentration.

The influence of differences between size and density of large and small particles in a binary mixture is irrelevant when the concentration of large particles that comprise the mixture is greater than approximately 0.65, line (c)- - - - -(c) on Figure 64. Above this region, segregation of the mixture will be solely dictated by the sieving-percolation mechanism. Under this segregating environment, the small particles percolate into the heap and the large particles are left at the surface of the avalanching layer. This occurs even if differences in density are greater than differences in size. Under such conditions the ability of the lighter small particles to percolate downward through the abundance of heavier large particles forming a matrix, is greater than the sinking ability of the heavier large particles influenced by the sinking migration mechanism.

When the concentration of large particles in the mixture falls below approximately 0.65, the mechanisms that influence heap segregation change. Below this point there are two regimes of segregation behaviour, dictated by the relationship of size and density of the large and small particles of the mixture:

- For a binary sized mixture where differences in density are greater than size (denoted as white symbols on Figure 64) and the proportion of large particles in the mixture is less than 0.65 the large particles act as sinkers. The large particles are influenced by the sinking-migration mechanism. Thus, all large particles sink down in the flowing mixture layer as there is an insufficient concentration of large particles to form a matrix in which to sustain the sieving-percolation mechanism of small particles.
- For a binary sized mixture where differences in density is greater than size (denoted as white symbols on Figure 64) and the proportion of large particles in the mixture is greater than 0.65 the large particles act as floaters. Although the large particles are heavier than the small particles and therefore in theory should sink under the influence of the sinking migration mechanism they actually behave as floaters. This is because the proportion of large particles is in sufficient quantity to form a matrix that facilitates the sieving-percolation mechanism to influence the percolation of small particles. The ability of the sieving-percolation mechanism to induce the sinking of small particles is greater than the sinking migration mechanism acting on the large particles. Thus, all large particles within the mixture remain at the surface and the small particles sink.

For mixtures of large and small particles where the difference in size is greater than density (denoted by black symbols on Figure 64), the large particles will be acted upon by the floating migration/stratification mechanism. Thus, all large particles within the mixture float to the surface of the flowing mixture layer. Irrespective of the proportion of small particles, the large particles would always behave as floaters. Alonso characterises this behaviour in terms of a linear relationship. However, one would envisage that when the proportion of large particles increased to a point where a matrix could be sustained, the propensity for the large particles to float would increase still further as the small particles would start to preferentially sink under the influence of the sieving-percolation mechanism. This would result in a non-linear relationship i.e. the superimposed convex trendlines (a) and (b) rather than linear ones proposed by Alonso. With this said, any proportion of large to small particles is still insignificant in influencing a large particle to sink when size differences are greater than density differences.

As can be seen the addition of the particle density variable influences a radical change in priority of segregation mechanism within the heap segregation process compared to size only segregation. This therefore warrants careful scrutiny of the precise segregation behaviour being simulated in an experimental test facility.

6.6 The Embedding Mechanism

Definitions of established mechanisms of heap segregation were documented previously in the literature review, Section 3.5.7 Although the mechanism of embedding was included in the review for completeness, it was conspicuous by its absence in the majority of segregation literature reviewed. It was evident from the work conducted and analysed in Chapter 6 that patterns of segregation were greatly influenced by the embedding mechanism. This mechanism was attributed to the orientation of the charging stream and its subsequent interaction when contacting the heap surface. The work conducted and documented in Chapter 7 shows that patterns of segregation associated with introducing the charging stream geometrically parallel to the heap produced patterns of segregation devoid of the influence of the embedding mechanism. Furthermore, Chapter 8 shows that vertical charging of the heap for identical test conditions produced a more pronounced 'hump' pattern of segregation around the fill point of the vessel. This pattern, attributed to the embedding mechanism, occurs due to the options the charging material is presented with upon contact with the heap surface. Upon contact, the vertically charged mixture can behave in several ways as described in Section 6.4.1.1 and shown schematically on Figure 60.

- The mixture can flow down across the heap surface in the form of an avalanche, the behaviour of which is outlined in Sections 3.4 and 6.7
- Particles of the mixture can embed into the heap surface under the feed point.
- Depending on particle characteristics of constituents of the mixture, particles within the charging stream could rebound and incur the mechanism of trajectory that dictates the final resting position of the particles. This behaviour was previously outlined in Section 3.5.6.

The influence of the embedding mechanism relies on the relationship between the momentum of the charging stream with particle characteristics of mixture constituents. If favourable conditions exist for a sustainable period then this mechanism can significantly influence the resulting hump pattern of segregation. For size only segregation, the large particles that are restrained from avalanching down the heap surface, embed themselves into the heap surface and remain under the feed point. This behaviour can be further enhanced when the large particles are denser than the small particles. Under prevailing conditions the dense particles on contact with the heap surface can force their way through the surface of the static heap and embed themselves several particles deep into the heap surface. Here they remain, unaffected by the ensuing feed mixture and are unaffected by any future avalanches. This behaviour presents itself by the appearance of some large particles directly under the feed point. However, this contradicts the form of mechanisms of segregation that are perceived to act in heap segregation, which should cause particles of this type to be found at the heap apex and not near the periphery of the heap formed.

6.7 Avalanching Behaviour

A review of published literature that explored avalanching behaviour was documented previously in Section 3.4. Heap segregation tests conducted were observed visually during vessel filling and analysed further by studying video footage taken of the vessel filling process. Standish et al. [26] and Yu et al. [28] reported that avalanching behaviour significantly contributed to the overall heaping process as the volume of a conical stockpile increased. However, these authors recognised that the relative geometrical position at which an avalanche started did not change as the heap length was increased when utilising a gravity-induced plane flow segregation tester of different lengths. In terms of feeding an unconstrained stockpile, avalanching greatly influenced the majority of segregation in the stockpile. As the stockpile increased so did the segregation induced by avalanches. Material that had progressed to the periphery of a large stockpile had generally been party to two or three avalanches and hence suffered greatly from the segregation mechanisms that prosper within an avalanche.

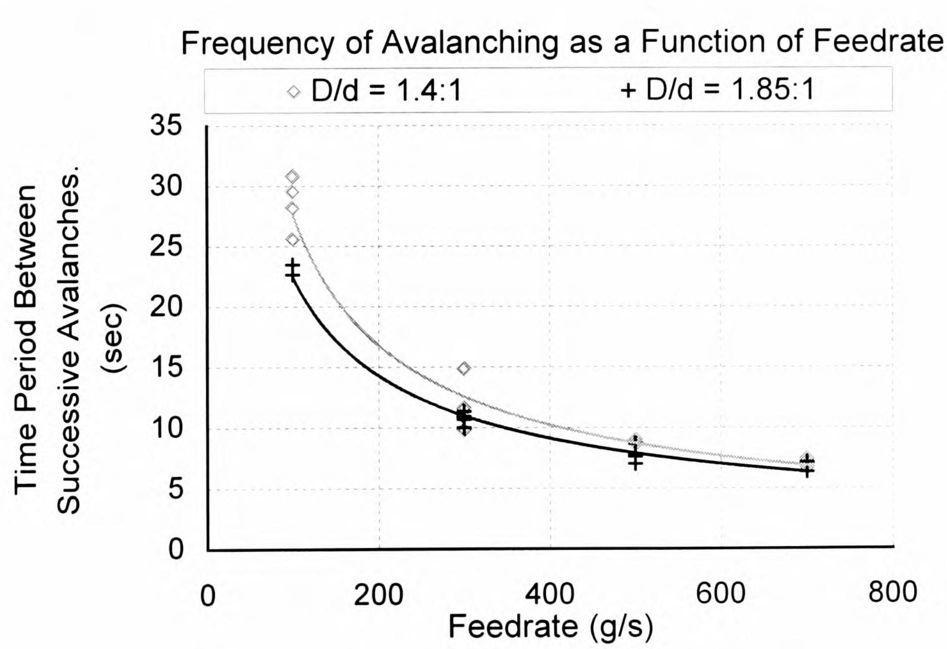


Figure 65 Relationship between Frequency of Avalanching and Feedrate

Figure 65 shows clearly that the frequency of avalanching was significantly influenced within the range of feedrates tested. It was observed from analysing video footage of heap segregation that upon avalanching the top seven to ten particle layers moved, each particle layer deep moving progressively less. From the fourth layer downward, the movement was generally restricted to one particle diameter or less. This observed avalanching behaviour was commensurate with the documented findings published by Drahun and Bridgwater [36]. Figure 65 indicates that the relationship of frequency of avalanching is both non-linear and sensitive to variations in particle size of the mixture. The total number of avalanches required to fill the same vessel volume decreased as a function of an increase in feedrate. This infers that an increase in feedrate induces an increase in particle thickness of the avalanching layer. Visual observation of avalanches of binary mixtures containing a small proportion of small particles indicated an increased time period of phase three (static surface, Section 6.4.3) of the heaping process compared to phases one and two, Sections 6.4.1 and 6.4.2 respectively. As the proportion of small particles in the feed mixture was increased, it became more difficult to differentiate between the three phases of heap segregation. This was due to an increase in chaotic bouncing of increasing numbers of small particles down the heap surface under the influence of the trajectory and rolling mechanisms. The frequency of avalanching also remained constant for a single feedrate condition, irrespective of the proportions of small particles in the mixture.

Figure 65 indicates that the frequency of avalanching increased as the diameter ratio of the binary mixture increased. Small differences in size between large and small particles resulted in increased shear strength of the material due to decreased voidage. This reduction in voidage increased surface contacts and enhanced possible frictional affects of particles. Consequently, this increased the stability of the heap structure and thus inhibited the frequency of avalanching of the mixture.

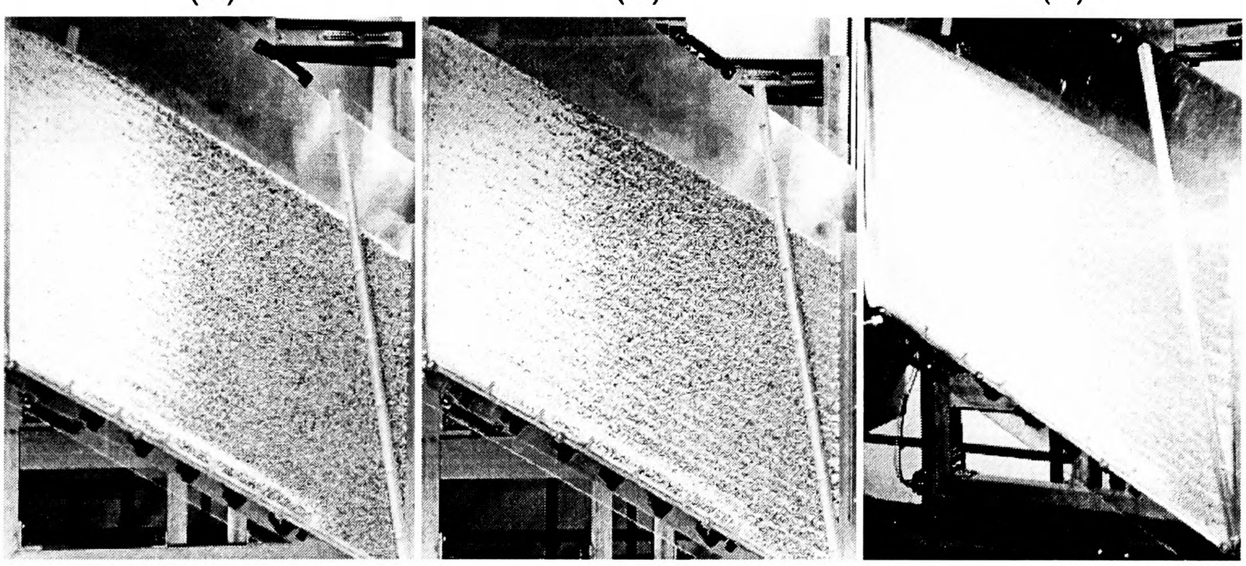
6.7.1 Stratification during Avalanching

Visual patterns of mixture stratification emanating from the heaping process have been documented by several researchers [6] [30] [73]. Often referred to as the 'Christmas Tree' affect, it is conspicuous when constituents of the mixture separate in a particular manner to reveal a clear separation of constituents across the height of the mixture bed in the vessel. This is often visually accentuated when constituents are of different colours, Figure 45 page 108, and Figure 66. The presence of stratification can be attributed to two areas of segregation behaviour.

6.7.1.1 Intermittent Avalanching

Throughout phases two and three of the heaping process there is no significant layer movement across the heap surface. If the feedrate of the charging mixture is sufficiently low then the duration of these two phases allows the trajectory mechanism to significantly influence the position of certain particles of the charging mixture feed. The trajectory mechanism causes chaotic bouncing of particles that distribute themselves at different positions away from the heap apex and onto the surface of the heap. This type of segregation also simultaneously occurs in conjunction with other mechanisms of segregation during phase one of the heaping process. To assist the illustration of this facet of segregation behaviour a binary mixture was composed where the small particles were of a different material type that had a particle resilience that was approximately double that of the large particles. Particle shape and density were of comparable magnitude. Consequently, charging the test vessel at a low feedrate allowed prevailing conditions to exist whereby the small particles positioned themselves furthest away from the point of charge as a result of the trajectory mechanism. The resulting pattern of segregation for this form of heap segregation behaviour can be seen in Figure 66 (c).

(a) (b) (c)



(a) =Test No **07/05/T12.** D/d = 2.9:1. Mr = 50/50. Fr = 700 g/s. Free-Fall Height = Constant.
(b) =Test No **07/05/T13.** D/d = 2.9:1. Mr = 50/50. Fr = 700 g/s. Free-Fall Height = 700mm.
(c) =Test No **08/05/T14.** D/d = 2.9:1. Mr = 50/50. Fr = 200 g/s. Free-Fall Height = Constant.

Figure 66 **(a) Segregation. No Stratification. Constant Free-Fall Height.**
(b) Segregation and Stratification. Fixed Free-Fall Height.
(c) Reduced Feedrate enhanced stratification affect

Normal heap segregation from phase one produced a clear demarcation between small lighter coloured particles under the feed point and the large dark coloured particles at the vessel walls. The time between successive avalanches i.e. the duration of phases two and three, caused the large particles to remain embedded under the feed point whereas the small particles scattered the entire heap length. This stratification is distinguishable as a series of fine light coloured lines that transcend the length of the vessel. These lines contain high concentrations of small particles and the time elapsed between successive avalanches dictated their ultimate thickness. Stratification of the segregated mixture is not visually present in Figure 66 (a) as the increased feedrate reduced the time period for phase three to significantly affect the resulting pattern of segregation. In addition, Figure 66 (a) and Figure 66 (b) show that for identical test mixtures and feedrates a free-fall height introduced into the test rig set up initiated some stratification as well as segregation of the mixture upon vessel filling. Figure 66 (a) and Figure 66 (c) used a constant free-fall height of approximately 50mm throughout the vessel filling cycle. The fixed free-fall height increased the momentum of the feed mixture and therefore increased the trajectory mechanisms influence on the resulting pattern of segregation.

6.7.1.2 Interaction of Particle Variables

As previously documented in Section 3.7.4.2, Makse et al. [30] proposed the interaction of particle size and shape as being responsible for the appearance of stratification when observing segregation patterns associated with heap segregation. The author suggested that irrespective of the angle of repose of mixture constituents, size segregation would occur. However, segregation will be magnified by the appearance of stratification of the mixture induced by differences in repose angles of mixture constituents. One of a number of factors that dictate the angle of repose of a size fraction is the shape of the particles. The author proposed that stratification was only expected to occur when the large particle size fraction had a greater angle of repose than the small particle fraction. Experimental evidence was provided to support this hypothesis, Figure 45 page 108.

The authors conclusions are plausible considering that the speed at which a mechanism will segregate a material will be influenced by the angle of repose of individual mixture constituents. This can be clarified by analysing the constituent properties of mixtures tested by Makse [30] as tabulated below:

Mixture No.	1	2	3	4
Material and size of large particle (mm)	Sand 0.3	Sand 0.3	Glass 0.55	Glass 0.77
Material and size of small particle (mm)	Glass 0.07	Glass 0.11	Sand 0.3	Sand 0.3
ρ of large particle (kg/m^3)	2700	2700	2950	2950
ρ of small particle (kg/m^3)	2950	2950	2700	2700
Stratification according to Makse [30]	Yes	Yes	No	No
Shape of large particle	Angular	Angular	Spherical	Spherical
Shape of small particle	Spherical	Spherical	Angular	Angular
Repose angle of large particle	35	35	26	26
Repose angle of small particle	26	26	35	35
Value of S. Alonso [59] Eq. 14, page 102	0.45	0.56	0.75	0.63

Visual indication of the existence of segregation and stratification for mixture one can be seen on Figure 67.

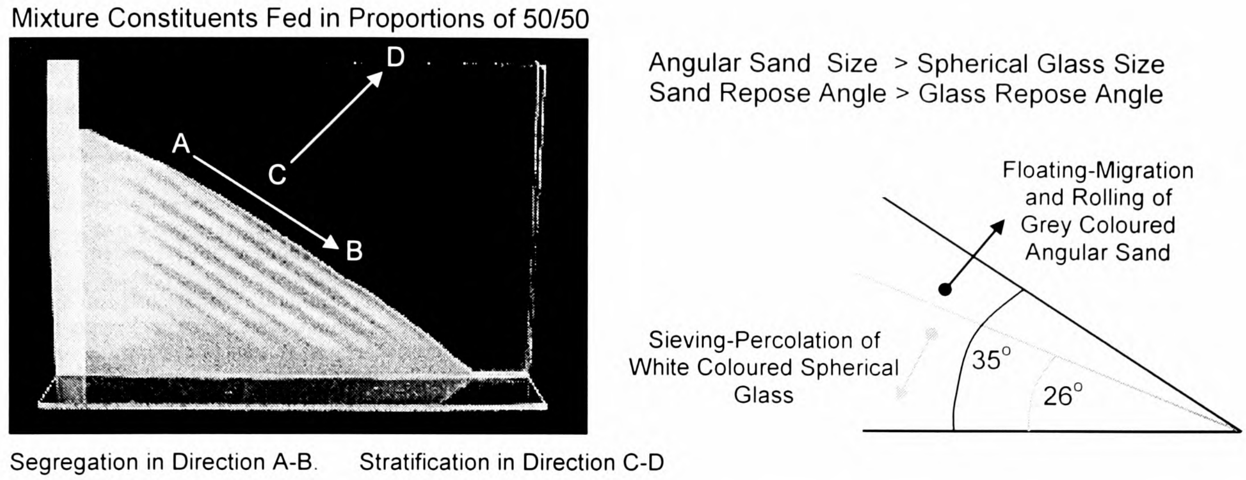


Figure 67 Representation of Variables that Describe Mixture No. 1's Segregation and Stratification Induced by Angle of Repose Differences. [30]

As can be seen from Figure 67 differences in angle of repose and size induce visible stratification that complements measured segregation of the mixture. Size differences initiate the migration and rolling mechanisms of segregation of the large particles and sieving-percolation of the small particles. This behaviour is further exacerbated by differences in angle of repose that provides further impetus for the separation of mixture constituents into two sub-layers of the avalanching layer. The angular and spherical sand separates into two strata layers in the direction C-D and these sub-layers proceed to segregate by size as they travel within the avalanche in the direction A-B.

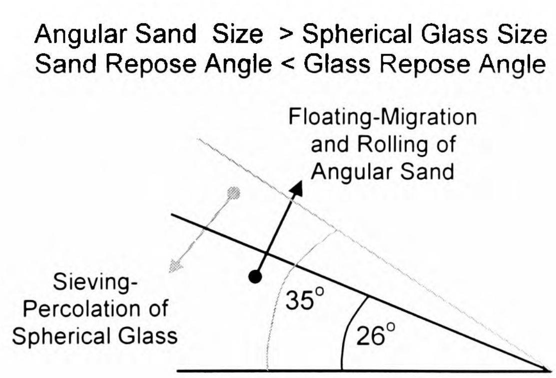


Figure 68 Representation of Variables that Describe Mixture No. 3's Segregation Induced by Size Differences of Mixture Constituents

The authors who documented this facet of segregation behaviour do not provide a photograph to visually illustrate this pattern of segregation. However, Figure 68 shows a schematic illustration that envisages how the larger particles of lower angle of repose are inhibited in their rate of progression to the surface of the heap. This is because they have to force their way through the small particles of bigger angle of repose. Simultaneously the smaller particles, trying to act as sinkers under the sieving-percolation mechanism are being impeded by the small particles large angle of repose that restricts the rate of the sieving-percolation mechanism. One impedes the other. Hence by the time the avalanching layer has progressed to the heap periphery, separation into two strata sub-layers within the avalanche has not occurred and there is no visible stratification of the segregated mixture.

By processing the mixture information into equation 14 presented by Alonso et al. [59] allowed an assessment to be made as to the propensity that a large particle will float or sink for the four binary mixtures utilised by Makse [30]. Although the theory of Alonso does not compensate for shape differences of mixture fractions, it does have the facility to incorporate the combined influences of differences in size and density. The resulting propensity of large particles to float or sink for mixtures used by Makse [30] is shown in the previous table. According to the prediction of Alonso prediction, if the equation yields a value less than 1, a large particle will act like a floater. Values produced for mixtures numbered one and two indicate that the large particles would indeed act like floaters. Although for all four mixtures there was some measurable degree of segregation, the appearance of stratification was dependent on the angle of repose of mixture constituents. Mixtures numbered three and four indicate that the large particles would also act like floaters, but to a lesser degree than those of mixtures numbered one and two. Hence there would be segregation of the mixture but a reduced tendency to stratify in comparison to mixtures numbered one and two. Alonso et al. [59] model predictions verified the statement by Makse that all mixtures tested segregated. In addition, the model predictions also suggest that mixtures one and two were more susceptible to floating and hence would encourage stratification of the mixture when the large particles angle of repose was greater than the small particles.

6.7.2 Influence of Vessel Walls on Avalanching Behaviour

A plan view visual observation of vessel filling indicated that the front (clear acrylic) and back (aluminium) walls of the plane-flow storage vessel influenced the directional energy of the avalanching layer. When charging an unconstrained stockpile the feed material dilates and disperses across the heap surface. However, within the constraints of the front and back wall of the plane-flow vessel the avalanche energy was directed solely in one direction down the heap. Consequently, the pattern of segregation when charging a plane flow vessel would be different to an unconstrained stockpile for identical test conditions. Detailed investigations into factors that cause different segregation patterns for an unconstrained heap and a plane-flow vessel is documented in Chapter 9.

Observation directly above the vessel during vessel filling revealed some lateral segregation of the material. This occurred irrespective of the fact that the feed material was delivered across the width of the vessel. Consequently, small particles preferentially travelled to the front and back walls of the vessel leaving a 'V' shaped core of large particles on the heap surface.

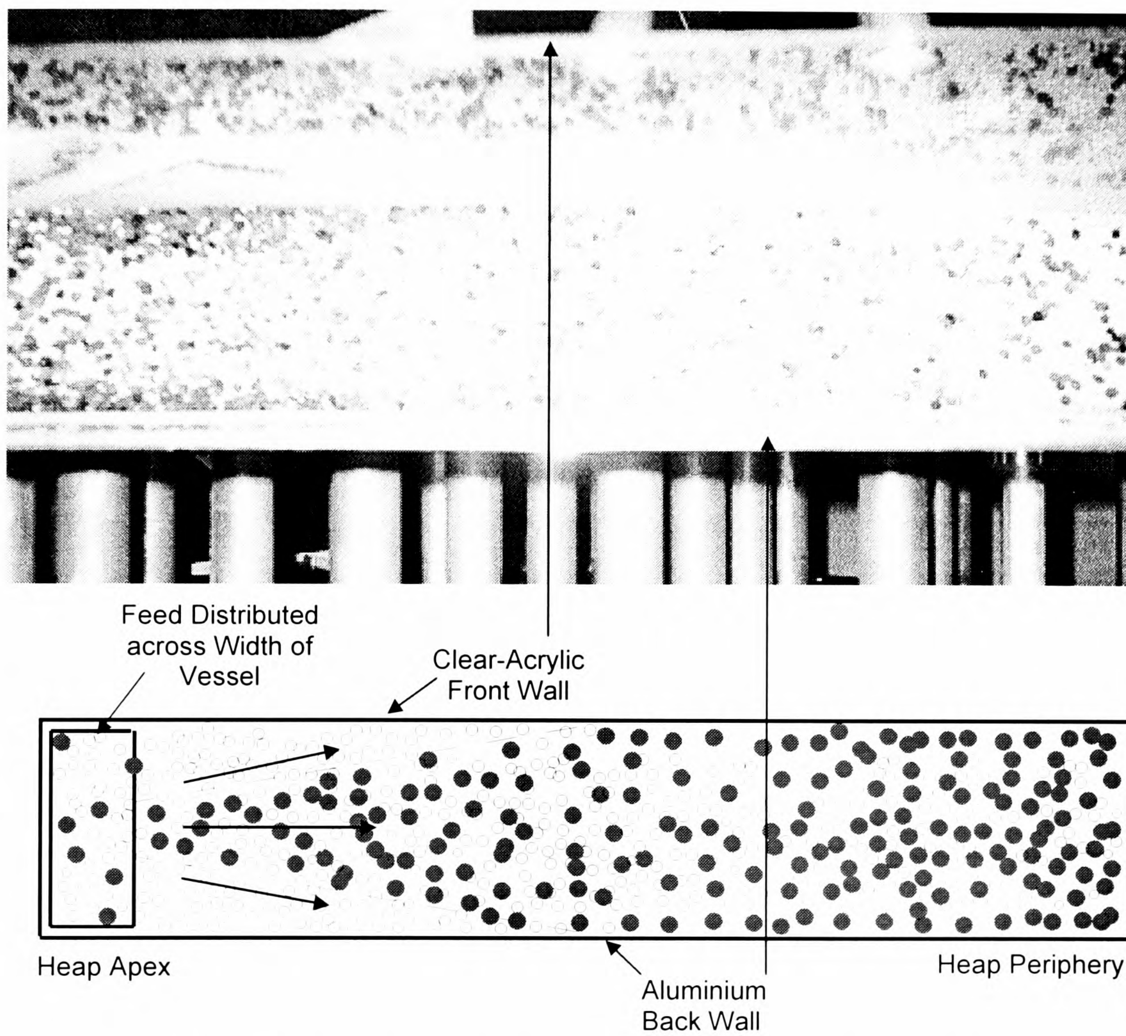


Figure 69 Photographic and Illustrative Plan View of Plane Flow test Vessel showing Charging Pattern of large and small Particles.

When analysing the visual pattern of segregation through the clear acrylic front wall, Figure 66, it was generally found that there existed a definite demarcation of the large and small particles into two regions. However, the measured proportion of small particles obtained from the sample probes did not always complement this clear line of separation, Figure 57. One factor that can be attributed to this ambiguity is the affect of the side-walls, which dictates preferential movement of some particulates of the bulk. Similar observations have been documented by Bridgwater et al. [39]. They observed that the percolating ability of particles was restricted when positioned at the side wall of a shear cell. The influence walls has on the avalanching velocity profile has also been documented by Drahun & Bridgwater [37]. These authors recognised from their testwork that their existed a significant velocity profile across the width of the avalanche induced by the side-walls of the vessel. Particles at the centre moved faster than at the front and back walls, thus inducing a transverse velocity gradient. Large particles under the influence of the floating migration mechanism are enticed into areas of highest velocity. Furthermore, as the large particles are less affected by the protuberances on the surface compared to small particles, the rolling mechanism induced into large particles has an influence on large particle movement. The momentum associated with large particles that reach the side vessel walls is sufficient for them to move back into the more dynamic regions of the avalanche. Small particles reaching the wall are less likely to return back into the flowing avalanching layer.

6.8 Structure of Subsequent Test Program

The findings reported in Chapter 6 result from undertaking a test programme for the purposes of commissioning the test facility. As a direct consequence of this testwork, an understanding of segregation behaviour was produced that suggested undertaking a three-stage test program. This program of work was used to focus on the following areas of segregation behaviour associated with heap segregation:

1. It was evident that the interaction of the charging feed stream with the heap surface produced patterns of segregation that did not conform to the generally associated pattern of small particle depletion rate per unit distance away from the feed point. The embedding mechanism of segregation was proposed as being responsible for dictating the severity of this pattern of segregation and was not accounted for and hence incorporated in existing theories or models. It was therefore a primary necessity to initially conduct investigations into segregation that was devoid of the influence of this mechanism. Consequently, segregation tests were conducted that introduced material geometrically parallel to the heap being formed. By undertaking this test work, existing modelling techniques could be applied to the segregation test data produced. This would verify the sensitivity and applicability of the models in predicting segregation for changes in particle and process characteristics. For all the tests conducted the free-fall height between point of charge and heap surface remained minimal and was held constant throughout the vessel filling process in order to minimise its influence.
2. Upon completion of stage one, stage two was implemented in order to investigate the generally encountered scenario where the feed is charged normally to the heap surface. This configuration of introducing the feed material into the rig was identical to that used when commissioning the test facility and formed the basis of the work previously documented in Chapter 6. This work was conducted with the intention of comparing the profiles of segregation established in stage 1 to those created in this stage, for identical test conditions.

3. Industrial cases of heap segregation are most commonly documented as occurring in a three dimensional geometry. The third stage of the test program involved exploratory investigation into correlating three-dimensional segregation results to those produced from a plane flow two-dimensional situation as a consequence of the work undertaken in stage two. In order to undertake the task a three-dimensional heap segregation environment was designed and constructed. The facility was scrutinised for its accuracy in producing repeatable, consistent heap segregation test results. An identical test program for stage two was then repeated for the formation of a conical three-dimensional heap. This then allowed the undertaking of the task of correlating patterns of segregation measured in a plane-flow storage vessel to that of a conical vessel or unconstrained three-dimensional heap.

CHAPTER 7

IN-LINE FEEDING OF PLANE-FLOW VESSEL

7 In-Line Feeding of Vessel

The first area of investigation as outlined in Section 6.8 focused on in-line feeding of the plane-flow test vessel. This was undertaken with the intention of eliminating the mechanisms of segregation that dictated the severity of a hump pattern of segregation conspicuous when graphically representing plane-flow test results in Figure 55 and Figure 56, page 134.

7.1 Test Variables and Configuration of Test Vessel

Figure 70 shows the method used to deliver the mixture in a manner that eliminated flow behaviour commensurate with normal direct charging of a heap. As established previously in Section 6.1, Figure 56 showed that employing a constant free-fall height during the entire vessel filling cycle eliminated differences in segregation across the vessel height. Consequently, charging sufficient material into the test vessel to cover the first two series of probes, 1-5 and 6-11, produced sufficient sample results to enable quantification of the segregation being produced.

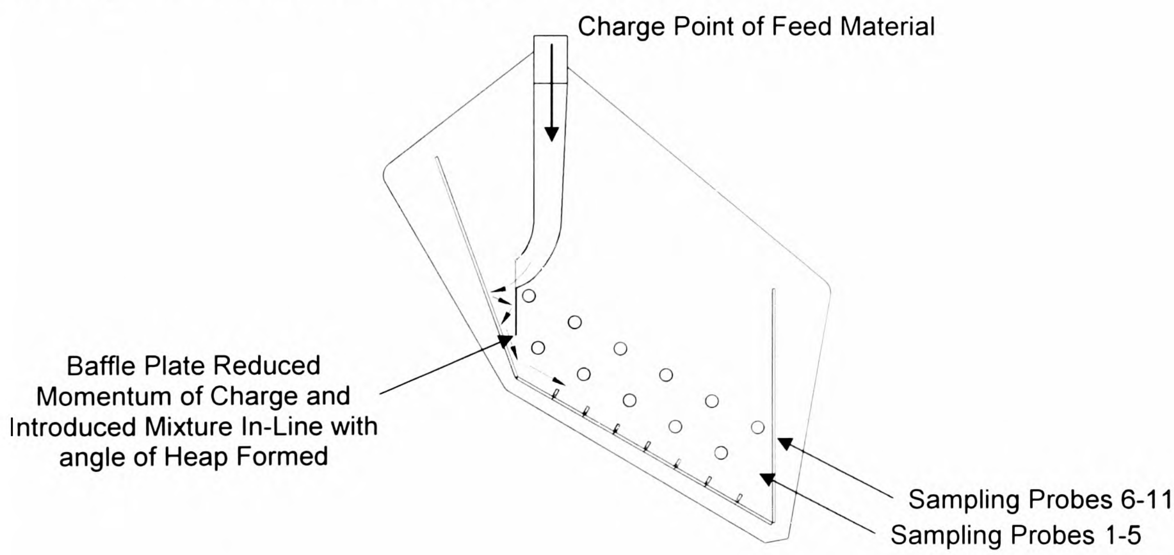


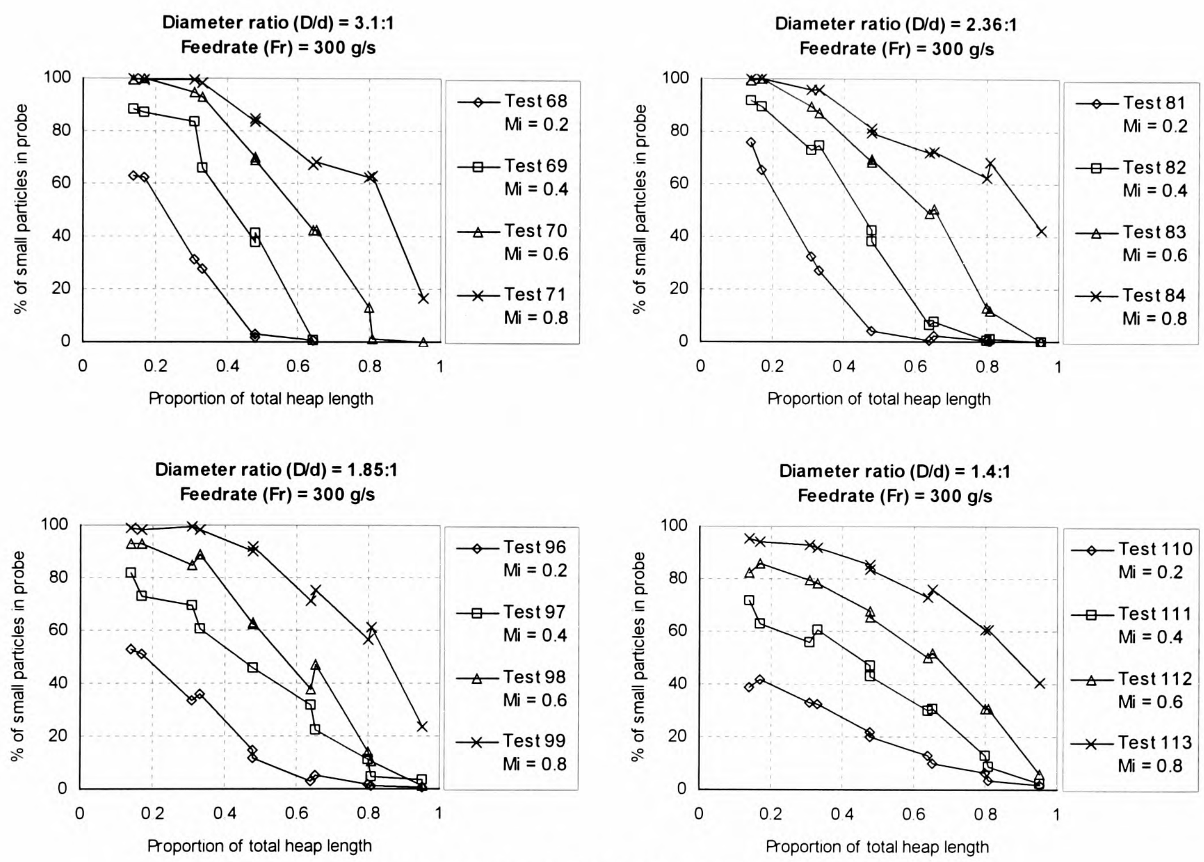
Figure 70 Diagrammatic Representation of Test Facility Configuration for In-Line Feeding of Charged Constituents.

The selection and range of variables tested using this geometry of vessel allowed a sufficient investigation into factors that induced segregation when in-line feeding the vessel. Furthermore, the results produced also satisfied the criteria that allowed a statistical appraisal of the significance and interactions of segregation variables, as previously documented in Section 6.3.

Test Variable	Low Level	>>>>>	>>>>>	High Level
Median Diameter Ratio (D/d)	1.4:1	1.85:1	2.36:1	3.1:1
Initial Proportion of Small Particles (Mi) mass	0.2	0.4	0.6	0.8
Feedrate (Fr) g/s	100	300	500	700

7.2 Test Results

Segregation results produced for this part of the investigation revealed the propensity of a mixture to segregate based solely on mechanisms within the avalanching layer as it descends the heap surface. The pattern of segregation produced is devoid of the influence of the interaction of the charging feed when contacting the static heap surface formed, characteristic of producing the hump pattern within the vicinity of the feed point. A comprehensive list of results produced for this stage of the investigation can be found in Appendix A.5.



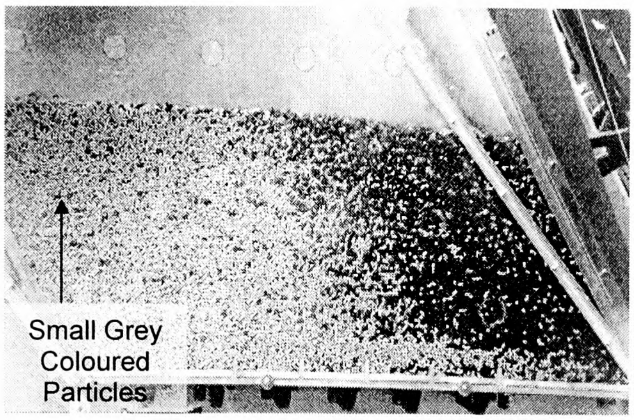
Mi = Proportion of Small Particles in Feed

Figure 71 Variation in Pattern of Segregation as a Function of Decreasing Diameter Ratio of Binary Mixture.

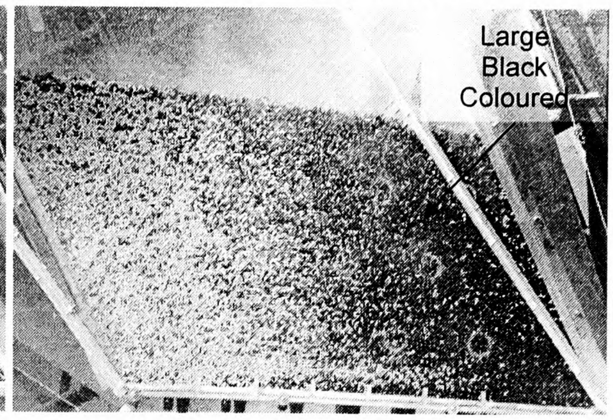
Figure 71 shows that across the range of diameter ratios tested the appearance of the hump pattern around the vicinity of the feed point has been successfully eliminated from the patterns of segregation produced. A series of tests were undertaken using different coloured lytag aggregate in order to enhance visual patterns of segregation to complement measured segregation. An example of the visual patterns observed when charging the test facility with three different feed proportions of small particles of lytag aggregate is shown on Figure 72.

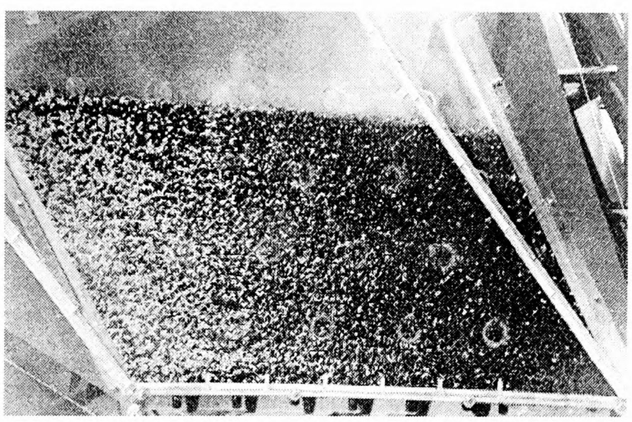
Constant Free-Fall Height. Feedrate = 500 g/s

Test 22. D/d =1.7:1 Mi = 0.8



Test 21. D/d =1.7:1 Mi = 0.5





Test 23. D/d =1.7:1 Mi = 0.2

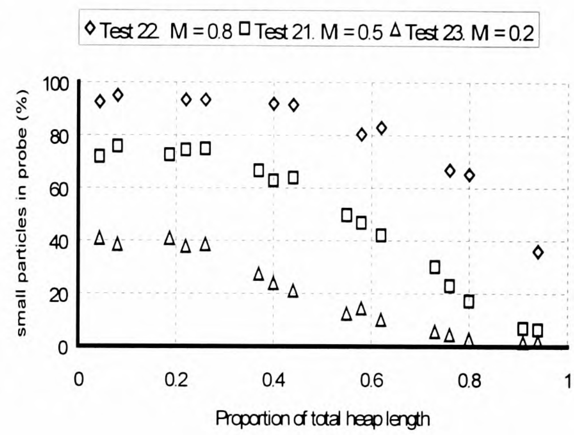


Figure 72 Visual and Graphical Indication of Size Segregation for Decreasing Proportions of Small Particles in Binary Mixture Feed.

The observed patterns of segregation resulting from differences in initial feed proportions of small particles complements measured profiles of segregation. For all three tests shown on Figure 72 there is a definite demarcation between regions of large and small particles. Even for a feed proportion of 20% small particles there is still a visual spattering of small particles that reach the vessel periphery as a result of the trajectory mechanism. However, these amounts are not significantly measurable and hence do not influence the profile of segregation towards the heap periphery.

As established previously in Section 6.3 statistical evidence indicated that feedrate and its interaction with diameter ratio and/or proportion of small particles was insignificant in influencing the resulting pattern of segregation, Figure 59. Figure 73 is an example of the range of results produced for an arbitrary 60% proportion of small particles in a binary sized mixture. Feedrate is relatively insignificant in influencing the pattern of segregation produced. The exception to this is at low feedrates, Figure 73(a) where feedrate does have some influence on the resulting profiles of segregation produced.

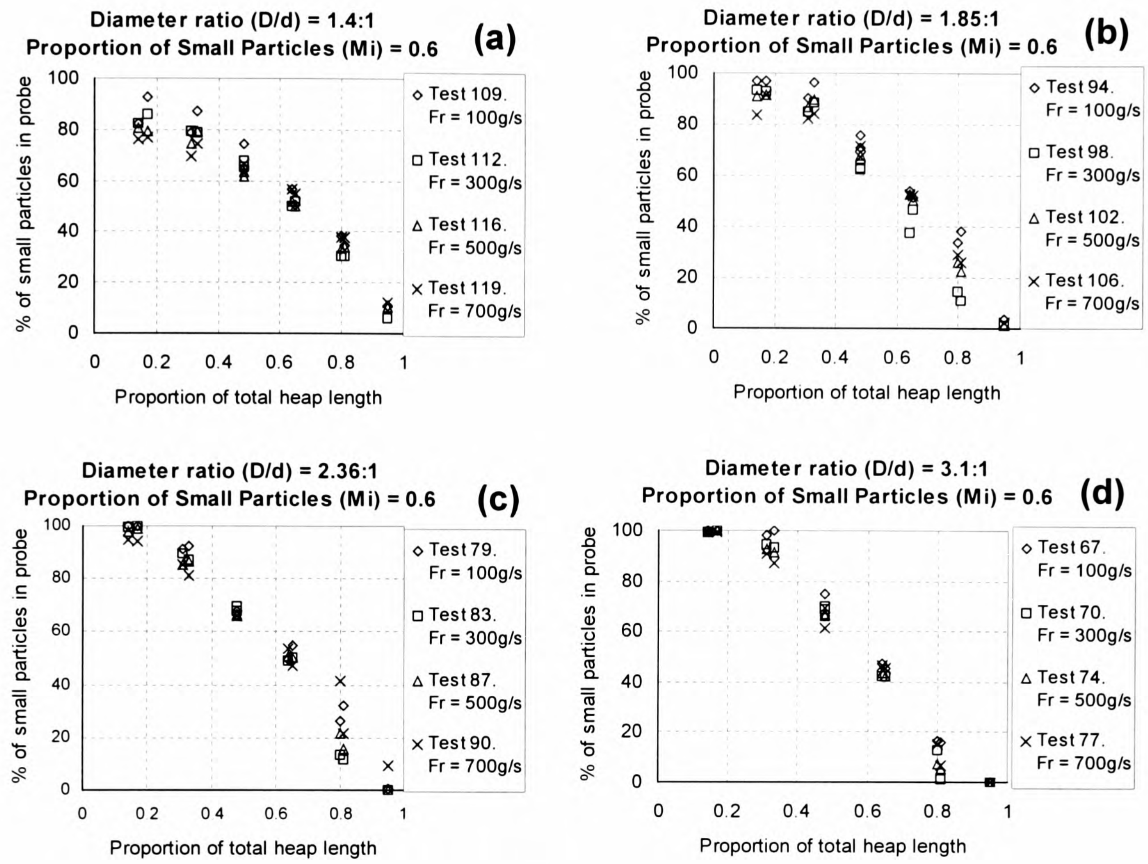
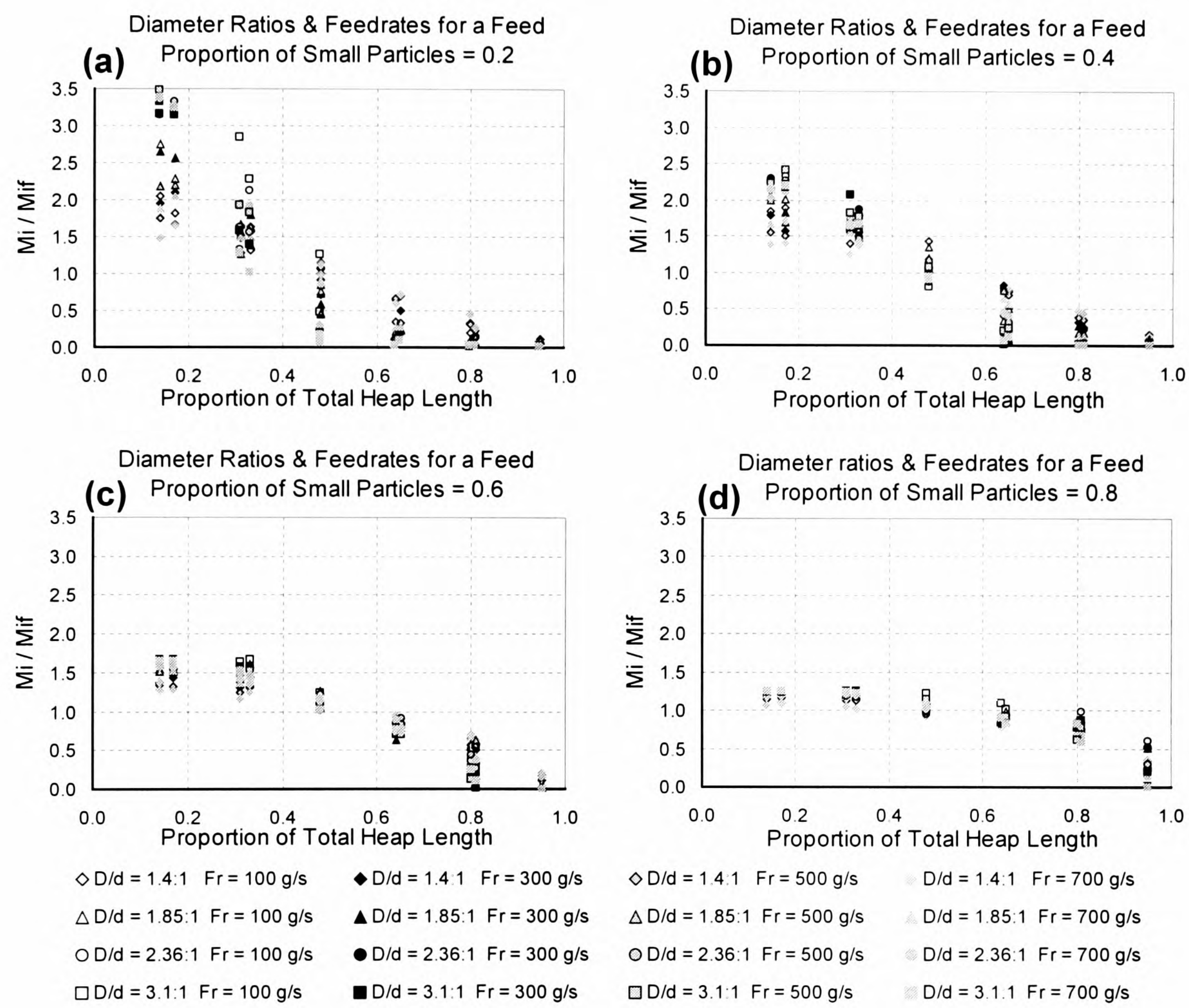


Figure 73 Influence of Feedrate for a 60% Proportion of Small Particles across the Range of Size Differences Tested.

It is clear that at a feedrate of 100 g/s a diameter ratio of 1.4:1 is sufficiently low to allow time for a greater number of small particles to separate from the avalanche and congregate near the feed point. Increasing the feedrate reduces the time available for mechanisms of segregation to separate the small particles to the same magnitude. When the size difference is increased to 1.8:1, the influence of feedrate is measurably reduced in dictating the patterns of segregation produced. Increasing the size difference still further to the maximum value tested causes the feedrate to have an insignificant affect on influencing the patterns of segregation produced.

As the feedrate for a binary sized mixture containing a certain proportion of small particles is increased, the population of large and small particles being charged to the heap surface at any given moment in time must also increase. This infers that there will be an increase in the number of particle to particle interactions and frequency of avalanching. An increase in either of these two factors will influence the type, number and time available for mechanisms of the heaping process to influence the segregation produced. However, the results shown on Figure 73 imply that an increase in frequency of avalanching and population of small and large particles per unit of time as a function of increased feedrate does not significantly alter the segregation produced. A thin infrequent avalanching layer associated with heap segregation at low feedrates produced a similar pattern of segregation compared to a more frequent thicker avalanching layer associated with a seven fold increase in feedrate.

The patterns of segregation for all test work in this chapter are presented in terms of a dimensionless concentration coefficient, as shown on Figure 74.



Mi = Proportion of Small Particles in Probe Sample.
Mif = Proportion of Small Particles in Original Feed Mixture.

Figure 74 Plots of Dimensionless Small Particle Concentrations at Positions down Heap Length for all In-line feeding tests of Binary Sized Mixtures.

Figure 74 highlighted the influence that the proportion of small particles in a mixture had on influencing the pattern of segregation produced. According to theory presented by Alonso et al. [59], irrespective of the proportions of large to small particles in a binary sized mixture the large particles will always float to the surface. This occurs although there is a recognisable change in mechanism within heap segregation as the proportion of small particles is increased from 0 to 100%, (solid triangle symbols) Figure 64. For all mixture types that contained 80% small particles in the initial feed, the dominant mechanism active in segregating the small components is the floating-migration mechanism of large particles within the heaping process. When this mechanism is active, the range of diameter ratios and feedrates is insignificant in influencing the profiles of segregation produced. Only when there is sufficient numbers of large particles in the mixture (Proportion of total heap length > 0.6, Figure 74(d)) does the segregation mechanism change from floating-migration of large particles to the sieving-percolation of small particles. When this occurs the patterns of segregation become more diverse and thus highlight the sieving-percolation mechanisms sensitivity to the range of diameter ratios and feedrates tested. Further verification of this behaviour can be gleaned when analysing the patterns of segregation when the initial feed content of small particles is reduced down to 20% (Figure 74(a)). This shows quite categorically that the sieving-percolation mechanism, which dominates in mixture formulations of this type is sensitive to the range of particle and process characteristics examined. The greater the reduction in the proportion of small particles the greater the disparity between patterns of segregation for differences in feedrate and size differences. This behaviour was highlighted by Bagster [54] [55] [56] and was used as a criterion for rejecting the use of the dimensionless coefficient as a means of presenting entire ranges of segregation data. It is clear that the change of segregation mechanism from floating-migration to sieving-percolation by reducing the proportion of small particles in the original mixture alters the sensitivity of the heaping process to externally applied process conditions. For low proportion small particulate mixtures, the heaping process becomes predisposed to the affects of particle and process characteristics. This culminates in producing varied patterns of segregation as shown in Figure 74.

7.3 Modelling Segregation Behaviour

The patterns of segregation produced in this type of segregating environment can be approximated as being linear in nature, see Figure 71 and Figure 73. As previously stated in Section 6.3, modelling was undertaken using a linear-line fit of the test data. It was established previously that the feedrate was relatively insignificant in influencing the resulting pattern of segregation compared to size differences and proportions of small particles in a mixture. Consequently, a relationship between the slope and intercept values of a straight-line law equation was investigated based solely on the range of size differences and proportions of small particles tested. This resulted in the derivation of an empirical equation that could predict patterns of segregation for the test vessel configuration shown in Figure 70. A detailed description of the predictive equation developed can be found in Appendix A.6.

$$Y = 305 \cdot I \cdot Ln\left(\frac{D}{d}\right) \cdot Mi - 261.5 \cdot I \cdot Ln\left(\frac{D}{d}\right) - 64.3 \cdot I \cdot Ln(Mi) - 86.2 \cdot I - 82.7 Ln\left(\frac{D}{d}\right) Ln(Mi) + 88.2 Ln\left(\frac{D}{d}\right) + 62 \cdot Ln(Mi) + 120.6$$

Equation 17

where

Mi Proportion of Small particles in Mixture (0 – 1)
D Diameter of large particles
d Diameter of small particles
I Proportional distance down heap length (0 -1)
Y Percentage of small particles at position I down heap surface (0-100)

Eight equation constants were generated as a by-product of developing these models. These values are unique to the characteristics of the material being tested and the segregating environment. Initial perceptions of the number of constants produced would suggest that there are too many in comparison to other predictive techniques proposed by O'Dea and Waters [6] [25] and Popplewell et al. [58] etc. These authors propose models that contain only one or two equation constants. However, these constant values change as a function of changing particle sizes, and proportions of small particles in the mixture, as shown on Figure 76 and Figure 77. The linear model proposed by Equation 17 does not require any change in model constant value in order for the model to fit the segregation profile under investigation.

O'Dea and Waters' [6] [25] model, derived on the assumption of two mechanisms of segregation, Section 3.9.3.5, was compared to the results produced from this configuration of test rig. This was possible as the authors method of introducing their charging sinter feed in-line to the heap being created was similar in configuration to that created using the test rig for this stage of the testwork. In addition to this, the modelling potential of Popplewell et al. [58], Section 3.9.3.3, was assessed in its applicability to segregation created within this test environment.

Figure 75 provides comparison of the straight line model, Equation 17, together with those derived by O'Dea and Waters [6] [25] and Popplewell et al.. These are compared to the experimental test conditions for four feed proportions of small particles of 20, 40, 60 and 80%.

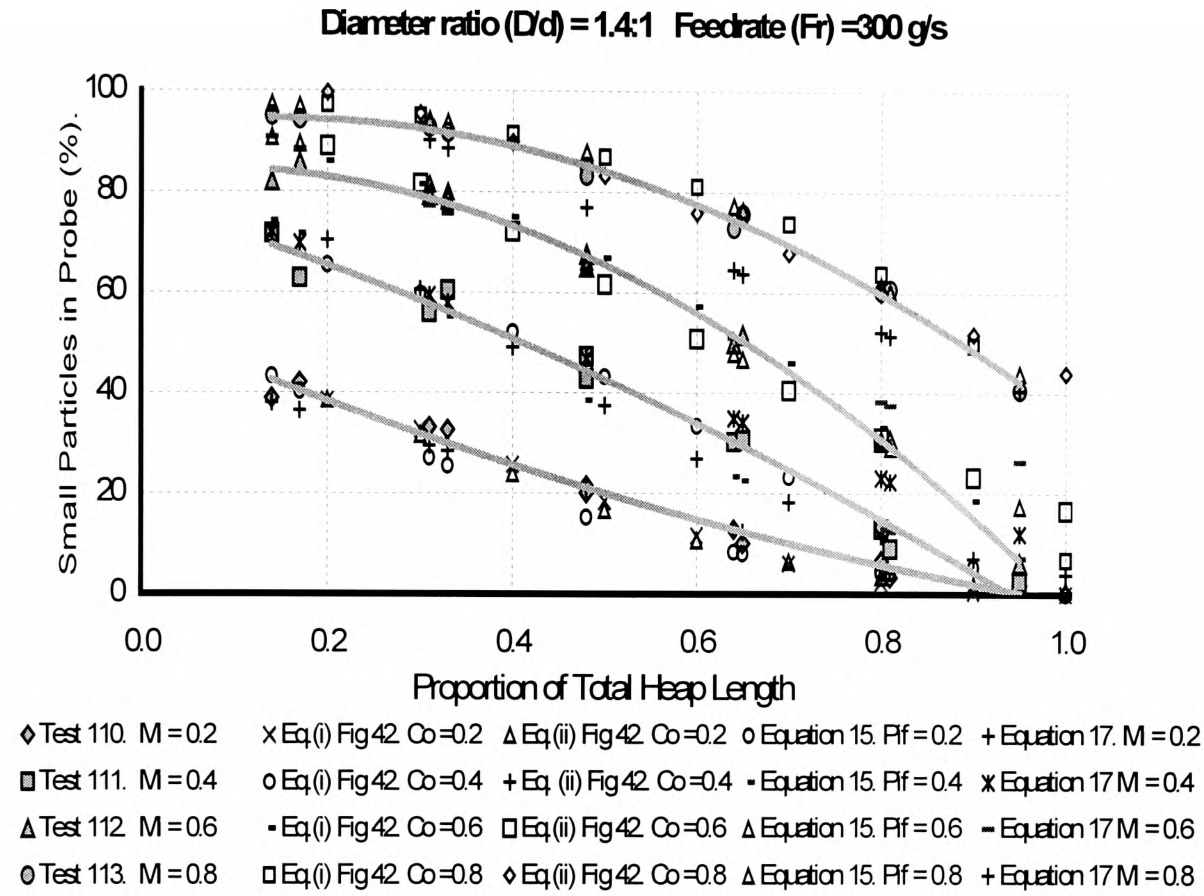
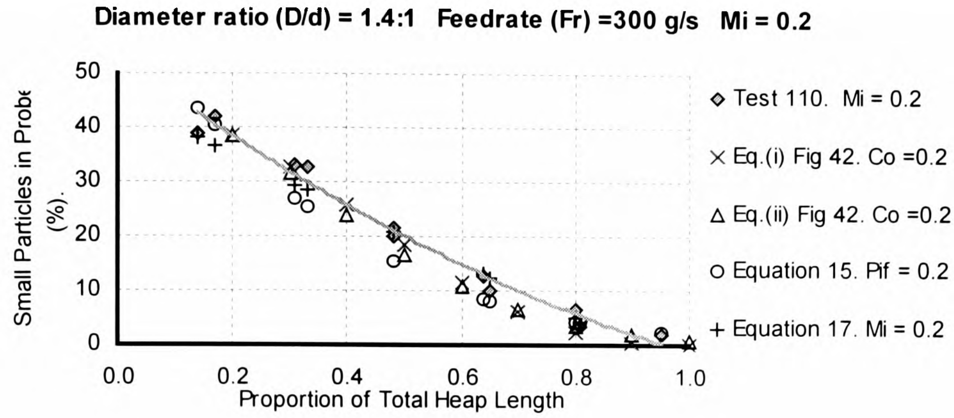
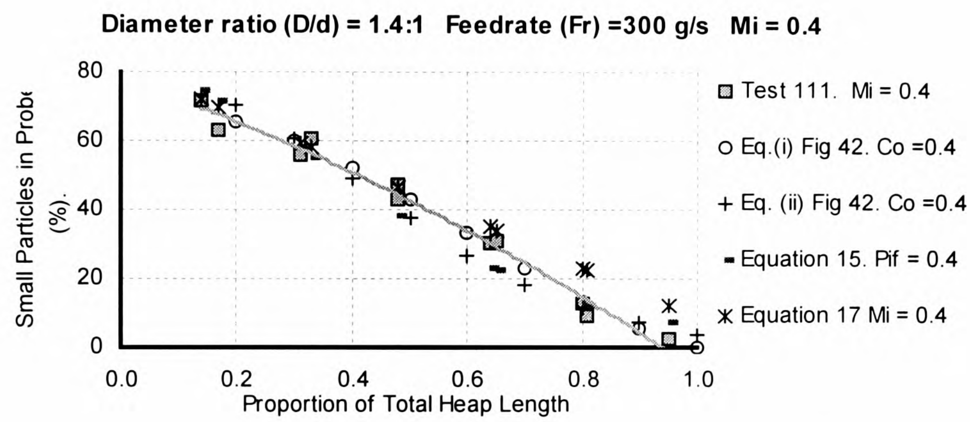


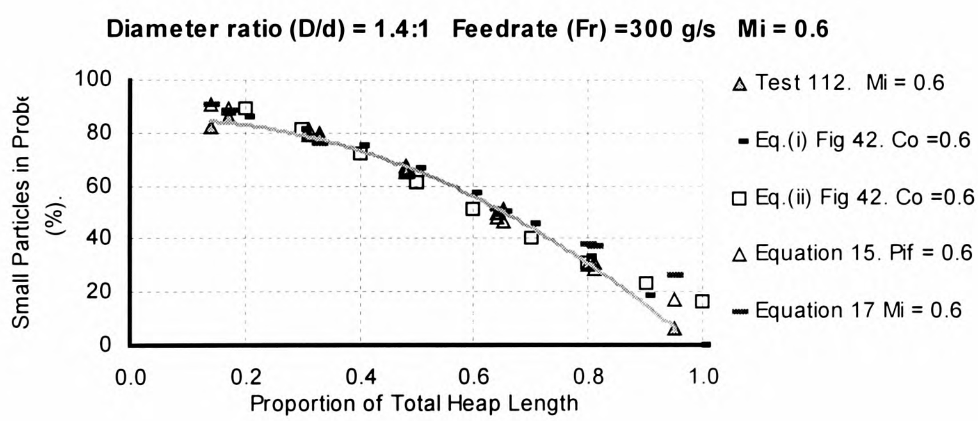
Figure 75 Predictive Model Comparisons with Experimental Results for a 1.4:1 Diameter Ratio Binary Mixture at a Feedrate of 300 g/s.

Experimental data points, denoted by the 'shaded' symbols on Figure 75 for four feed proportions of small particles of 20, 40, 60 and 80 % are represented by four lines. These lines have been constructed using the computer software package Excel [74]. The lines have been constructed by means of the polynomial [74] fitting technique that interpolates a least squares regression approach between the experimental data points. Figure 75 shows the potential of appropriate models in predicting the form of segregation produced in this vessel geometry for increasing proportions of small particles in the original mixture. A clearer picture of the ability of the models to predict this segregating environment can be obtained by analysing each mixture proportion of small particles separately. Consequently, the following four graphs show the ability of the models in predicting segregation patterns for the four test conditions of small particles in the feed.

Separate graphs showing the ability of current models in predicting segregation patterns







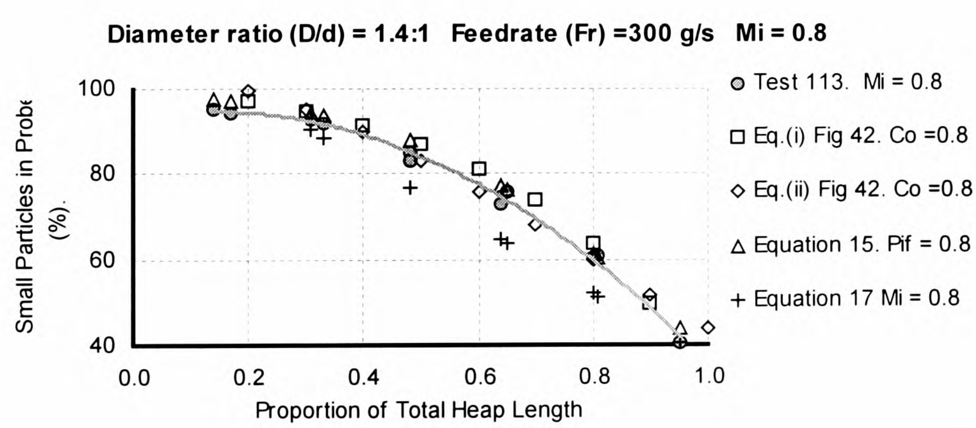


Figure 75(a) Four Graphs Providing a Clearer Indication of the Predictive Ability of Current Segregation Models

The ability of the models to predict profiles of segregation for three other diameter ratios tested can be assessed in Appendix A.7. For an arbitrary feedrate of 300 g/s, modelling predictions compare closely to the test data produced using all four binary sized diameter ratio mixtures used. Figure 75, Figure A.7.1., Figure A.7.2., and Figure A.7.3. documented in Appendix A.7 show the patterns of segregation and potential model accuracy for mixtures that segregated in the test facility configuration shown on Figure 70. Irrespective of the size differences of particles of the mixture, the line denoting the experimental pattern of segregation was slightly concave in nature for small proportions of small particles. As the proportion of small particles increased the pattern reverts to become linear in nature before ultimately changing to a convex curve when using high proportions of small particles in the feed mixture. The modelling techniques developed by O'Dea and Waters [25] and Popplewell et al. [58] can accommodate for a change in curvature of segregation profiles. The linear model, however, represented by Equation 17, Page 168 cannot compensate for this change in curve and is restricted to predicting linear segregation profiles. Consequently, the linear model is relatively inaccurate at predicting segregation patterns for mixtures that contain high or low proportions of small particles in the feed mixture in comparison to the other models shown.

The relationship of model constant values as a function of changes in sizes of small and large particles and feed proportions of small particles in a mixture can be seen on Figure 76 and Figure 77.

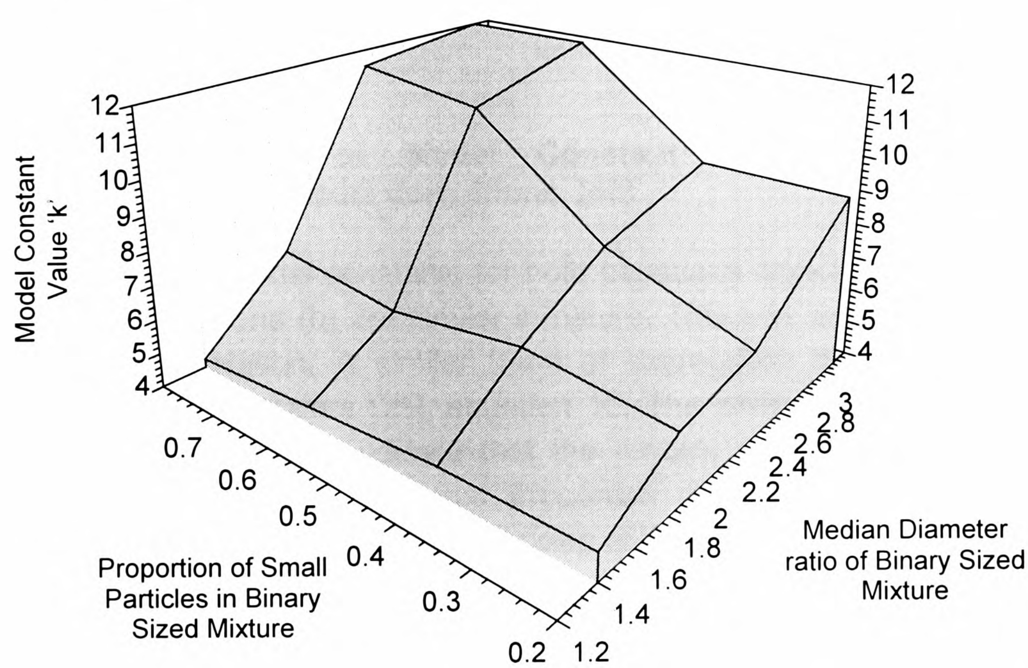
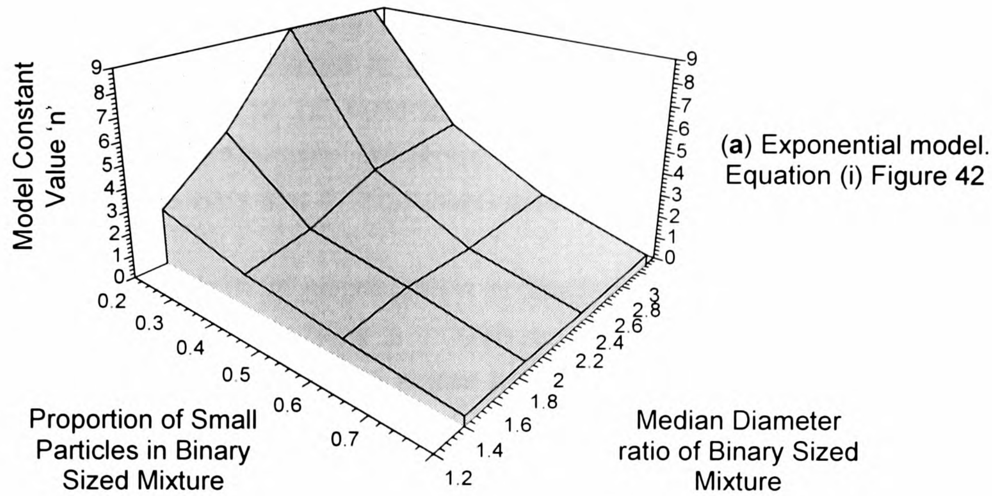


Figure 76 **Relationship of Model Constant produced from O'Dea and Waters predictive model derivation [25]**



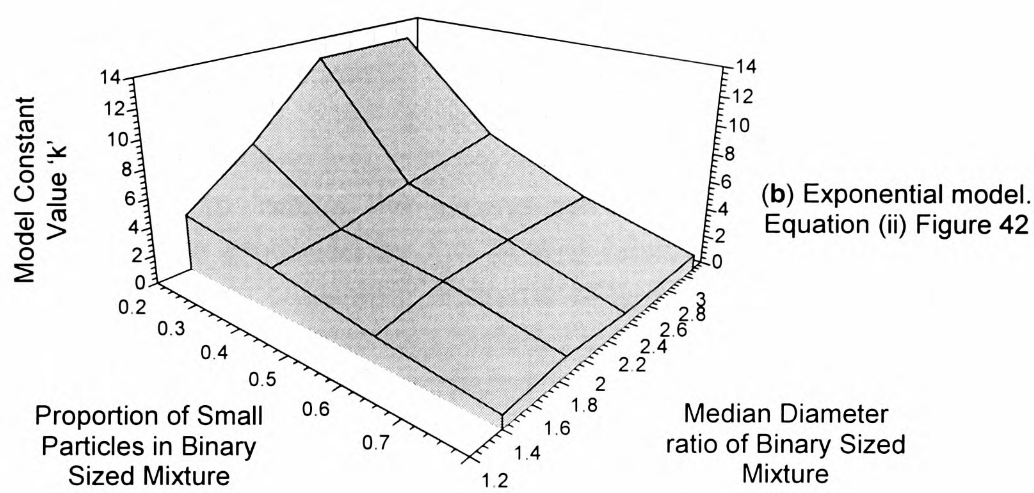


Figure 77 Relationship of Model Constant Values produced from Popplewell model derivations. [58]

The relationship of the model constants for both equations depicted in Figure 42 are shown on Figure 77(a) and (b) are similar in nature. This was expected due to their similar theoretical derivation. A similar trend of segregation constant profile was exhibited by O'Dea and Waters [25], equation 15. The similar profiles exhibited by these three predictive models indicate that the models recognise the appropriate mixture combinations of size ratio and proportion of small particles that would produce the most severe segregation tendencies of a mixture.

7.4 Conclusions

From analysing the results produced during this stage of the research it can be seen that certain variables dictate an influence on the pattern of segregation produced. Feedrate can influence the pattern of segregation produced, especially when there are small proportions of small particles in the feed mixture, Figure 73(a). However, feedrate was generally not considered significant in influencing the pattern of segregation produced in the plane-flow test vessel in comparison to differences in size and proportions of small particles in the feed. Nevertheless, this statement is only applicable within the range of feedrates tested. Mosby [64] indicated that extremes of feedrate can measurably influence segregation patterns, and as such should not be ignored when very low or high feedrates are used.

Figure 74 shows that the pattern of segregation produced as a function of increasing proportions of small particles in the feed is influenced by the dominating mechanism of segregation. For mixtures that contain a low proportion of small particles so that the sieving-percolation mechanism is dominant, the patterns of segregation produced are affected by the range of size differences and feedrates tested, Figure 74(a) and (b). When the proportion of small particles in the feed is high so that the floating-migration mechanism of large particles is dominant, the range of feedrates and size differences are less influential in dictating different patterns of segregation, Figure 74(c) and (d). This is further emphasised on Figure 74(c) and (d) where a change in mechanism occurs when the total proportion of the heap length exceeds approximately 0.6. Up to this heap length there are insufficient large particles present in the avalanching layer to induce the sieving-percolation mechanism, therefore profiles of segregation are produced by the floating-migration mechanism of large particles and remain relatively consistent. Patterns of segregation are unaffected by the range of feedrates and size differences tested. For heap lengths greater than 0.6 the population of large particles has increased to an extent where the sieving-percolation becomes dominant. Consequently, the patterns of segregation beyond this point become more diverse due to the influence of size differences and feedrate variation.

An empirical model, equation 17, was formulated according to the linear nature of the patterns of segregation produced. The accuracy of this model was assessed in comparison to established segregation models that exist in segregation literature that were in a suitable form for assessment. The results shown in Figure 75 and those listed in Appendix A.7 indicate the successful ability of segregation models that can predict patterns of segregation produced when in line feeding the vessel. In addition, the empirical fitting constants exhibited similar behavioural trends as a function of variation in size differences and feed proportions of small particles, Figure 76, Figure 77.

The conditions that dictate the severity of the 'hump' pattern of segregation at the heap apex have been successfully removed allowing the satisfactory appraisal of relevant models that are claimed to predict segregation of this form. However, vessels are seldom fed in line with the angle of heap being produced. It is of more relevance, therefore, to investigate vertical feeding of vessels that induce the 'hump' pattern of segregation commensurate with industrial scenarios. The affects of such a feed geometry can then be incorporated into developing existing predictive models.

CHAPTER 8

VERTICAL FEEDING OF PLANE-FLOW VESSEL

8 Vertical Feeding of Plane-Flow Vessel

As outlined in the conclusions of Chapter 7 there is a need to address the more industrially relevant area of vertical feeding The second area of investigation as outlined in Section 6.8 focused on the generally encountered method of vertical, central point charging a vessel. This was undertaken with the intention of inducing the mechanisms of segregation that produce the hump pattern of segregation conspicuous from test results shown on Figure 55 and Figure 56, Section 6.1 page 134.

8.1 Test Variables and Configuration of Test Vessel

As previously documented in Section 7.1, employing a constant free-fall height throughout the vessel filling cycle eliminated differences in segregation throughout the vertical depth of the vessel. Consequently, charging enough material to cover the first two series of probes,1-5 and 6-11, was sufficient in producing enough sample results to enable an accurate quantification of the segregation being produced in the vessel.

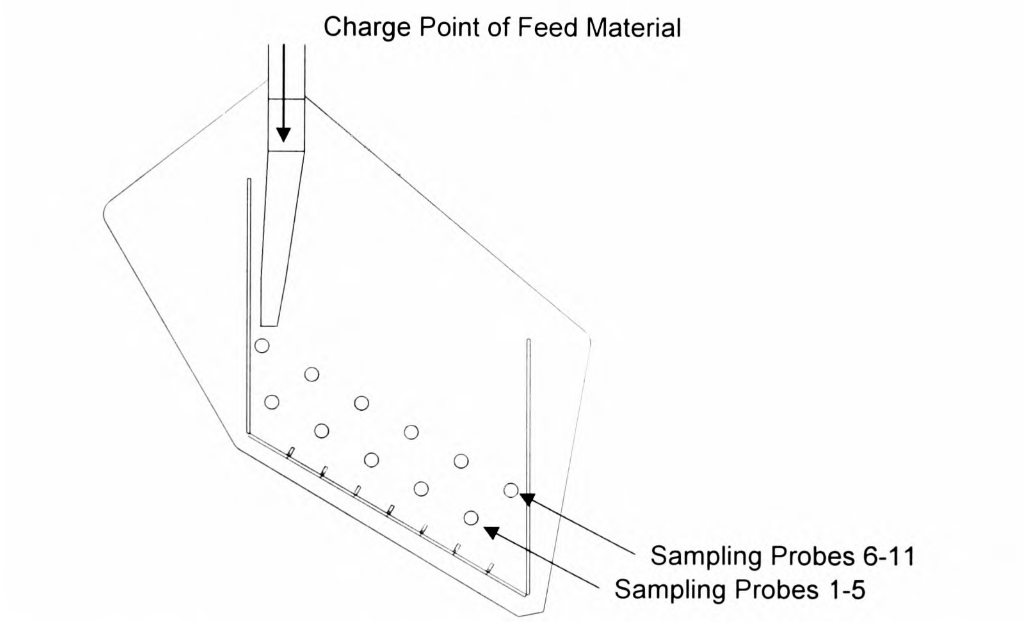


Figure 78 Diagrammatic Representation of Test Facility Configuration for Vertical Charging of Feed Constituents.

In order to gauge a direct comparison of the work conducted in this stage to that of stage one, Chapter 7, a test program was undertaken that repeated all stage 1 test conditions. Undertaking this would then allow verification of the proposed elimination of affects of the embedding mechanism produced in stage one and also highlight the magnitude of its affect when repeating test conditions for this alternative configuration of vessel charging.

8.2 Test Results

As expected, the segregation results produced for this stage of the investigation revealed the propensity of the segregated mixture to exhibit a 'hump' pattern of segregation around the vicinity of the feed point associated with vertical charging. Under identical test conditions, stage one (in-line feeding) successfully eliminated this characteristic 'hump' profile, Figure 73, Section 7.2. A comprehensive list of results produced for this stage of the investigation can be found in Appendix A.8.

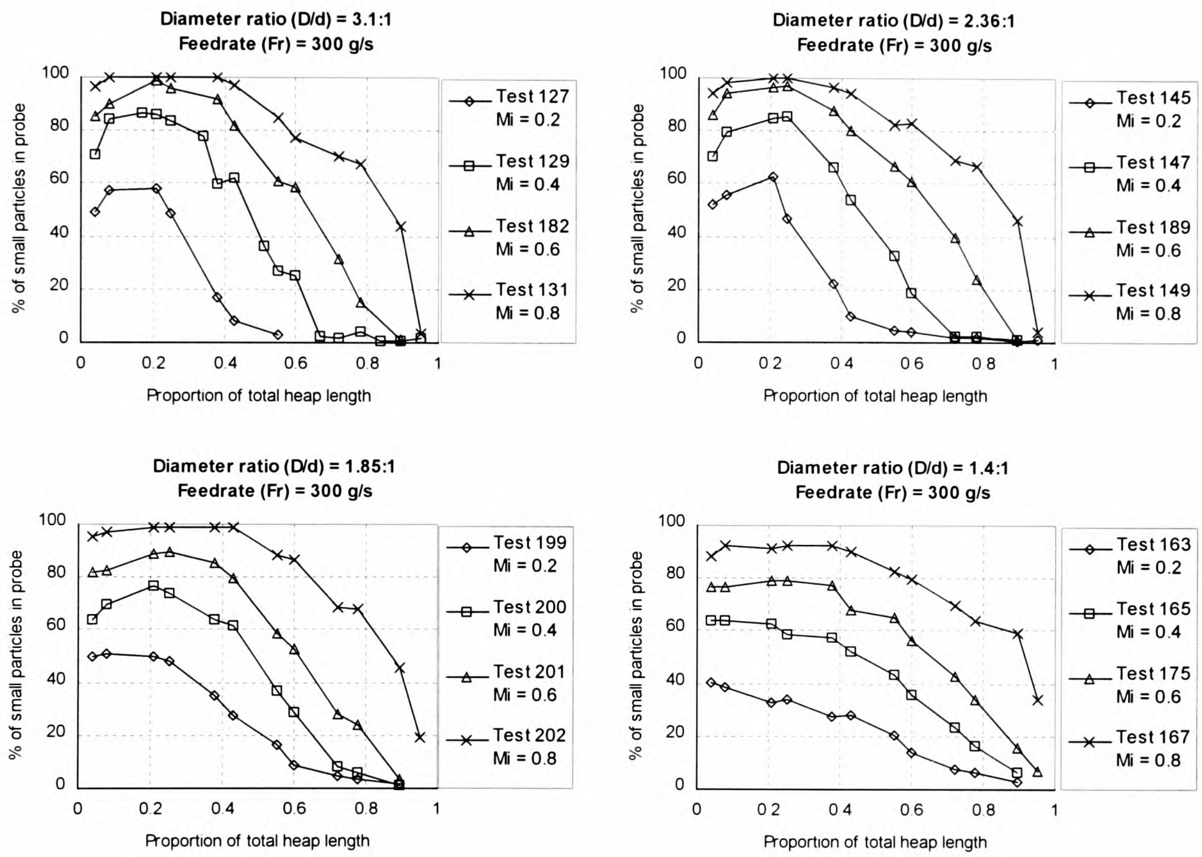
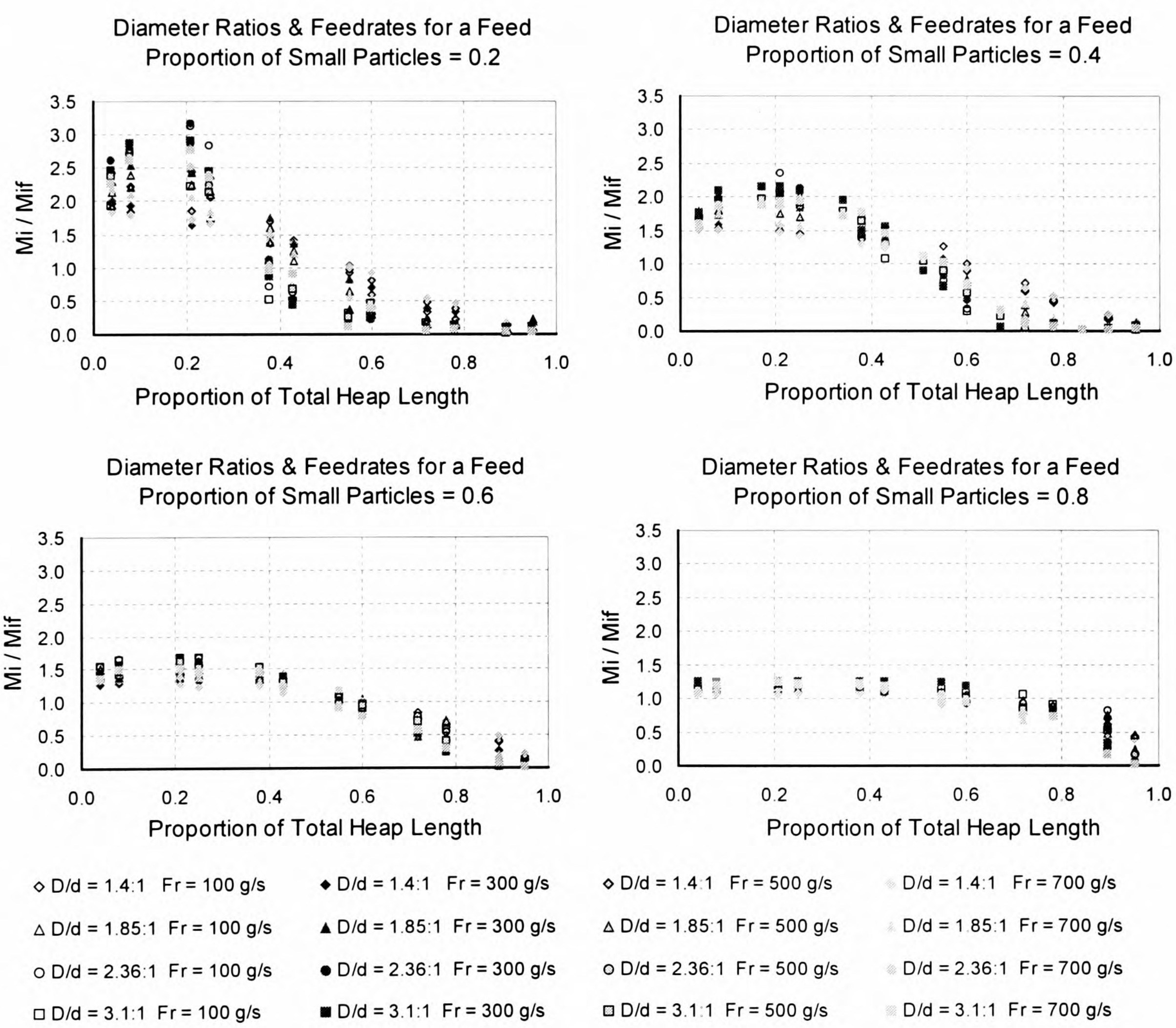


Figure 79 Variation in Pattern of Segregation as a Function of Increased Diameter Ratio of a Binary Sized Mixture.

An arbitrary feedrate of 300 g/s was selected to illustrate the patterns of segregation for changing size distributions and proportions of small particles in the mixtures shown on Figure 79. The same trends of segregation pattern, however, apply across the entire range of feedrates tested. It is of significance to note that mixtures containing a greater size difference between small and large particles produce a more pronounced 'hump' pattern within the vicinity of the apex of the heap. This is attributed to the relative difference in momentum of large particles and small particles. As previously documented in Section 6.4.1.1, an increase in large particle size induces a cubic increase in particle volume ad subsequently a significant increase in particle momentum. This then endears the large particles to penetrate further into the heap and remain stationary and unexposed to any influences induced by any successive charged material.

The same dimensionless concentration coefficient procedure used for plotting results from stage one Figure 74 was adopted for plotting the entire results for this stage of the investigation. It was then possible to ascertain the influence that the proportion of small particles had on influencing patterns of segregation produced for this stage of the investigation. This method of graphically representing test results allowed the verification of the hypothesis proposed by Bagster [54] [55] [56] as documented previously in Section 3.7.3.3.



Mi = Percentage of small particles in probe sample
Mif = Percentage of small particles in original feed mixture

Figure 80 Vertical Feeding Patterns of Segregation Induced by Variations in Diameter Ratios and Feedrate for Binary Sized Mixtures

Figure 80 shows that for low proportions of small particle mixtures commensurate with high proportions of large particle mixtures utilised by Bagster, Figure 33 a similar scatter of results is produced. This confirmed the conclusion drawn by Bagster that the interaction of proportions of small and large particles affects the pattern of segregation produced. Large and small scales of disparity for the segregation profiles shown on Figure 79 indicate the change in segregation mechanism as a function of proportions of small particles in the feed mixture. This still occurs despite a change in geometrical orientation of the charging point. It can be assumed that changing the orientation of the charging point does not significantly alter the disparity of results. Comparisons of Figure 74 and Figure 79 suggest this to be the case.

8.3 Comparison of Stage One and Stage Two Test Results

The normalised segregation results for stage one, Figure 74, and stage two, Figure 79, indicate that the relative amount of small particles found around the vicinity of the feed point does not increase with increasing feed proportion of small particles. For a 20% feed proportion of small particles, 80% of the 20% small particle feed remains under the feed point. For a 60% feed proportion of small particles only 50% of the 60% small particle feed remains under the feed point. Therefore, the rate at which a mechanism can remove the small particles from the avalanching layer and position them under the fill point cannot remain at the same magnitude with increasing numbers of small particles being introduced as the feed proportion of small particles is increased. The time available for a 60% feed proportion of small particles to segregate the same number of small particles per unit length as a 20% feed proportion of small particles fed at the same feedrate is the same but both mixtures will segregate at different rates. This is because the proportion of small particles in the feed dictates the dominant segregation mechanism and the rate at which each mechanism separates the small particles from the flowing layer is different. For a small amount of small particles in the feed, the sieving-percolation mechanism rapidly removes the small particles from the avalanching layer (significantly larger visible hump). When the initial amount of small particles in the feed is increased, the rate at which the sieving-percolation mechanism operates is reduced. The dominant mechanism reverts to the floating-migration mechanism of large particles that move to areas of high shear i.e. towards the surface of the avalanching layer. The small particles by default sink throughout the duration of this mechanism but at a lesser rate than when subjected to the sieving-percolation mechanism. Therefore there still exists a 'hump' pattern but less pronounced and extends further from the feed point.

Irrespective of the proportions of small to large particles in the feed mixture or feedrate, the amount of large particles directly underneath the feed point never exceeded the amount in the feed. This behaviour was consistent throughout the entire range of tests undertaken for this investigation. This indicated that although the embedding mechanism influences the proportion of large particles directly under the feed point, the mechanism has an insufficient influence on segregation to produce a mixture to the extent where the proportion of large particles found under the feed point is greater than those present in the initial feed. This remains valid across the entire range of tests undertaken for mixtures differing only in size. However, when mixtures contain differences in density as well as size then it may be possible to significantly alter the amount of large particles being positioned under the feed point. For such mixtures it has been documented that it is possible to produce mixtures where the proportion of large particles positioned under the feed point is far greater than the amount of large particles in the original feed mixture.

By graphically comparing results for stage one and stage two, a clearer understanding of the influence that feedrate and size differences have on the pattern of segregation produced can be established. A feed proportion of 40% small particles was selected to allow this graphical comparison as shown on Figure 81.

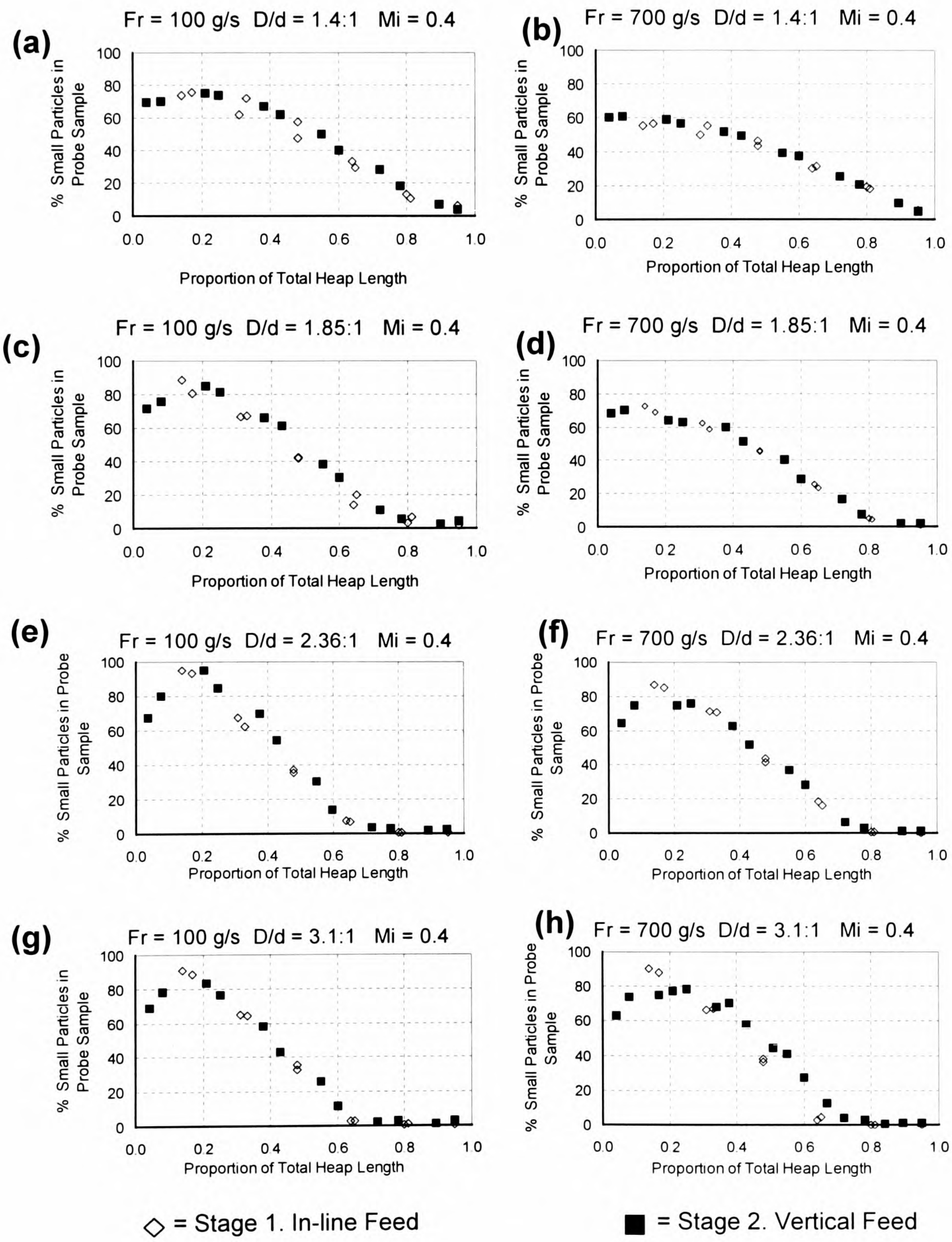


Figure 81 Comparison of Feed Configuration and its Influence on the Resulting Patterns of Segregation Produced

As shown on Figure 81 the embedding mechanism dictates the severity of the hump pattern produced as it determines the starting position of the segregation profile at the heap apex. Comparison of Figure 81(a)&(b), (c)&(d), (e)&(f) and (g)&(h) indicate that the range of feedrates tested has altered the starting position of each segregation pattern. For matching test conditions, lower feedrates produce a profile of segregation that starts at a higher position in comparison to higher feedrates. The reduction in small particle population for higher feedrates indicates an increase in large particles as a function of the embedding mechanism initiated by the increase in feedrate. The embedding mechanism is initiated when the large particles have sufficient momentum in comparison to small particles in the mixture and embed themselves into the static heap surface directly under the feed point. The results shown on Figure 81 indicate that even the smallest size difference tested was sufficiently large enough to allow the range of feedrates to instigate a different starting position of the segregation profiles produced.

As previously mentioned the affect of feedrate on dictating the starting position of the segregation patterns produced was not eliminated, even for the smallest difference of mixture size tested. However, the profiles of segregation produced along the heap length were affected by size differences of the mixture and the range of feedrates tested. Comparison of the low and high feedrate conditions for the smallest size difference tested Figure 81(a) and (b) indicate that a slightly more pronounced hump pattern of segregation is produced for the lower feedrate. Although the profiles are not significantly different, the small difference in size of the mixture has restricted the influence of the mechanisms acting within the avalanching layer. The patterns of segregation for both tests are of a similar form, even though the low feedrate of 100 g/s provides the necessary time for the mechanisms to induce a more 'humped' profile. For the next increase in mixture size tested, Figure 81(c) and (d), the higher feedrate test restricted the time available for the mechanisms of segregation within the avalanching layer to dictate a more pronounced pattern of segregation. For the lower feedrate, the size difference is significantly larger and allowed the extended avalanche time to dictate a more pronounced 'hump' segregation pattern to be produced. Figure 81 (e) and (f) indicates that the next increase in mixture size has reached a point where, irrespective of feedrate, the size difference is large enough to allow mechanisms of segregation to dictate a hump pattern of segregation. Figure 81 (g) and (h) is further confirmation that that the size difference between large and small particles has reached a point where feedrate will not impede the mechanisms of segregation from producing a 'hump' pattern of segregation.

8.4 Conclusions

Comparison of test data for both feed configurations as shown in Figure 74, Figure 80 and Figure 81 indicate that constituent feed proportions, feedrate, and variations in particle size, all influence different patterns of segregation produced. Whilst it has been shown on Figure 75 that predictive techniques that exist in current segregation literature can successfully predict segregation patterns produced for an in-line feeding geometry, Figure 82 shows that the same predictive techniques are not readily applicable to modelling the more relevant scenario of vertical feeding a vessel.

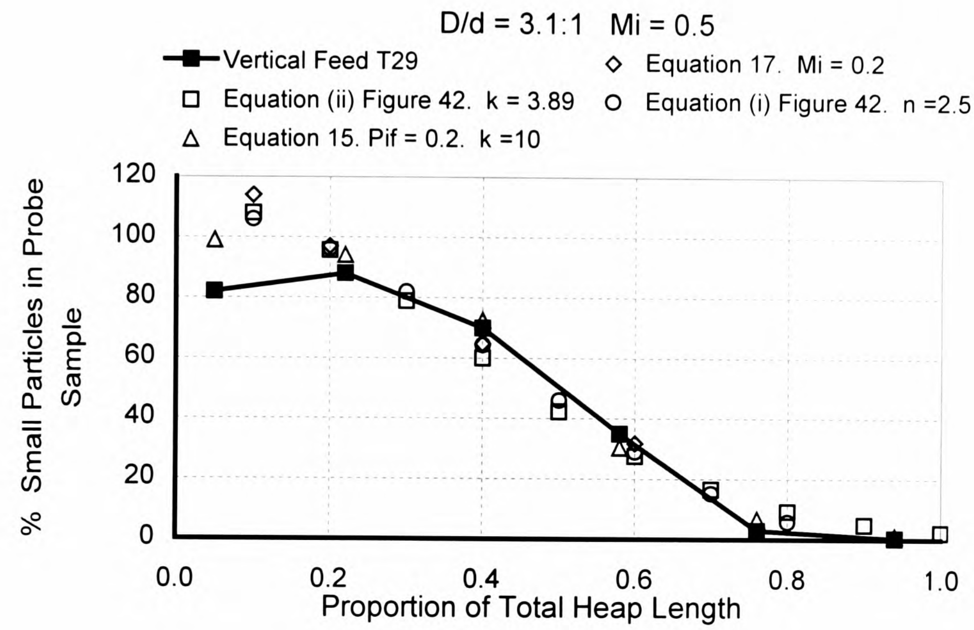


Figure 82 **Graphical Indication of the Inability of Existing Segregation Models to Accommodate the Segregation Pattern Produced within the Vicinity of the Heap Apex**

The points denoted by the 'solid' symbols on Figure 82 and connected by a solid line is the experimental test segregation profile. For the majority of tests undertaken, when the heap length is greater than approximately 0.2 of the total length the predictive models as shown in Figure 82 will satisfactorily predict the experimental pattern of segregation produced. However, they are unable to predict segregation within the vicinity of the heap apex in their current format where the influence of the embedding mechanism comes into effect. This necessitates expansion of these current predictive models to incorporate the multitude of behavioural characteristics and interactions known to occur around the heap apex as a function of vertical feeding. The vertical-feed geometry test program undertaken has indicated that feedrate and size differences are significant in dictating the severity of the embedding mechanism in influencing the pattern of segregation produced, Figure 81. However quantification of the relationship of these variables, their trends, and their interactions in inducing this 'hump' pattern in order to undertake predictive modelling of its occurrence cannot be undertaken from the test data provided by this test programme. The test programme has discovered an indication of the behavioural trends of these variables but does not quantify their range of applicability and interaction with other process, geometric and particle variables to an extent where current predictive techniques can be satisfactorily re-appraised or developed.

CHAPTER 9

CONICAL HEAP FORMATION

9 Conical Heap Formation

It was proposed in Section 6.8 that a program of work be implemented to investigate heap segregation when forming conical three-dimensional heaps. Conical heap experiments were initially undertaken with the purpose of fulfilling four objectives:

- Familiarisation and commissioning of test rig performance.
- Ascertaining integrity of segregation data.
- Analysing pattern of segregation within a three-dimensional vessel environment.
- Assessing relevance of data obtained from plane-flow vessels to more realistic conical heap environments.

A method of sampling was used that extracted sufficient samples to give an accurate representation of segregation produced in a three-dimensional environment. The sampling device was based on a design devised and utilised extensively by Mosby [64] who undertook a significant amount of investigative research into conical heap segregation patterns and their relationship with those produced when charging plane flow vessels.

9.1 Test Rig and Sampling Procedure

Mixture formulation and delivery for subsequent segregation in a three dimensional conical heap vessel was undertaken using the same feed and mixing technique employed for investigations into plane-flow vessel segregation, Figure 51 and Figure 52 pages 128, 129 respectively. The primed mixture was charged via the flow-converging section into the centre of a circular vessel of the design shown in Figure 83. The distance between the charge pipe and apex of the heap being formed was kept constant throughout the entire vessel filling process, commensurate with the test conditions undertaken in stage one, Chapter 7 and stage two, Chapter 8.

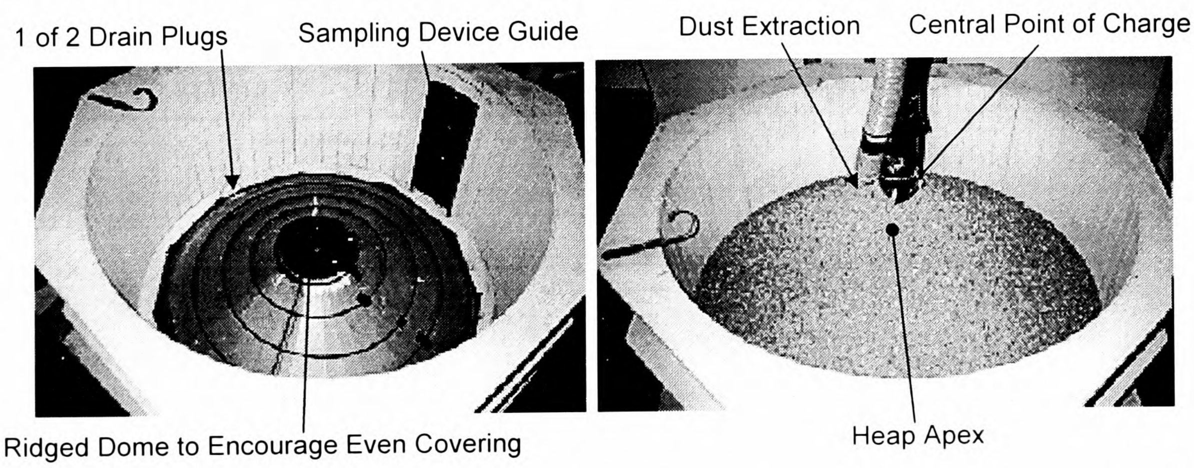


Figure 83 Layout of three-dimensional Vessel and Picture Showing Typical Heap Formation

After vessel filling the sampling device was placed in position for extracting heap samples. For initial trials to ascertain the integrity of the data being obtained a datum sampling position was used. However, sampling at different radial heap positions was also conducted in order to gain a more representative picture of the overall radial heap segregation.

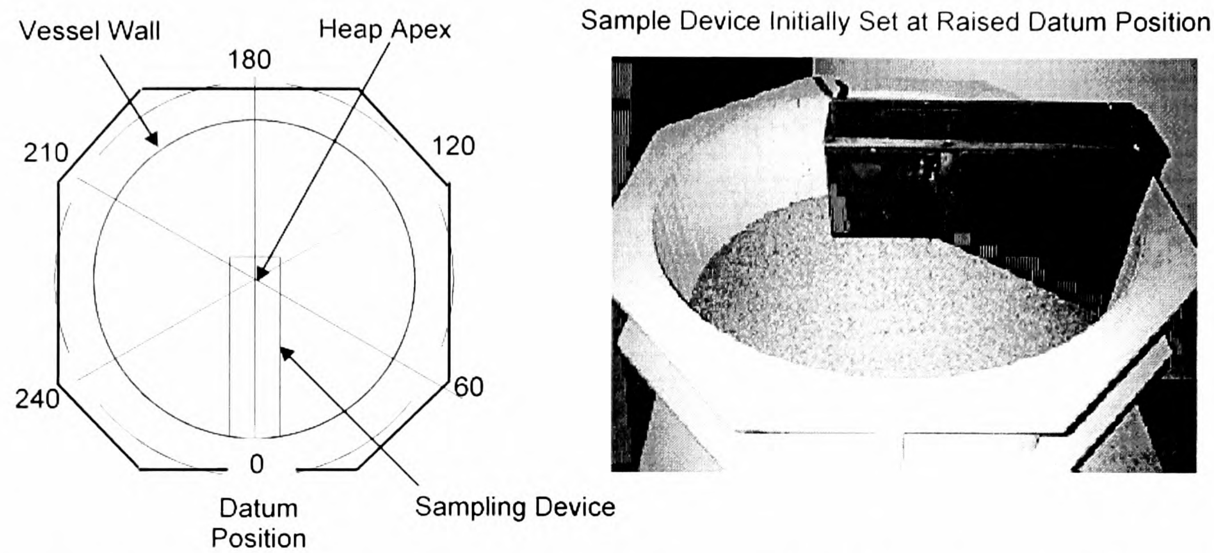


Figure 84 Schematic Plan View Showing Possible Angular Sample Positions and a Picture Showing Initial Position of the Device.

The sampling device was pushed down through the heap until contact was made with the metal dome fixed to the vessel base. This was undertaken relatively quickly in order to minimise any distortion to the heap structure and thus helped preserve as closely as possible the state of the segregated heap. The device encapsulated a portion of the heap into a two-dimensional sample zone ready for sampling, Figure 85(a). One of two drain plugs was removed which allowed the spent mixture adjacent to the sample device to be drained away. This then revealed the sampling points that run in a line parallel to the repose angle of the material in the device, Figure 85(b).

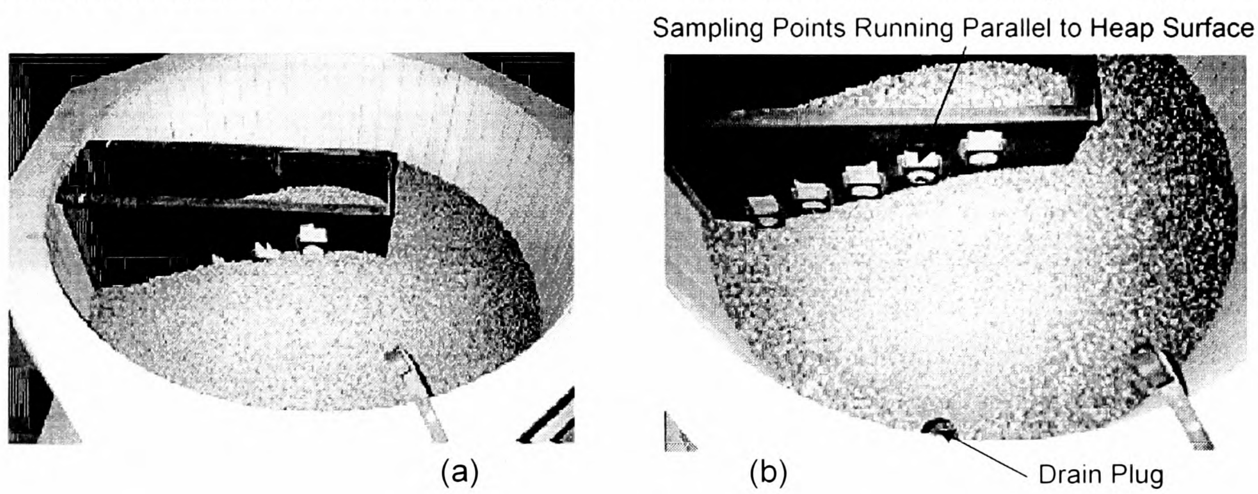
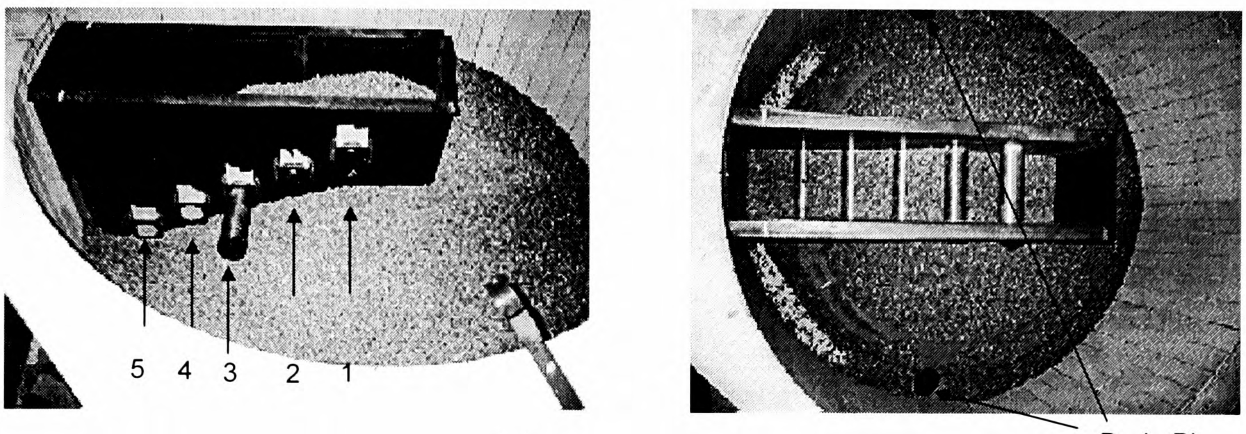


Figure 85 Insertion of Sampling Device and Subsequent Drain of Spent Material to Reveal Sampling Points

Sampling probes could then be pushed through the hole-covers on the side of the sample box to capture material samples for analysis, Figure 86(a). When all the probes were inserted into the sample box the remainder of the spent material was drained away and re-processed through the screening station as shown previously in Figure 54.



(a) (b)

Figure 86 (a) Sample Probe Insertion. (b) Removal of Spent Material through Drain Holes.

Figure 86(b) shows the sample device when all the surplus material has been drained out of the two drain plugs. Draining of the surplus material allowed removal of the device which permitted separate analysis of the contents of each probe.

9.2 Integrity of Three-Dimensional Test Data

When testwork was initiated into conical heap formation, it became immediately apparent that avalanching behaviour associated with building a conical heap was significantly different in comparison to charging the plane-flow test vessel. For the majority of tests conducted when charging a plane-flow vessel, an avalanche, irrespective of duration, induced bed movement across the entire width of the vessel. In contrast, charging a three-dimensional heap produced avalanching behaviour that was erratic. Although there was some semblance of consistency in avalanche frequency, its direction was not predictable. This behaviour led to a two-stage approach to testing the integrity of the segregation data being obtained in the three-dimensional test facility.

- Undertake testwork to establish the consistency in which conical segregation occurred in the test rig whilst simultaneously assessing the performance of the sampling device.
- Undertake an investigation into varying the angular sampling position around the heap in order to establish any radial variation in segregation.

9.2.1 Reproducing Consistent Conical Heap Segregation

To test the integrity of segregation data produced from the samples extracted, a series of five identical tests were undertaken using an arbitrary process and particle characteristic conditions. These results together with a complete list of results for all test conditions can be found in Appendix A.9. The content of the samples extracted were analysed using the same standard sieving techniques that were employed for analysing samples extracted from the plane-flow test vessel as previously documented in Section 5.1.3.

Median Diameter Ratio (D/d)	1.4:1
Initial Mixing Ratio of Small Particles. (Mi) % mass	40
Feedrate (Fr) g/s	300

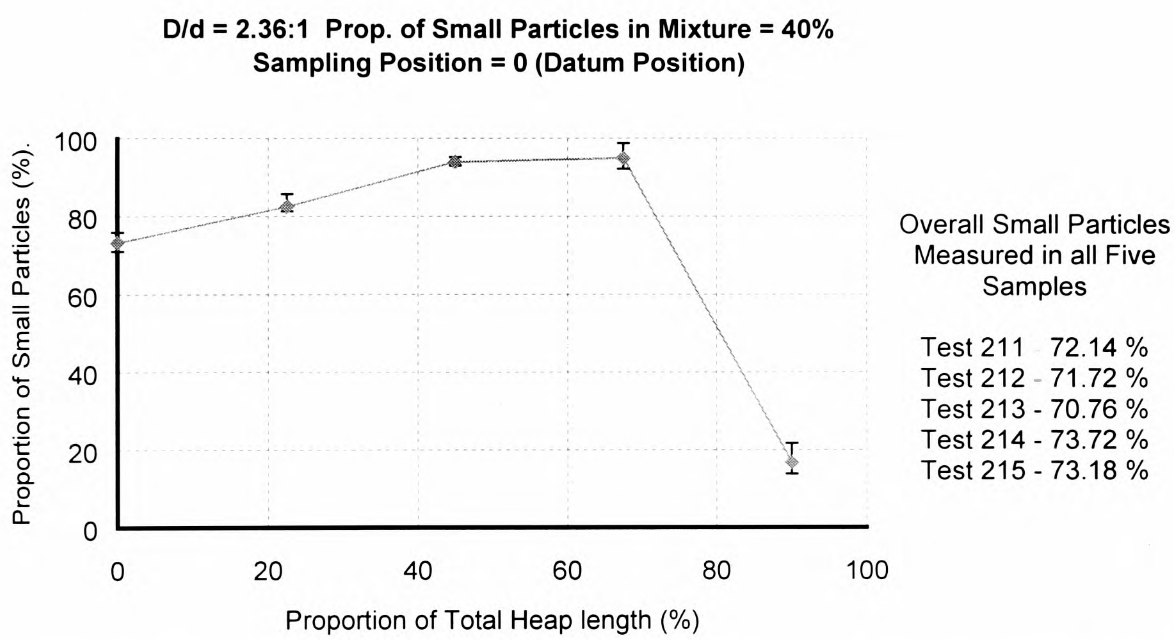
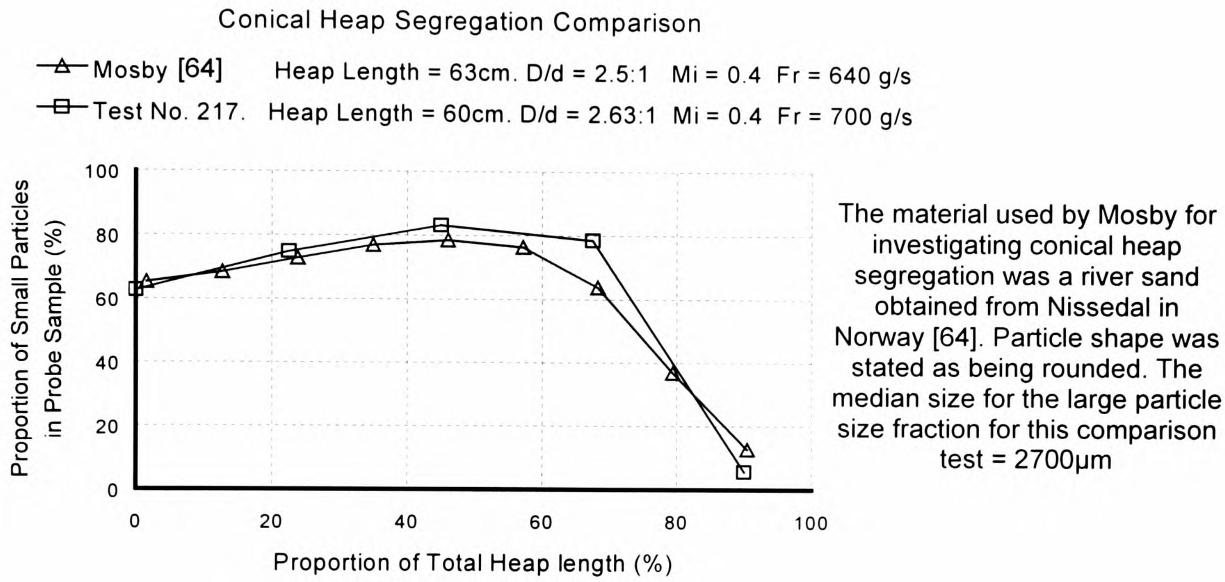


Figure 87 Graphical Representation of Five Repeated Segregation Tests when Forming a Conical Heap

It was evident from Figure 87 that the method adopted for extracting samples produced consistent results. The pattern of segregation produced indicated a progressive increase in the proportion of small particles per unit length away from the heap apex until a point was reached where there was a rapid drop in numbers of small particles measured. To provide further evidence to authenticate that the segregation measured was truly representative of genuine conical heap segregation required comparison with actual conical heap segregation data. Unfortunately, limited published documentation is available that contained data in a form that could be used for comparative purposes. However, Mosby [64] did provide at least one data set that matched closely to one of the test conditions conducted in this program of work.



Mosby [64] Mean % of small particles in all probes = 61.2%
Test No 217. Mean % of small particles in all probes = 60.9%

Figure 88 Comparison of Heap Segregation with a Commercial Data Set

Figure 88 indicates that the results compare closely. This evidence was further confirmation that the desired conical heap segregation behaviour sought was being successfully produced in a repeatable fashion using this design of test facility.

9.2.2 Angular Variations in Radial Segregation

Initial quantification of conical heap segregation was accomplished by sampling radially along a single line from heap apex to vessel wall. However, this sample volume represented only 1% of the total material that formed the heap. Furthermore, the evidence tabulated on Figure 87 indicated that measurements of segregation produced a disproportionate amount of small particles within the heap that did not concur with the proportion of small particles charged in the original mixture. It was plausible to suggest that one single radial line of sampling did not provide an accurate representation of the segregation occurring radially around the heap. This seemed reasonable considering the inconsistent and chaotic avalanching behaviour associated with conical heap formation, which could produce significant variations in mixture proportions throughout the heap. This information suggested the undertaking of a series of tests in which variations in radial sampling was performed with a view to yielding a more accurate representation of the spread of small particles within the heap. Consequently, three separate conical heaps were formed under an identical arbitrary test condition. One heap was sampled at an angular position of 0 degrees, the second was at a position of 120 and the third was 240 degrees, as shown on Figure 88.

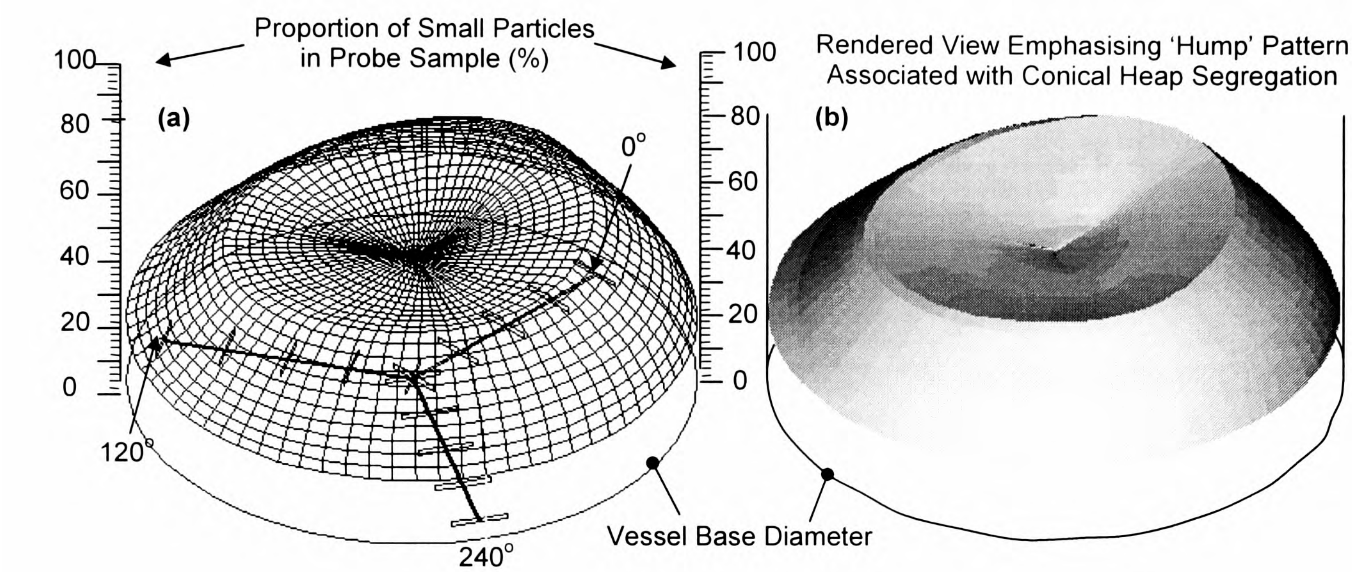


Figure 89 Composite Picture of Conical Heap Segregation based on Three Angular Sampling Positions. (3% of Total Heap Sampled)

Test Number and Radial Sampling Position	T223 – 0°	T225 – 120°	T227 – 240°
Average % of Small Particles in Samples	56.4	50.5	57.8
Median D/d = 1.4:1. Feedrate = 300 g/s. Proportion of Small Particles in Feed = 40%			

As shown on Figure 89 and in the above table, the three angular positions used to quantify the segregation in the conical heap produced similar profiles of segregation. The discovery of a higher proportion of large particles at different positions in the heap in order to maintain a material balance with the proportions of small and large particles in the initial feed mixture was not found. To investigate this behaviour still further, six separate tests were repeated and sampled at six different angular positions. Figure 90 shows that sampling was undertaken across complete cross-sections of the heap as opposed to equidistant around the base, Figure 89.

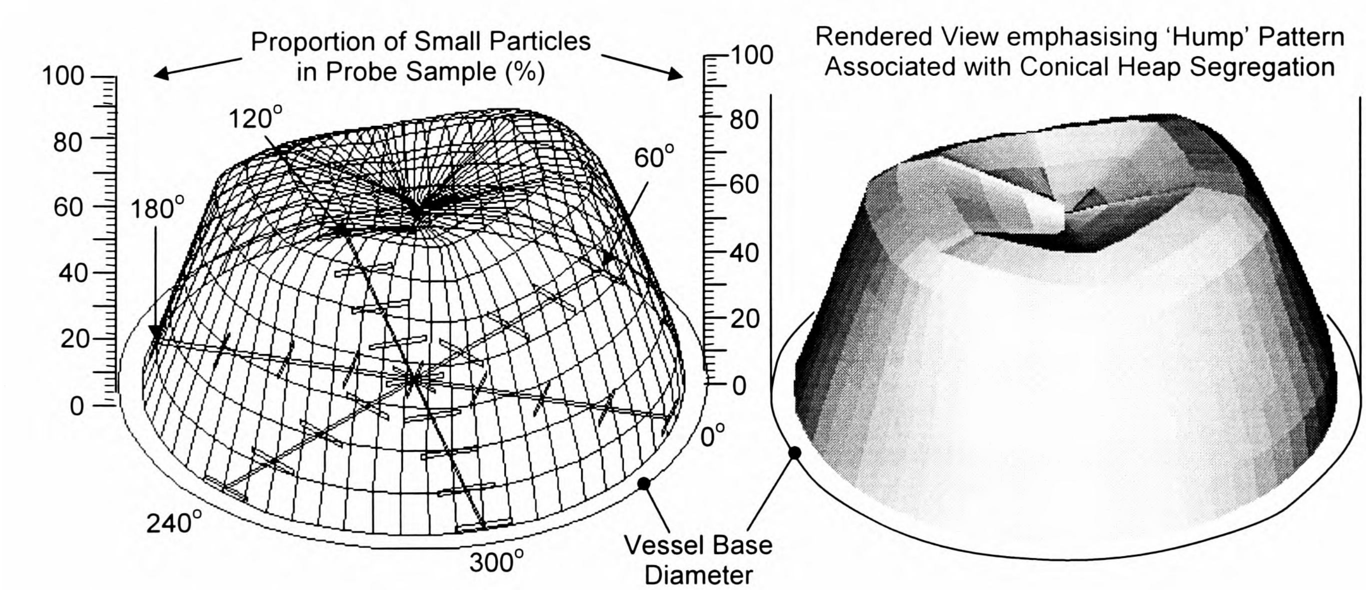


Figure 90 Composite Picture of Conical Heap Segregation based on Six Angular Sampling Positions. (6% of Total Heap Sampled)

Test No.	T211	T231	T219	T229	T221	T234
Angular Sampling Position	0	60	120	180	240	300
Overall Av. % of Small Particles	72.14	66.16	53.9	66.28	63.56	62.46
Median D/d = 2.36:1. Feedrate = 300 g/s. Proportion of Small Particles in Feed = 40%						

Figure 90 showed that for six angular sampling positions the proportion of small particles distributed within the heap remained consistent, irrespective of angular sampling position. Figure 89 and Figure 90 suggest that sampling a conical heap in terms of one angular position from heap apex to periphery would be sufficient to provide enough information to describe segregation at all positions around the heap. Consequently, successive conical heaps formed in the test program were sampled only once in order to quantify the degree of material segregation. Full details of conical heap segregation investigations can be found in Appendix A.9.

9.2.3 Factors Influencing Conical Heap Segregation

As previously established in Section 6.3 page 136, when charging a plane flow storage vessel, differences in feedrate of the charging mixture proved insignificant in dictating resulting patterns of segregation in comparison to other process and particle characteristic variables. A series of tests were undertaken to ascertain whether this statement was applicable when forming a conical heap. Visual observation of these tests indicated that avalanching behaviour associated with feedrate variation differed markedly. For the highest feedrates, the frequency of avalanching was more repeatable with each avalanche progressing across the entire heap length. For low feedrate conditions, avalanching was more sporadic in terms of frequency, duration and direction.

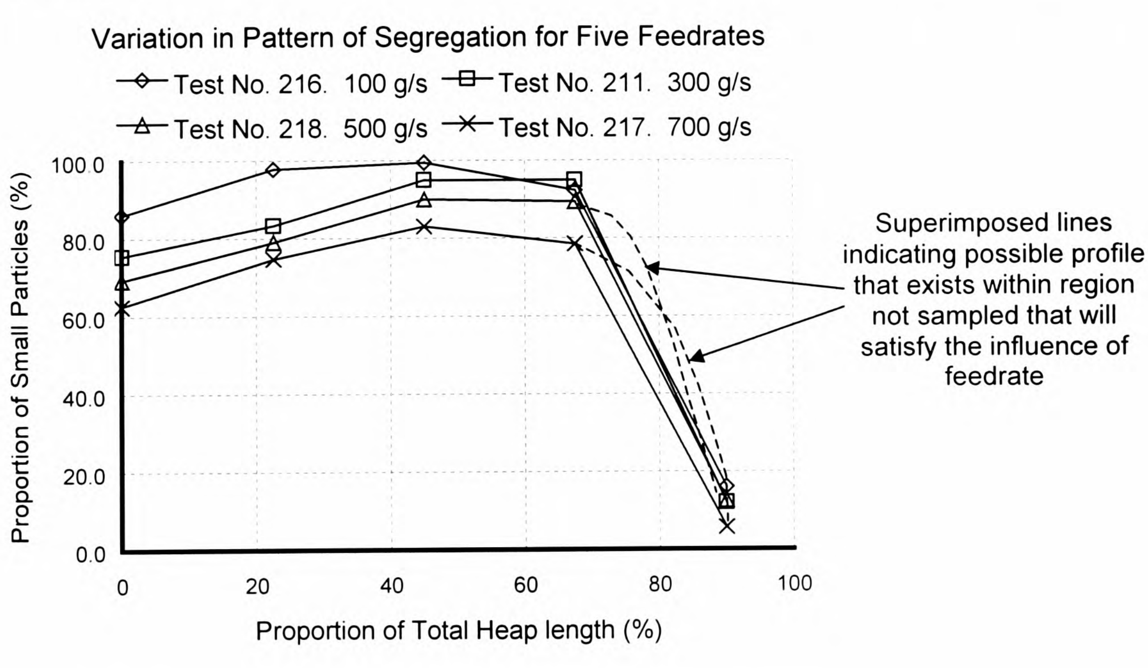


Figure 91 **The Influence Feedrate has on the Pattern of Segregation Produced when forming a Conical Heap**

As shown on Figure 91, feedrate significantly altered the pattern of segregation. One behavioural aspect that featured prominently in Figure 91 was the increasing proportion of small particles segregating nearer the heap apex as the feedrate was reduced. When charging the vessel at low feedrates the mechanisms of segregation were sustained for longer periods as a result of the extended duration of an avalanche. However, to compensate for an increase in proportion of small particles near the heap apex as the feed is reduced, there should be a correspondingly sharper depletion rate of small particles per unit length away from the feed point. This should occur in order to maintain a material balance but the information tabulated below and on Figure 91 indicated that this was not the case. However, sampling was not performed between 68% and 90% of the heap surface length. Within this region the rate of segregation is high and the fall in population of small particles is significant. The measured profiles shown on Figure 91 indicate that the reduction in population of small particles is linear in nature, however this may not be representative of the actual profile in the heap. Further sampling between within this region may reveal a more representative profile commensurate with satisfying material balances of small and large particles. The dotted lines superimposed on Figure 91 suggests an alternative profile that is more realistic. These profiles indicate a less rapid depletion of small particles for Test No's 217 and 218 than the linear profile. This would re-align the profiles that may be occurring and therefore more small particles progress further from the heap apex due to restricted exposure to mechanisms of segregation occurring within the heaping process.

Figure 58 on page 137 is a representative example of the majority of tests undertaken when charging a plane-flow storage vessel in terms of the total average proportion of small particles sampled along the heap length. For each test the averaged sample values compared favourably with the original proportion of small particles in the feed mixture. Throughout all tests undertaken when forming a conical heap the proportion of small particles in the initial feed remained constant at 40%. However, the mean proportion of small particles extracted along the heap length when sampling conical heaps did not equate to the initial feed proportions in the original mixture.

Test No	216	211	217	218
Feedrate (g/s)	100	300	500	700
Average % of Small Particles in All Probes	78.3	72.1	68.0	60.9
% Difference from Initial Feed Proportions	96	80	70	52

Similar anomalies for conical heap segregation were also reported by Mosby [64] who attributed these discrepancies to the fact that for the plane-flow vessel each sample was representative of the same heap volume. When sampling a three-dimensional heap each sample volume represented a heap volume that increased from the apex of the heap to its periphery, Figure 92(b). To address the problem of averaging results of the entire probe samples required weighting probe samples with respect to the part of the heap that they represent. Sample probes positioned further down the heap length represent a greater surface area or heap volume than those positioned near the heap apex. Consequently, techniques were explored that weighted a sample towards the proportion of the total population that it represented. Mosby [64] attempted this by weighting probe positions according to their distance from the heap apex to probe position down the heap. This was measured as a line running parallel to the heap surface from heap apex to probe position. Alternatively, it has been attempted to weight probe samples according to the torroid volume of the heap at the probe position. Furthermore, it has been attempted to weight probe samples according to the angle (α), Figure 92(a) which a probe subtends according to the distance of the probe down the slope from the heap apex.

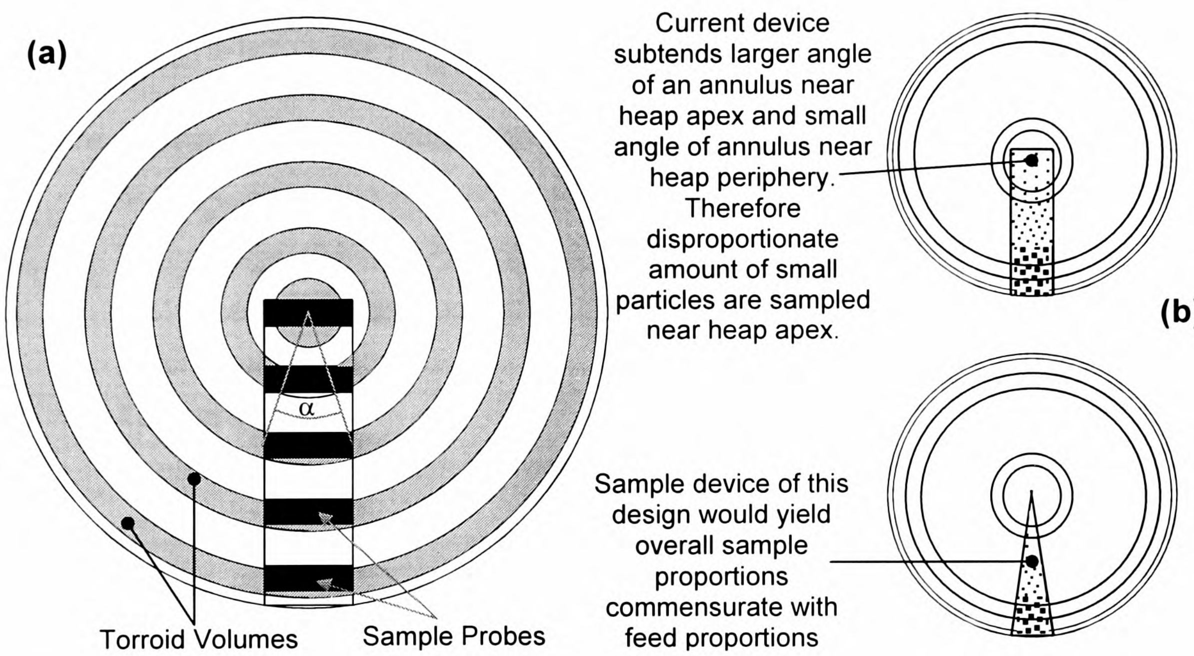


Figure 92 (a) Plan view of conical heap indicating sample positions and torroid volumes of heap that they represent. (b) Illustration of How Sample Device incurs Misrepresentation of Sample Contents

The three model equations used in this approach and the results they produced are shown below:

$$M_i = \frac{\sum_{j=1}^{n} x_j . M_j}{\sum_{j=1}^{n} x_j} \qquad \text{Equation 18}$$

$$M_i = \frac{\sum_{j=1}^{n} V_{tj} . M_j}{\sum_{j=1}^{n} M_j} \qquad \text{Equation 19}$$

$$M_i = \frac{\sum_{j=1}^{n} \left(V_j . \frac{360}{\alpha_j} \right) . M_j}{\sum_{j=1}^{n} V_j . \left(\frac{360}{\alpha_j} \right)} \qquad \text{Equation 20}$$

Where the variables are defined as:

M_i Averaged Percentage of Small particles in all Samples (0 – 100)

M_j Percentage of Small Particles in Probe Sample (0 – 100)

x_j Distance from heap apex measured on a line parallel to angle of repose

V_j Volume of Sample Probe

V_{tj} Torroid Volume

α_j Angle probe subtends from heap apex

Test No.	Median Diameter Ratio	Prop. of Small (%)	Proportional Distance Down Heap Length / Small Particles in Probe Sample (% Mass) 0	0.225	0.45	0.675	0.9	Measured Average (%)	Mosby [64] Average Eq. 18 (%)	Torroid Subtend Angle Eq. 19 (%)	Torroid Volume Eq. 20 (%)
225	1.4:1	40	53.3	54.3	54.7	56.2	33.8	50	41.7	47.1	47.1
226	1.4:1	40	54.5	53.7	56.5	53.2	32.1	50	40.9	46.0	45.9
233	1.85:1	40	52.1	63.8	73.3	84.4	27.8	60	42.9	57.5	57.5
218	2.36:1	40	69.2	79.0	90.0	89.4	12.4	68	38.2	58.6	58.4
217	2.36:1	40	62.6	74.7	83.0	78.5	5.7	61	36.9	50.9	50.7
219	2.36:1	40	68.3	71.0	80.6	45.3	4.3	54	32.2	40.3	39.9
220	2.36:1	40	66.2	74.9	85.7	41.8	3.7	54	31.9	40.4	40.0
222	2.36:1	40	62.6	73.6	88.2	69.7	4.8	60	36.0	48.9	48.7

Figure 93 Results of Techniques used to Weight Sample Proportions with Respect to their Position down the Heap Surface.

In general any of the weighting techniques shown on Figure 93 produced a weighted averaged overall proportion of small particles value that was more representative of the proportion charged in the original feed mixture.

Discrepancies can be attributed to:

- Possible inhomogeneities of small and large particles around the heap.

- Insufficient sampling probes down the heap length. Introducing more probes may produce a more representative profile towards the heap periphery, which would have had more of an influence on weighting results and hence reducing discrepancies.
- The error bars representing sample deviations on Figure 87 show a greater deviation of results for the 63% and 90% heap length probes in comparison to the others. Samples extracted further down the heap are more influential on weighting the overall averaged proportion of small particles produced. Consequently, great care must be taken in drawing conclusions of the applicability of the three equations when they are assessed using the consistency of the current segregation data available.
- No sampling was undertaken at the edge of the heap and therefore the material in this region had no influence on weighting the overall averaged proportion of small particles produced.

As shown on both Figure 89 and Figure 90, a change in the diameter ratio of the mixture dictated a shift in the pattern of segregation produced. An intermediary diameter ratio was selected in order to verify that this change in pattern of segregation was being influenced solely by the change in diameter ratio of the mixture. It was established previously that only a single sample line was needed to indicate the segregation profile within the heap.

Test No.	223	233	211
Feedrate (g/s)	300	300	300
Median Diameter Ratio (D/d)	1.4:1	1.85:1	2.36:1
Proportion of Small Particles in Feed (%)	40	40	40
Average % of Small Particles in All Probes	56.5	60.3	72.1
% Difference from Initial Feed Proportions	41	51	80

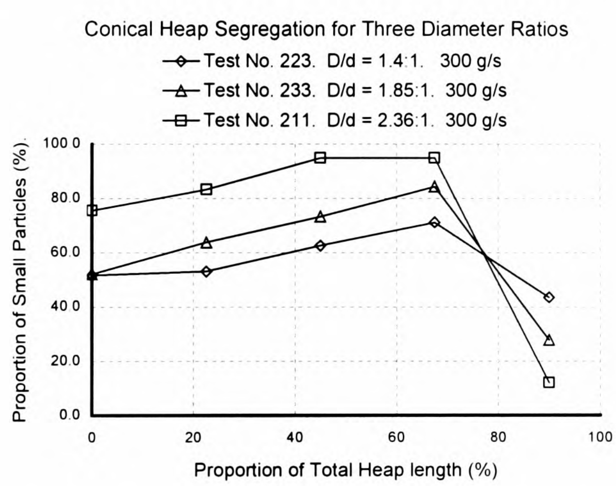


Figure 94 Variation in Conical Heap Segregation for Three Different Median Diameter Ratio Mixtures

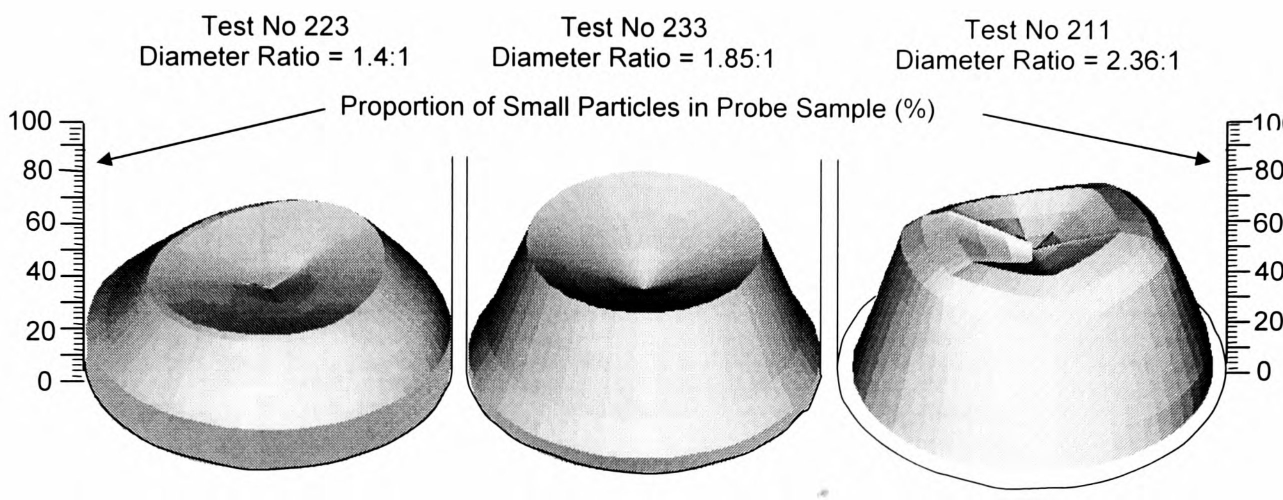


Figure 95 Profiles of Conical Heap Segregation for Three Different Diameter Ratio Binary Sized Mixtures.

Figure 93 and Figure 95 show quite distinctly that a change in diameter ratio altered the radial positions of small particles of the mixture. For the smallest diameter ratio mixture tested (D/d = 1.4:1) mechanisms of heap segregation did not prevent some small particles reaching the vessel wall. In comparison, the largest diameter ratio tested (D/d = 2.36:1) allowed mechanisms of segregation to dictate that no small particles reached the vessel wall. The intermediate test undertaken produced a result of a mixture condition appropriate in profile to fit between the two extremes of particle diameter ratios tested.

9.3 Relating Plane-Flow Segregation to a Conical Heap

It has been reported by several authors that avalanching behaviour associated with conical heap formation is different to that observed when charging a plane flow vessel [64] [36] [65]. Drahun and Bridgwater [36] reported that the most noticeable difference was a general decrease in frequency of avalanching for conical heap segregation compared to plane-flow segregation under identical test conditions.

From the experience gained visualising segregation in both plane-flow and conical heaping environments it was reasonable to expect different segregation profiles for an identical test condition. Different avalanching behaviour and characteristics of heap formation for plane-flow and conical heaps will ultimately contribute to different patterns of segregation. Graphical representation of plane-flow and conical test results for an identical test condition are shown on Figure 96.

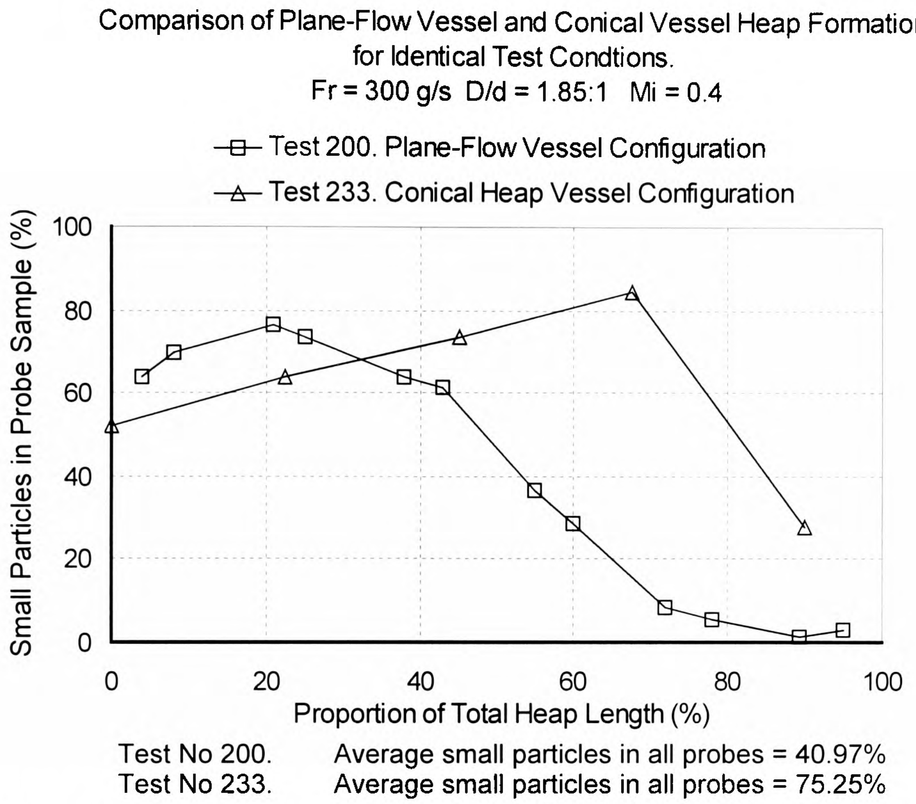


Figure 96 Profiles of Segregation for Plane-Flow Vessel and Conical Heap.

Figure 96 shows a wide disparity between segregation profiles for the two heaping environments subjected to an identical set of test conditions. An avalanche flowing down a plane-flow vessel was confined by the vessel walls and consequently its energy was concentrated solely into a single direction. For a conical heap an avalanche is not constrained and was able to dilate laterally as it descends over the conical heap surface. Subsequently, as the avalanche descends over the heap surface it was confronted with an ever-increasing surface area formed from previously charged segregated material. As stated by Savage and Lun [65] the occurrence of void spaces of sufficient size to permit transfer of particles from one layer to another will increase significantly as an avalanche descends across a conical heap. This is due to dilation of the flow. Consequently, the geometries or heap surface areas in each segregating environment are not comparable. Therefore, a direct comparison of segregation data for plane and conical flow for an identical test condition should produce a more pronounced segregation profile for a conical heap. To this end, Figure 96 shows this to be the case.

In order to derive a predictive technique that will scale the results of a plane-flow vessel to that of a conical heap, emphasis should be placed on analysing the differences in surface area that the avalanche descends across when forming each heap type. Each probe measurement along a conical heap using the sampling technique employed represents a different surface area of the heap. Correspondingly, scaling of the plane-flow vessel probe measurements must be suitably modified. Sample probes furthest from the apex should be scaled a greater distance than those nearest the heap apex in order to compensate for the conical heap surface areas which they represent. In reality the plane-flow sample probe positioned nearest the heap periphery will be scaled further than those positioned nearer the heap apex. A four stage approach was undertaken in an attempt to scale the plane-flow segregation profile to that of the conical heap. A more detailed procedure for scaling can be found in Appendix A.10. The four stages can be summarised as follows:

1. Determine the surface area of the conical heap
2. Determine the Width of a Plane-Flow vessel that has the same surface area and heap length as those calculated in (1)
3. Determine the surface area in a plane-flow vessel from heap apex to probe position under consideration using the original plane-flow vessel length and width determined in (2)
4. Determine new scaled length for conical heap apex to probe position using scaled surface are calculated in (3)

This four stage scaling process can be reduced to the following expression:

$$\text{New scaled probe length on conical heap} = \left[\frac{\sqrt{L_{CH}}\ \sqrt{L_{PF}}}{L_{CH}}\right] \cdot \frac{100}{1} \qquad \text{Equation 21}$$

The variables are defined as:

L_{CH}	Distance from apex to periphery of conical heap or vessel boundary measured along a line parallel to the angle of repose. (m)
L_{PF}	Distance from apex to position of probe in plane-flow vessel measured along a line parallel to the angle of repose. (m)

Simplifying decisions made in the scaling process:

- Flow occurs around and along the whole surface area of the cone when there is material movement.
- The layer descending the cone remains at constant thickness and the scaling technique does not take into account any change in segregation mechanism which occurs as the avalanching layer thins due to depositing particles along the heap surface as it travels.

The predictive technique represented by Equation 21 was used to scale plane-flow vessel segregation profiles to allow comparison with conical vessel profiles for identical test conditions.

Probe No.	Plane-Flow Vessel Probe Distance from Apex (% of total)	Plane-Flow Probe Distance Scaled to Equivalent Position on conical Heap. (%)	Test 165	Test 200	Test 147
			% Small Particles in Probe Sample		
7	4	26.9	63.78	63.85	70.23
1	8	36.9	63.48	69.55	79.49
8	21	61	65.23	76.39	84.97
2	25	65.7	56.68	73.52	85.14
9	38	82	57.20	63.78	66.1
3	43	85.6	51.92	61.16	53.71
10	55	98.6	43.08	36.72	32.99
4	60	101.6	35.43	28.76	18.58
11	72	112.8	23.19	8.32	2.34
5	78	115.4	16.51	5.57	2.50
12	89	125.4	6.23	1.10	1.09
6	95	127.7	3.91	2.90	1.10

Graphical representation of scaling for three different diameter ratios is shown below:

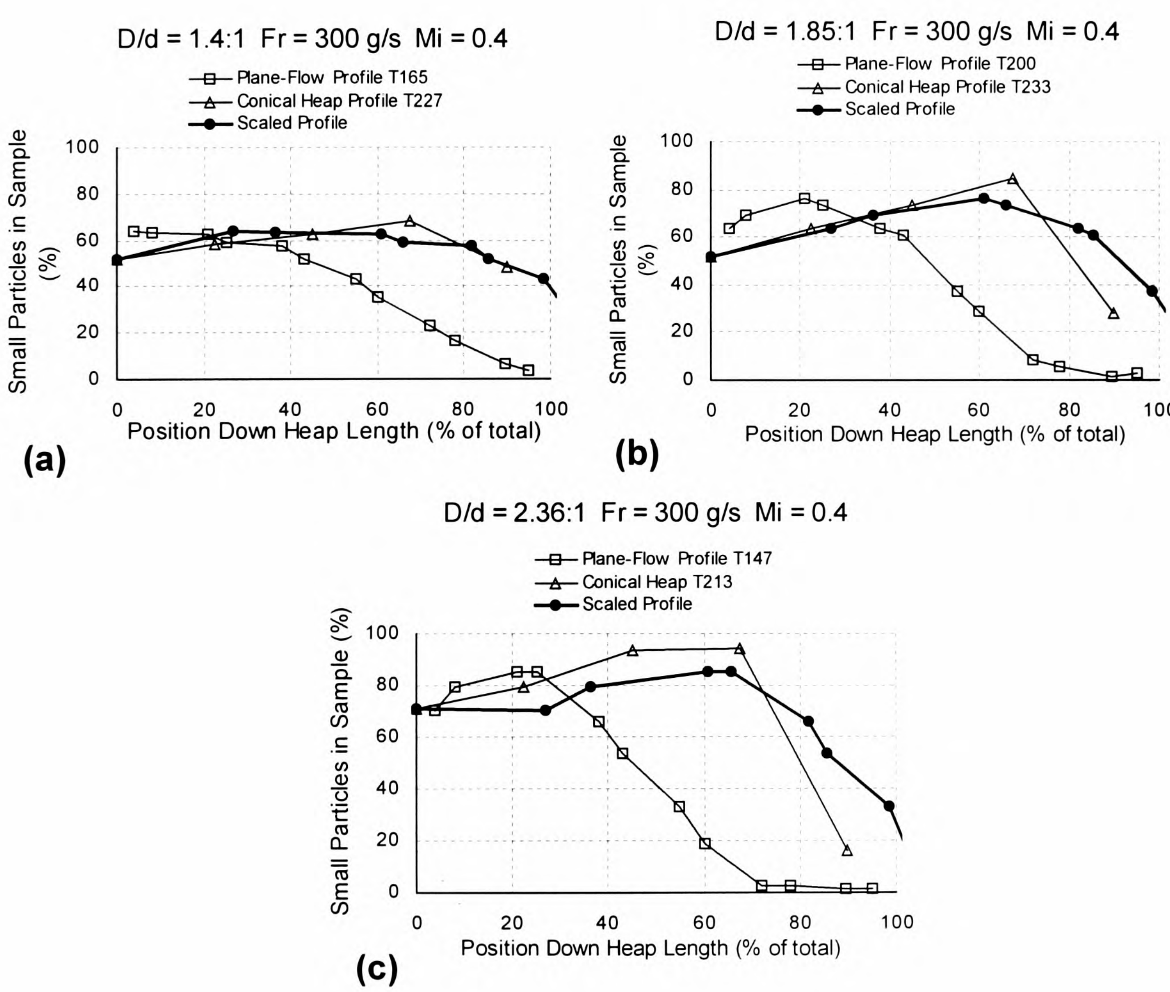


Figure 97 Scaling Plane-Flow Vessel Segregation Profiles to Predict Conical Vessel Segregation Profiles

Figure 97 shows that the method of ensuring equivalence of surface areas in scaling profiles between the two test facilities produces encouraging results. It was clear from analysing Figure 97 that there existed a trend whereby the predictive technique used to scale between both vessel geometries became less accurate when the size difference between size fractions of the mixture was increased. This behaviour could be attributed to the momentum associated with the size difference of the particles. For all conical heaps formed, segregation behaviour of the flowing layer was not constrained by vessel walls and hence influenced by their affects. However, for the plane-flow test rig the segregation behaviour was significantly influenced by the constraining side-walls, Figure 69. For the smallest diameter ratio mixtures, the momentum associated with the large particles was small enough to inhibit any tendency for them to rebound upon contact with the vessel walls. In comparison, the large particles of large size difference mixtures are more likely to rebound back into the centre of the flowing stream and hence travel further down the vessel before stopping at their final resting position. Consequently, samples measured down the plane-flow heap length will contain a greater proportion of large particles. Hence, the plot of small particles in a sample per unit length is uncharacteristically low. When scaling of this profile is attempted the scaled profile of small particle content will also remain lower than the actual conical heap profile produced. Evidence to support this hypothesis can be gained by analysing the predictive segregation profiles on Figure 97(a) and (b) and especially Figure 97(c) where the scaled profile remains below the actual conical heap profile for the majority of the heap length.

9.4 Appraisal of Predictive Technique

To appraise the predictive technique proposed in Section 9.3 required detailed measurements of segregation patterns for plane-flow and conical heaps that were formed under identical particle, process and geometric test conditions. Unfortunately, experimental results that satisfied these requirements were not available in the literature with the exception of Mosby [64]. Mosby provided a detailed data set of two identical test conditions that were repeated for plane-flow vessel and conical heap environments. Leighton Buzzard sand was chosen to represent the large size fraction and primary alumina (used in the production of aluminium) was selected to represent the small size fraction. Particle characteristic information of both materials can be seen below:

	Alumina	Sand
Dynamic Angle of Repose	32°	36°
Static Angle of Repose	34°	37°
Poured Density kg/m^3	1000	1510
Tapped Density kg/m^3	1120	1660
Particle Density kg/m^3	3400	2650

The segregation data sets used to appraise Equation 21 page 196 are listed in the table below.

D_{small} µm	D_{large} µm	D/d	D_{small} feed	Feed (g/s)	Distance down heap length from feed point (%) 1.6	13	24	35	46	57	68	79	90	
90	650	7.2	08 %	260	16	18	14	11	10	6.0	0.4	0.0	0.0	(a)
90	650	7.2	08 %	260	29	32	34	27	18	12	6.5	0.7	0.2	
415	2700	6.5	89 %	209	94.5	93.3	92.3	92.2	91.7	91.5	88.8	87.0	85.4	(b)
415	2700	6.5	85 %	185	91.8	91.1	91.7	90.8	89.1	89.6	89.5	90.2	89.2	

= 2D Plane-Flow Segregation Data = 3D Conical Heap Segregation Data

Plane Flow and Conical Heap Length = 0.63m

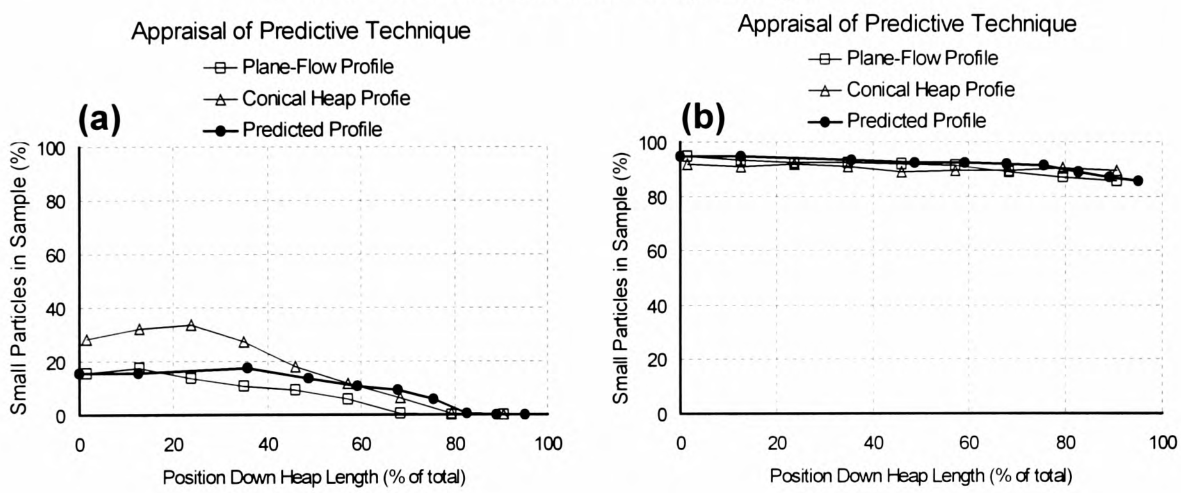


Figure 98 Appraisal of Predictive Model to Segregation data published by Mosby [64].

As shown on Figure 98(a) Equation 21 in its current form was unable to predict the conical heap segregation profile from the plane-flow segregation data to a similar degree of accuracy as that shown in Figure 97. This can be attributed to the particle characteristics of the mixtures tested. The diameter ratio of the mixture for Figure 98(a) was 7.2:1 and 6.5:1 for Figure 98(b). Consequently, both mixtures have a size difference within region that would induce spontaneous percolation affects into the mixture. The segregation results shown in Figure 97 utilised mixtures that did not reside in this area and were therefore subjected to the established mechanisms of segregation that exist within the heaping process, upon which this research into segregation is based. In addition, the mixtures used for the test represented by Figure 98(a) had an absolute mean particle size of approximately 370µm and a small particle size of 90µm. As established in Figure 16, Section 3.7.1.1 the absolute mean particle size and small particle size are within defined regions and induces segregation of the mixture to be influenced by cohesive forces. Investigation into the segregation characteristics of such mixture sizes has not been the subject of this research into segregation. These reasons may have contributed to a two-dimensional plane-flow profile being significantly lower than the correspondingly three-dimensional profile or vice versa. The exact environment for this behaviour has not yet been established.

The mixture formulation that produced the patterns of segregation in Figure 98(b) is indicative of such types where the proportion of small particles in the original feed is high. The dominant mechanism of segregation for such a mixture is the floating-migration mechanism and the pattern of segregation produced suggests that the mixture is relatively insensitive to the difference in segregating environments. Therefore, as there are such small numbers of large particles in the feed mixture their segregation behaviour is insignificant in producing a significant measurable difference in patterns of segregation produced in both a plane-flow and conical vessel environments. Consequently, an appraisal of the predictive power of Equation 21 cannot be determined using the segregation test data that produces patterns of segregation as shown on Figure 98(b). The segregation results used to compare the predictive capabilities of Equation 21 on Figure 97 were identical except for the vessel geometries. The plane-flow and conical vessel had different heap lengths. The plane-flow heap length was 1.0m in length and the conical heap length was 0.6m. Although there was a difference in heap lengths, Equation 21 could still predict profiles of segregation accurately as shown in Figure 97. However, equation 21 was unable to predict the conical heap profile as shown in Figure 98(a), even though the segregation results were for identical data sets that had the same heap lengths of 63cm. This may be attributed to the fact that Equation 21 scales for heap length and does not scale for proportions of small particles in the mixture. Therefore, any profiles with different magnitudes of measured segregation at the heap apex as shown in Figure 98(a) will not scale accurately between plane-flow and conical heaping environments. This suggests that some different behavioural facet was present in the segregating environments used by Mosby that induced different magnitudes of segregation that was not being experienced in the environments used in this investigation. This highlights the sensitivity of the conical heap segregation environment to particle, process and geometric variables and necessitates further investigation of the relationship of these affects on the resulting pattern of segregation produced in both.

A further appraisal of Equation 21 was undertaken using similar segregation data sets that were extracted from similar test conditions undertaken by Mosby [64].

D_{small} µm	D_{large} µm	D/d	D_{small} feed	Feed (g/s)	Distance down heap length from feed point (%) 1.6	13	24	35	46	57	68	79	90	
90	650	7.2	19 %	92	42.6	44.6	36.4	24	16.3	8.2	1.8	0.1	0.0	(a)
90	650	7.2	20 %	260	43.7	48.3	47.8	44.1	40.3	27.5	12.1	1.2	0.3	
90	650	7.2	30 %	95	44.5	54.1	51.8	48.1	43.2	27.5	12.7	5.1	0.7	(b)
90	650	7.2	30 %	260	41.6	46.6	51.5	53.9	52.1	48.7	44.4	26.8	9.5	
1100	2700	2.5	37 %	53	66.5	74.8	71.0	62.5	42.4	19.3	8.2	4.1	0.9	(c)
1100	2700	2.5	40%	640	65.2	68.4	72.7	76.9	78.5	76.3	63.7	36.8	12.7	

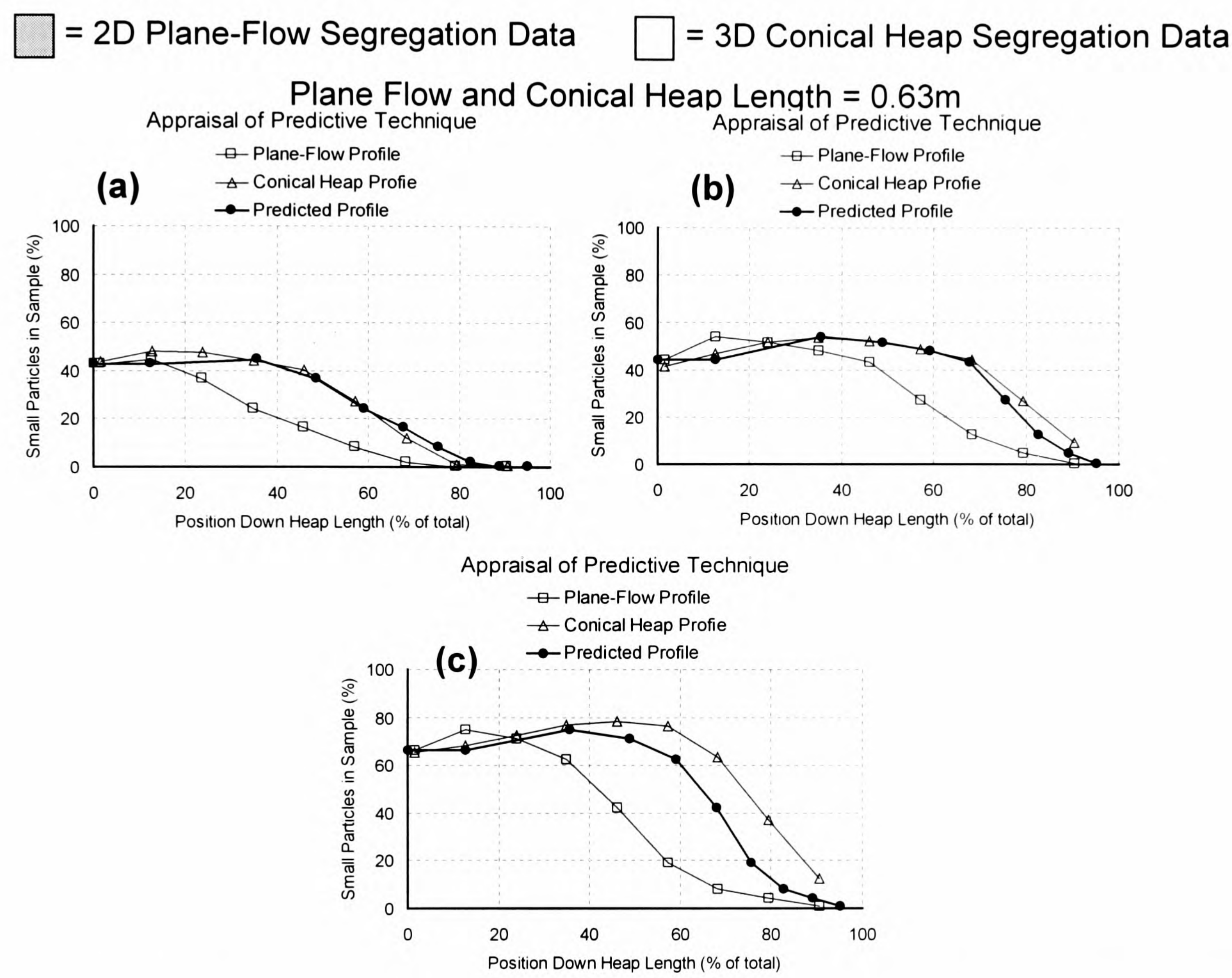


Figure 99 Appraisal of Predicting Segregation Profiles for Plane-Flow and Conical Heap Environments [64]

The segregation results produced in Figure 99 indicate the predictive capabilities of the technique developed. For similar particle and geometric conditions, the model can accurately predict the conical heap segregation profile from plane-flow segregation measurements. It has the potential to predict segregation profiles for the heaping process that segregates particles of the mixture when sieving-percolation is the dominant mechanism of segregation. However, it is apparent that conical patterns of segregation are sensitive to variations in feedrate and, as such, further work into this area is necessary in order to establish the relationship of this and other process, particle and geometric variables.

The derivation of the predictive technique has been based on investigative work using only one material differing in size and also knowing that the sieving-percolation and migration mechanisms would be the dominant mechanisms of segregation. These particle characteristics were then tested within a range of geometric and process variable conditions. Consequently, the predictive techniques wide-ranging applicability to different material segregation scenarios can only be established after undertaking further work that focuses on investigating segregation that resides outside the range of process, geometric and particle variables tested here.

CHAPTER 10

CONCLUSIONS

10 Conclusions

The motivation and original aims for undertaking this research project was previously set out in Section 1.5 of this thesis. These conclusions presented here attempt to address these aims. The conclusions are then developed to suggest a series of proposals for additional work that should be undertaken in order to further the knowledge base of segregation behaviour relating to heap segregation.

The phenomenon of segregation is generally an undesirable outcome of handling free-flowing materials that induce relative movement between particles. It was self evident upon initiating the investigation that anomalies between authors conclusions were apparent in the literature. The review highlighted the lack of a single source of literature available that provided all the necessary information on all aspects associated with heap segregation. However, combining all relevant literature has produced an interlocking web of related information. Although this has provided a unique knowledge base on the interaction of particle, process and geometrical variables, conclusions provided in the literature were often based upon results analysed from patterns of segregation produced in various non-standardised heap segregation environments. This has ultimately resulted in a variety of:

- Diverse literature in terms of area of application
- Limited standardisation of segregation and mixing terminology
- Misinterpretation of segregation patterns when defining mechanisms relating to segregation
- A lack of understanding of the interaction of mixture compositions within certain segregating regimes of flow
- Diverse types of experimental environments being used to quantify segregation for a particular scenario.

A major step in rectifying this problem in terms of standardising segregation terminology has been presented in Chapters 2, and 3. Segregation mechanisms such as percolation and sieving-percolation which are often assumed to be identical in terms of the method of re-ordering particles have been re-classified as separate mechanisms according to the different regime of material flow in which each occurs. The literature review proved a major undertaking in order to standardise, clarify and document these findings and consequently forms a substantial part of the thesis produced. This was deemed necessary, however, in order to understand the global implications of segregation and in an attempt to bridge the gaps between information produced from the multidisciplinary areas of research undertaken. This has been successfully achieved and culminated in the production of a variable flow diagram, Appendix A.1. Re-classifying this mass of non-standardised segregation literature into a clear logical, hierarchical format is considered an original contribution that makes clear to industry the exact ramifications segregation has on different process/handling operations and how best to tackle related problems caused by the phenomenon. By understanding the ramifications to industry for all prevailing conditions a better understanding provided in this thesis has resulted in a more considered opinion on the best means by which to address the problem

Authors who have investigated segregation have often studied size segregation and results indicate that this research is still it its infancy with experimentation generally restricted to 'ideal' binary systems. These binary mixtures are not representative of most bulk solids, which behave differently to such ideal binary systems. Therefore, it has not been possible to tell which of these idealised research efforts should be incorporated into developing a universal predictive technique and which ones should be disregarded. Results of the literature review and testwork undertaken in this investigation clearly indicate that a general predictive model, free of invalid assumptions, is still not available in a form that can be utilised in an industrial application.

A literature review and variable flow diagram of this intensity has contributed to furthering segregation knowledge in the sense that for defined segregating scenarios, particle, process and geometrical characteristics have been identified as ordering themselves into a hierarchy of influential importance. Any one of these characteristics can, in isolation, induce segregation. In terms of interactions, current research is still aimed at a level that scrutinises the interaction between two variables. Conflicting conclusions are reported in the literature reviewed that have attempted to understand these interactions at a two variable level. It has therefore been necessary to instigate research into segregation at this level in order to resolves these anomalies. The full understanding and development of predictive techniques remains unresolved at a two variable interaction level, therefore understanding and resolving cumulative interactions is a difficult undertaking at this moment in time.

The problem of segregation of free-flowing particulate solids when charging storage vessels has been addressed in this research program, mainly from the standpoint of differences in particle size. Clearly, financial and time constraints have limited the scope of work reported here, and there is no doubt that considerable efforts still have to be made before a predictive technique is produced that can universally model segregation patterns produced when charging storage vessels. These efforts would need to focus on extensive further practical work, and also a more theoretical approach, using techniques that can account for the severity of the 'hump' pattern of segregation which has been uniquely recognised and attributed to the embedding mechanism of segregation.

A major undertaking of this programme of work focussed on the observation of a 'hump' profile segregation pattern within the vicinity of the feed point, which is seen as one of the contributions to existing knowledge. This characteristic behaviour was analysed with respect to variations in certain process and particle characteristic variables. The severity of the 'hump' affect was recognised as existing when vertical single point charging of plane-flow vessels was undertaken. This behaviour was successfully removed from patterns of segregation produced in the plane flow testing facility by altering the geometry of the charging feed stream. Recognition and control of this behaviour then allowed the verification of existing proposed heap segregation techniques that could predict patterns of segregation devoid of the 'hump' pattern. Existing relevant model derivations extracted from segregation literature have been formulated without taking into account this characteristic behaviour, however, this behaviour has been shown to significantly alter the pattern of segregation produced in such vessel geometries. Variation of process and particle variables which highlighted trends of segregating behaviour that produced this 'hump' pattern was recognised, however, a more extensive test program is required in order to reappraise current predictive models in their current format.

10.1 Have Project Goals been Successfully Achieved?

It is considered that progress has been made with respect to advancing knowledge into segregation when charging vessels. A more structured approach to defining and standardising segregation terminology relating to vessel filling has been used throughout this thesis that reports the findings of this research. The results of undertaking a 'design of experiments' [72] statistical analysis confirmed the significance of certain process and particle characteristic variables that were generally recognised within segregation literature as being the dominant ones in affecting segregation behaviour when forming a heap.

When investigating segregation behaviour for charging plane-flow storage vessels, plotting the results in terms of dimensionless small particle concentrations Figure 74 and Figure 80 highlight a significant change in segregation behaviour according to mechanism change that occurs according to the segregating mixture structure within the avalanche as it descends along the heap length. The pattern of segregation produced as a function of increasing proportions of small particles in the feed is influenced by the dominating mechanism of segregation, Figure 74 and Figure 80. For mixtures that contain a low proportion of small particles in the feed so that the sieving-percolation mechanism dominates, the patterns of segregation produced are significantly affected by the range of size differences and feedrates tested. This is indicated as scatter of results on Figure 74 and Figure 80 (a)&(b). When the proportion of small particles in the feed is high so that the floating-migration mechanism of large particles dominates, the range of feedrates and size differences are less influential in dictating different patterns of segregation. This is indicated by a lack of scatter of results on Figure 74 and Figure 80 (c)&(d). This behaviour is further emphasised when comparing the patterns of segregation towards the end of the heap lengths on Figure 74 and Figure 80 (c)&(d). A change in mechanism occurs from floating migration to sieving-percolation when the total proportion of the heap length exceeds approximately 0.6. Up to this heap length, there are insufficient large particles present in the avalanching layer to induce the sieving-percolation mechanism, therefore the patterns remain unaffected by the range of feedrates and size differences tested. However, for heap lengths greater than 0.6 the population of large particles has increased to an extent where the sieving-percolation becomes dominant. Consequently, the patterns of segregation beyond this point become more diverse due to the influence of size differences and feedrate variation. Plane-flow vessel segregation's sensitivity of feedrate and size differences according to the dominating mechanism instigating segregation and the resulting pattern of segregation produced is considered an original contribution to knowledge that has not been presented in such a format before.

In terms of furthering knowledge of mechanisms within the process of heap segregation, this program of work served to formulate a coherent descriptive hypothesis on the heaping process, as documented in Section 6.4. A proposed mechanism of embedding has been postulated as a result of investigative work undertaken on the interaction of the charging feed mixture upon contact with the surface of the static heap surface formed. The descriptive process of heaping has explained the path of an avalanche from apex to periphery where continual re-ordering and depositing of contents of the avalanching layer induces changes in priority of various mechanisms of segregation. In addition, this work complements the theoretical and experimental findings proposed by Alonso et al. [59]. The author illustrated the possible change in direction that a particle can experience when segregating within an avalanche as a function of critical combinations of particle and process characteristics. Alonso et al. [59] highlighted the type of segregation mechanism a large particle is subjected to according to the proportions of large and small particles in the mixture. This was further verified by the results produced in Figure 74. The segregation hypothesis proposed by Alonso et al. [59] has been identified as being attributable to changes in segregation mechanism within the heaping process. Figure 64 indicates these changes in segregation mechanism and has been superimposed on the observed behaviour proposed by Alonso. This is seen as a contribution to segregation knowledge that complements the work undertaken by Alonso et al.. Their technique quantifies the propensity of a mixture to segregate based on particle and process characteristics that can be measured using standard industrial procedures. This technique was also successfully verified by cross-referencing the technique with patterns of segregation produced in other relevant literature. Classification and description of segregation mechanisms that change priority within the heaping process has not been established before and as such predictive models developed to date do not compensate for changes in mechanism that occur throughout the heap filling cycle.

Although segregation strongly depends on externally applied regimes of flow, the relative tendency of powders to segregate has proved to be an inherent property that largely depends on particle size distribution and the surrounding affinity of their components. A goal of this research has been to form simple usable models or techniques to determine the propensity to which a material will segregate in an industrial application from undertaking laboratory scaled investigations. The majority of industrial applications involve the formation of three-dimensional piles, usually in the form of conical heaps. The state of predictive segregation model development when this research was instigated revealed that it was not possible to predict, with any certainty or accuracy, conical heap segregation. This was because the majority of modelling techniques developed were based on assumptions drawn from analysing plane-flow vessel experiments. Research that has developed predictive techniques designed to predict segregation in conical heaps is relatively non-existent. It is clear from undertaking this program of work that profiles of segregation produced in plane-flow vessels are very different in comparison to conical heaps formed under identical test conditions. Consequently, a procedure has been developed which can predict the segregation in a conical vessel environment from results produced in a plane-flow vessel environment. This technique gives quantitative results of an accuracy that is of real practical and economic value and is considered an original and valuable step towards the understanding of the heap segregation process. This suggests a way forward in that it might be possible to undertake initial investigative work in small plane-flow models and be able to predict the behaviour in real conical heaps.

The conical heap predictive technique has been derived based on investigative work that utilised one material differing only in size where the sieving-percolation and migration mechanisms were known to be the dominant mechanisms of segregation. The techniques wide-ranging applicability to different material segregation scenarios can only be established after undertaking further investigative work in areas such as:

- Deliberately promoting or activating different mechanisms of segregation during heap formation.
- Utilising test materials that have differing particle characteristics other than size.
- Formation of heaps in alternative geometric vessel designs using different geometry and process fill conditions.
- Increasing the range of process and geometric variables that have been tested in this programme of work.

10.2 Recommendations for Further Work

The programme of work undertaken for investigating plane-flow vessel segregation revealed the influence the vessel walls had in dictating a velocity profile across the leading edge of the avalanching layer. In terms of results produced in the plane-flow test facility, quantification of the influence of the front (clear acrylic) and back (aluminium) walls remains unknown. Further work is needed to assess the role that these containing walls play in influencing the difference in segregation profiles produced for plane-flow and conical vessel environments. Avalanching during the heaping process has been visually observed to be inhibited in terms of its natural tendency to dilate as it progressed from apex to periphery. Undertaking a series of investigations, where the distance between walls of a plane flow vessel could be varied or allowed to diverge along the heap length would reveal the significance of the vessel walls in influencing the pattern of segregation produced.

There is a requirement to undertake a more substantial investigation into the behaviour between the vertical charging feed and its interaction with the heap surface at the apex that induces the severity of the 'hump' pattern of segregation produced. More detailed information and understanding on the influence of particle, process and geometric variables will permit a more productive attempt at re-appraising existing predictive techniques that currently do not accommodate this behaviour or the development of new predictive models.

The testwork undertaken for the conical heap segregation programme of work revealed that the predictive technique developed to transpose two-dimensional tests results into three-dimensional heap segregation profiles may be a viable approach to predicting conical heap segregation profiles. To further validate this there is a need to expand and investigate the various processes and material characteristic variables that are known to influence segregation in order to obtain more corroborative evidence of the predictive ability of the proposed scaling technique. The anomaly of measuring more small particles in the samples obtained from the heap that does not relate to the proportions fed into the heap have been successfully overcome by the technique employed to weight the significance of the three dimensional probe samples according to the part of the conical heap that they represent.

Confidence in the ability of the device used to sample three-dimensional heap segregation was best illustrated by the insignificant angular variation in measured segregation profiles produced, Figure 89 and Figure 90. The technique used provided satisfactory results, however, further work is required into investigating the significance of disturbing the heap formed when inserting the sampling device into the heap. There may be a significant disturbance induced into the material when sampling that causes the samples contents, when analysed, to yield a misinterpretation of the actual segregation occurring in the heap.

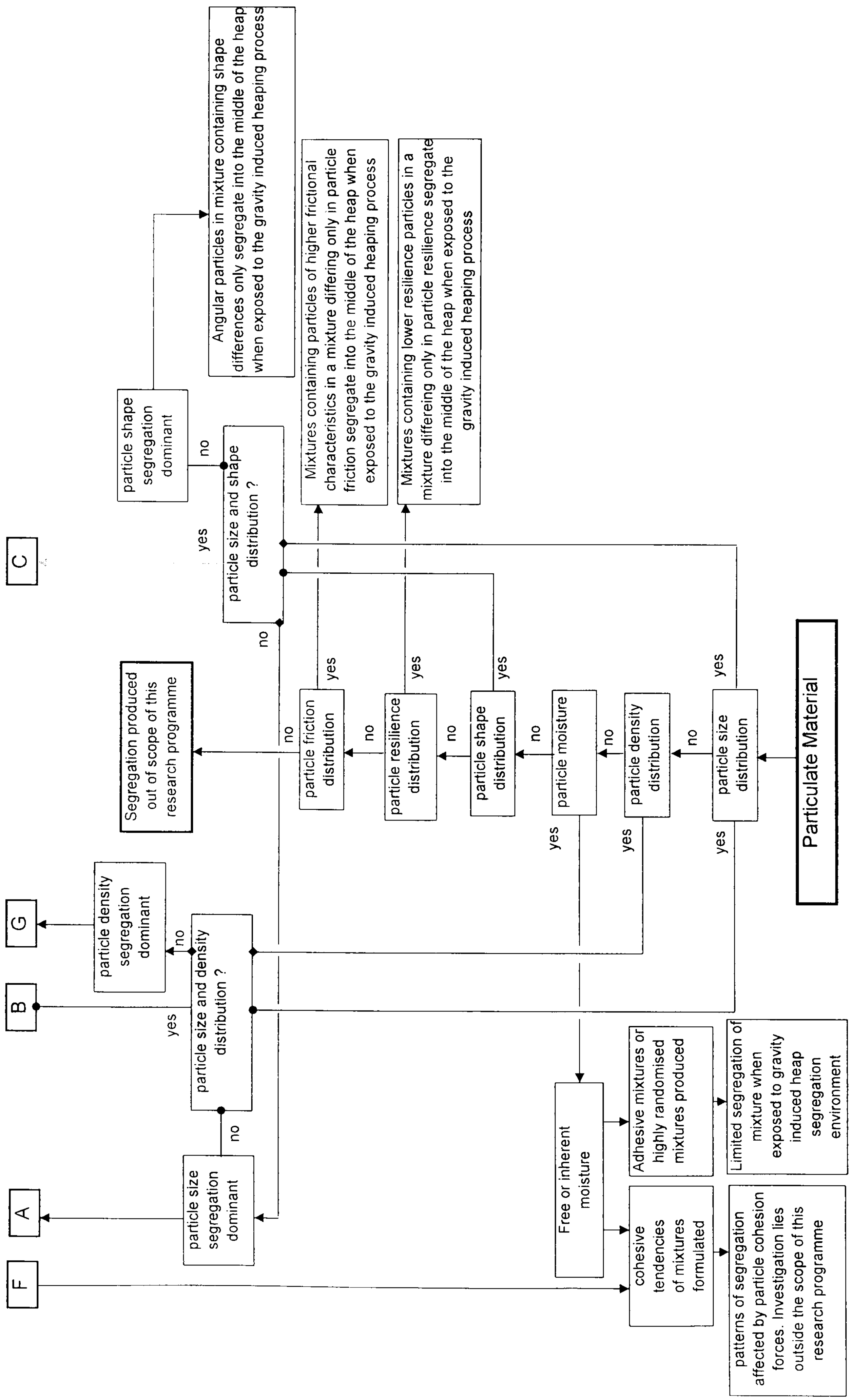
The ratio of inlet feed pipe diameter to vessel diameter is relatively small for the laboratory scale investigation undertaken that produces the 'hump' pattern of segregation. Further work is required to establish whether an increase in this ratio will induce a reduction in the influence of the 'hump' pattern on the overall pattern of segregation produced.

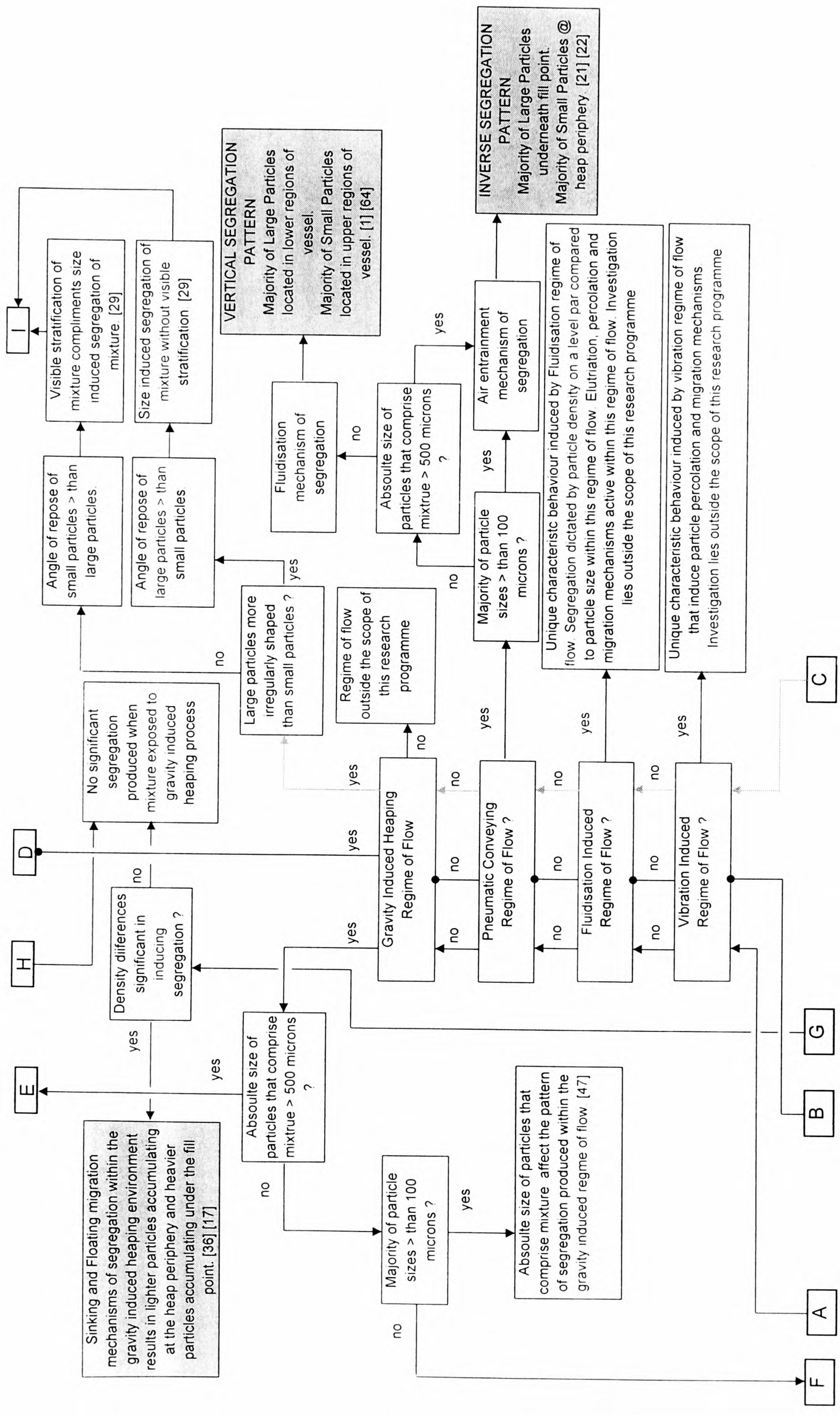
Both mathematical and empirical modelling undertaken can be generally categorised into those that mechanistically model the heaping process according to one or two mechanisms of segregation or empirical models that use mathematical forms in conjunction with segregation constants to fit predicted segregation profiles to experimentally quantified patterns of segregation. A current method of predicting segregation that compensates for all mechanisms of segregation identified as having a significant role to play within the definition of the heaping process does not exist. Undertaking predictive model development that incorporates all recognised influences and interactions remains the ultimate objective and modelling attempts that can accommodate as many mechanisms of segregation as possible remains the goal of any future work undertaken.

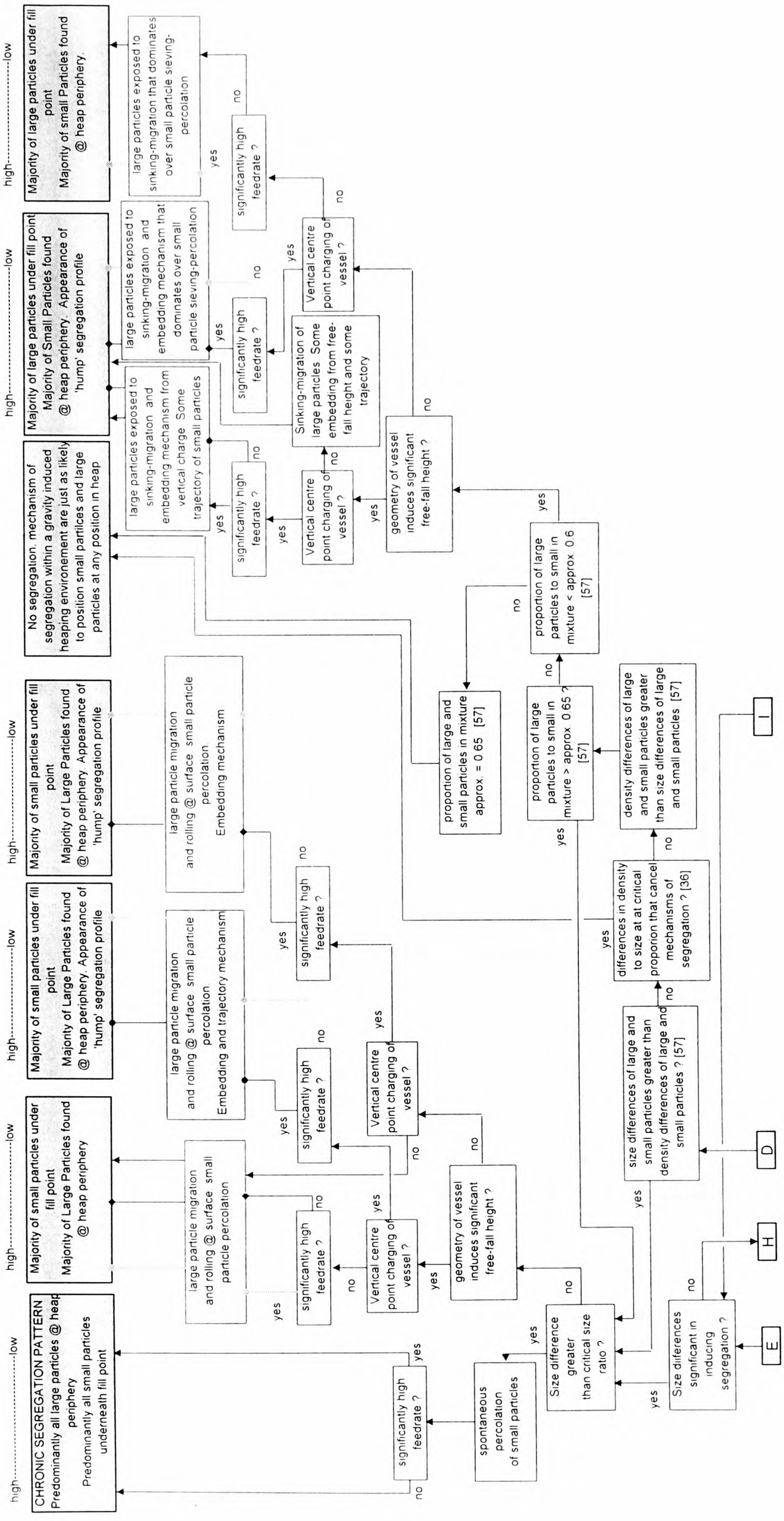
APPENDICES

APPENDIX A.1

VARIABLE FLOW DIAGRAM


Particulate Material
particle size distribution
particle density distribution
particle moisture
particle shape distribution
particle resilience distribution
particle friction distribution
yes
no
Segregation produced out of scope of this research programme
particle size and shape distribution ?
particle shape segregation dominant
Angular particles in mixture containing shape differences only segregate into the middle of the heap when exposed to the gravity induced heaping process
Mixtures containing particles of higher frictional characteristics in a mixture differing only in particle friction segregate into the middle of the heap when exposed to the gravity induced heaping process
Mixtures containing lower resilience particles in a mixture differeing only in particle resilience segregate into the middle of the heap when exposed to the gravity induced heaping process
C
particle size and density distribution ?
particle density segregation dominant
G
B
particle size segregation dominant
A
F
Free or inherent moisture
Adhesive mixtures or highly randomised mixtures produced
Limited segregation of mixture when exposed to gravity induced heap segregation environment
cohesive tendencies of mixtures formulated
patterns of segregation affected by particle cohesion forces. Investigation lies outside the scope of this research programme


VERTICAL SEGREGATION PATTERN Majority of Large Particles located in lower regions of vessel. Majority of Small Particles located in upper regions of vessel. [1] [64]
INVERSE SEGREGATION PATTERN Majority of Large Particles underneath fill point. Majority of Small Particles @ heap periphery. [21] [22]
Visible stratification of mixture compliments size induced segregation of mixture [29]
Size induced segregation of mixture without visible stratification [29]
Angle of repose of small particles > than large particles.
Angle of repose of large particles > than small particles
Large particles more irregularly shaped than small particles ?
Fluidisation mechanism of segregation
Absoulte size of particles that comprise mixtrue > 500 microns ?
Air entrainment mechanism of segregation
Majority of particle sizes > than 100 microns ?
Regime of flow outside the scope of this research programme
Unique characteristc behaviour induced by Fluidisation regime of flow. Segregation dictated by particle density on a level par compared to particle size within this regime of flow. Elutriation, percolation and migration mechanisms active within this regime of flow. Investigation lies outside the scope of this research programme
Unique characteristic behaviour induced by vibration regime of flow that induce particle percolation and migration mechanisms. Investigation lies outside the scope of this research programme
No significant segregation produced when mixture exposed to gravity induced heaping process
Gravity Induced Heaping Regime of Flow
Pneumatic Conveying Regime of Flow ?
Fludisation Induced Regime of Flow ?
Vibration Induced Regime of Flow ?
Density differences significant in inducing segregation ?
Absoulte size of particles that comprise mixtrue > 500 microns ?
Sinking and Floating migration mechanisms of segregation within the gravity induced heaping environment results in lighter particles accumulating at the heap periphery and heavier particles accumulating under the fill point. [36] [17]
Majority of particle sizes > than 100 microns ?
Absoulte size of particles that comprise mixture affect the pattern of segregation produced within the gravity induced regme of flow [47]
yes
no
A
B
C
D
E
F
G
H
I


CHRONIC SEGREGATION PATTERN Predominantly all large particles @ heap periphery Predominantly all small particles underneath fill point
Majority of small particles under fill point Majority of Large Particles found @ heap periphery
Majority of small particles under fill point Majority of Large Particles found @ heap periphery. Appearance of 'hump' segregation profile
Majority of small particles under fill point Majority of Large Particles found @ heap periphery. Appearance of 'hump' segregation profile
No segregation, mechanism of segregation within a gravity induced heaping environement are just as likely to position small particles and large particles at any position in heap
Majority of large particles under fill point Majority of Small Particles found @ heap periphery. Appearance of 'hump' segregation profile
Majority of large particles under fill point Majority of small Particles found @ heap periphery.
high--------------low
large particle migration and rolling @ surface small particle percolation
large particle migration and rolling @ surface small particle percolation Embedding and trajectory mechanism
large particle migration and rolling @ surface small particle percolation Embedding mechanism
large particles exposed to sinking-migration and embedding mechanism from vertical charge Some trajectory of small particles
large particles exposed to sinking-migration and embedding mechanism that dominates over small particle sieving-percolation
large particles exposed to sinking-migration that dominates over small particle sieving-percolation
Sinking-migration of large particles Some embedding from free-fall height and some trajectory
significantly high feedrate ?
Vertical centre point charging of vessel ?
geometry of vessel induces significant free-fall height ?
spontaneous percolation of small particles
Size difference greater than critical size ratio ?
Size differences significant in inducing segregation ?
size differences of large and small particles greater than density differences of large and small particles ? [57]
differences in density to size at at critical proporion that cancel mechanisms of segregation ? [36]
density differences of large and small particles greater than size differences of large and small particles [57]
proportion of large and small particles in mixture approx. = 0 65 [57]
proportion of large particles to small in mixture > approx 0 65 ? [57]
proportion of large particles to small in mixture < approx 0 6 [57]
yes
no
E
H
D
I

APPENDIX A.2

PARTICLE PACKING STRUCTURES

A.2.1. Particle Packing Structures

When considering a particulate material of uniform sphere size, it is theoretically possible for it to form one of several different packing structures. Fiske [18] provided examples of these that include the simple cubic, orthorhombic, tetragonal-sphenoidal and rhombohedral type which have been shown to have theoretical maximum packing fractions of 0.534, 0.605, 0.698 and 0.741 respectively.

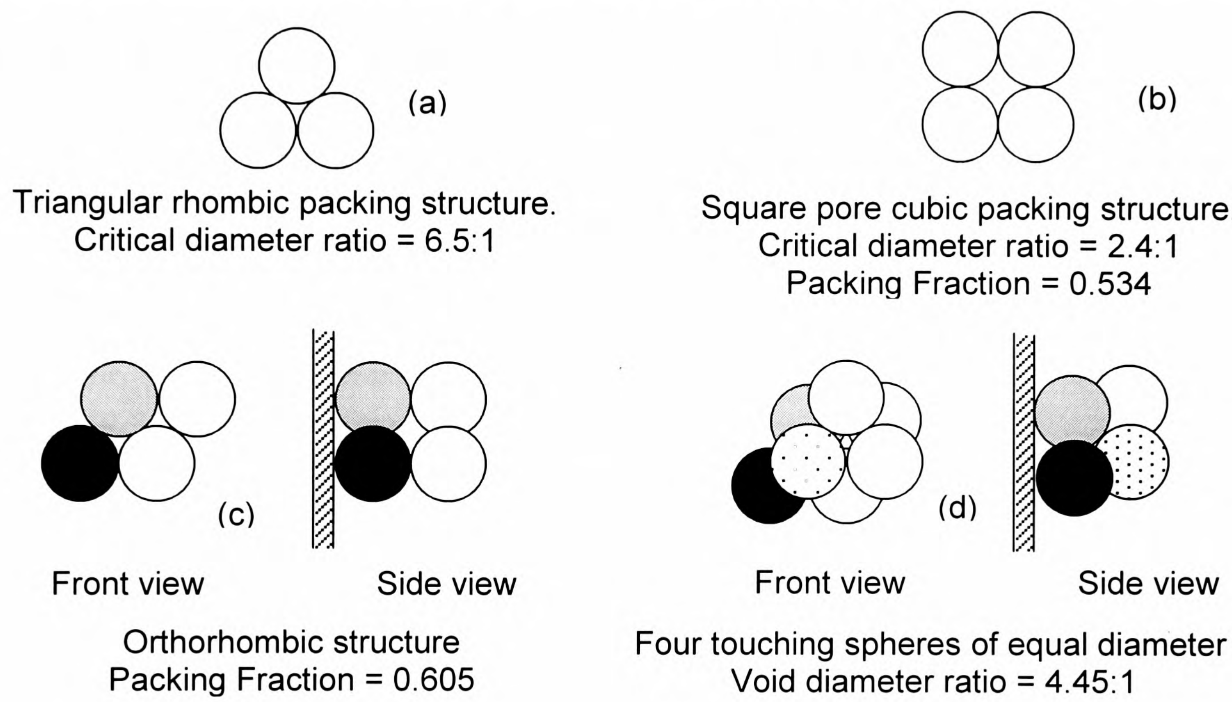


Figure A.2.1. Packing Arrangements and Critical Diameter Ratios that Indicate the Size of Particle that Fits Within Voidage Created by Packing Structure. [18] [60]

The term 'packing fraction' is used to quantify the degree of packing of the material bed and is defined as the ratio of the volume of solids to the total bed volume (solids and voids). Experimentally it has generally been observed that a mixture of uniform spheres has a numerical packing fraction value of approximately 0.62 thus indicating that in general an orthorhombic structure predominates. Consequently, the critical diameter ratio that permitted spontaneous percolation of particles for this structure type could be used to limit the size ratios required for a complete investigation into size segregation. However, the instability of the orthorhombic structure in this particular segregating environment necessitated the determination of critical diameter ratios for other packing arrangements that induced spontaneous segregation. As can be seen from Figure A.2.1., the critical diameter ratio that could instigate spontaneous percolation varied widely according to the type of packing structure formed. The void diameter ratio as shown in Figure A.2.1.(d) refers to the size of particle that can fit within the voidage created by four touching spheres of equal diameter. This is not the critical spontaneous percolation diameter ratio, as a particle that fits within this voidage is bounded by the touching larger particles. Therefore, the critical diameter ratio that induces spontaneous percolation for this particular arrangement will be greater than the void diameter ratio. During the heaping process, it is reasonable to assume that the packing structure of the segregating material will exhibit some or all of the above structural patterns at some point in its journey down across the heap surface. Therefore, it would be inadvisable to use only the critical diameter ratio for an orthorhombic packing structure as the limiting diameter ratio of test material sizes required to be used in any proposed segregation investigation.

The proportion of small to large particles was found to greatly influence the type of packing structure of the material bed. Fiske [18] provided documented graphical evidence from a number of authors who published literature pertaining to the relationship that packing structure had when mixture proportions varied with sizes of particles of the mixture. For a mixture that predominately consists of either all large or all small particles, the packing structure remains unaffected by the presence of small quantities of particles of other sizes. Consequently, the packing fraction of such a mixture remains indicative of a uniform sized mixture at approximately 0.62. However, the increase in proportion of one size of the mixture greatly influences the structure type and maximum achievable packing density of the bed. Information on the influence of varying proportions of sizes of a mixture and the relative difference that particle size has on the resulting packing fraction has been provided theoretically by Fiske [18]. This was further complemented by the experimental work published by Arteaga and Tüzün [60].

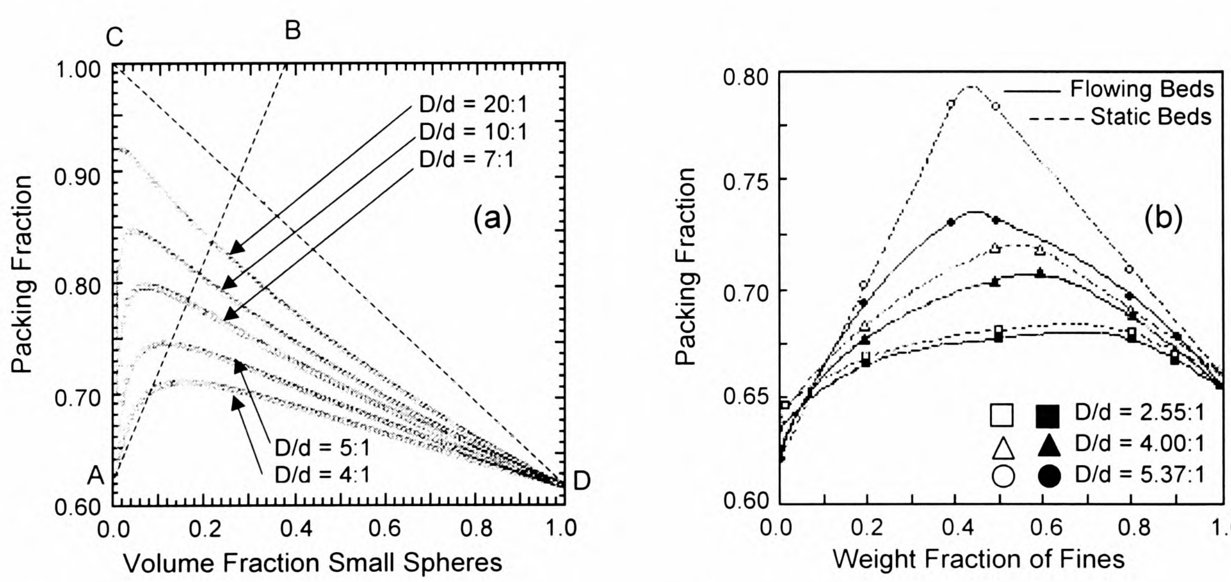
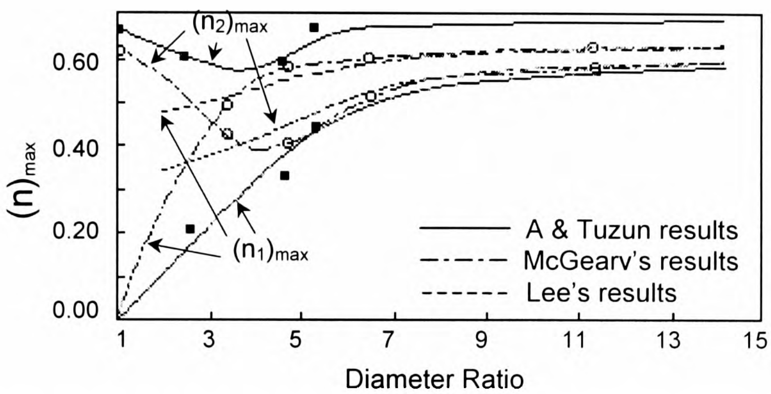


Figure A.2.2. (a) Predicted Packing Curves for Various Diameter Ratio Mixtures and Limits of Packing Structure. [18] (b) Experimental Packing Structure for Static and Flowing Material Beds. [60]

For a single sized material, the theoretical and experimental packing fractions yield a value of approximately 0.62 thus indicating an orthorhombic form of packing structure. The limiting regions, as indicated by lines A-B and C-D on Figure A.2.2(a) indicate the limiting envelope of possible packing fractions for a binary sized mixture:

- Line A-B represents the packing fraction behaviour when adding small particles to a bed of larger particles. Here the small particles are able to completely embed in the interstitial space between the larger spheres and as a direct result increase the packing fraction of the bed. A packing fraction that fits closely to this line can be defined as a predominately large particle packing fraction structure.
- Line C-D represents the packing fraction behaviour when adding large particles to a quantity of infinitely small particles. Here the large particles completely immerse themselves within the small particle structure. A packing fraction that fits closely to this line can be defined as a predominately small particle packing fraction structure.

Within these two boundary limits shown on Figure A.2.2.(a) are packing curves for various diameter ratio mixtures. It seems that for low concentrations of small spheres and high diameter ratios, the theoretical predictions are less representative when compared with the limiting boundary conditions. However, the behaviour of the predicted packing fractions for different diameter ratios compare favourably to experimental ones provided by Arteaga and Tüzün [60]. For the experimental results shown in Figure A.2.2.(b) low concentrations of small particles in the mixture did not prevent a larger particle lattice being formed. The voids are filled with small particles until a point of saturation is reached at a maximum bulk density or packing fraction. After this point the material is considered a continuous matrix of small particles where the large particles cannot fit into the voidage created so reside individually in the mixture surrounded by small particles. Consequently, the bulk density or packing fraction reduces. In addition to this behaviour induced by constituent proportions, Arteaga and Tüzün [60] also provided evidence that the shape as well as the size of voidage created within a matrix of large particles dictated the packing fraction formed. This in turn affected the ability of smaller particles to spontaneously percolate through a large particle lattice structure. For particle structures formed like those shown in Figure A.2.1., the size of the voidage might be similar in allowing a small particle to pass. However, the difference in projected area through which the smaller particle can pass may prevent it from doing so. To illustrate this point requires analysis of Figure A.2.3. that compares the authors findings with other documented literature on the subject area.



Where

$(n)_{max}$ = Maximum packing density of mixture.
n_1 = Number of large particles in mixture.
n_2 = Number of small particles in mixture.
n_1 (max) = Number of small particles packed into interstices of large particle lattice at maximum packing fraction.
n_2 (max) = Number of large particles in mixture at maximum packing fraction.

Figure A.2.3. Variation of Fractional Solids Content of Large and Small Particle Lattice Structure in Binary Mixtures at Maximum Packing Fraction with Diameter Ratio. [60]

The size of large particles of the binary mixture remains constant. To increase the diameter ratio of the mixture the small particles are reduced in size. For a proportion of small particles commensurate with inducing the maximum packing density (top of curves on Figure A.2.2.(b)), the small particle content within the interstices created by the large particle matrix at first appears to reduce as the diameter ratio of the mixture increases, line (n_2) max on Figure A.2.3.. This continues until a diameter ratio of approximately 3.5:1 is reached. Beyond this the amount of small particles contained within the interstices at maximum packing fraction increases in behaviour akin to an asymptotic relationship. Arteaga and Tüzün attribute this behaviour to the geometry as well as the size for different diameter ratio mixtures. For diameter ratios less than 4:1 the void filling process by the fine particles is inevitably affected by the void geometry and hence the spontaneous percolation mechanism of segregation of such a mixture is pore-geometry limiting. At diameter ratios greater than 4:1, the geometry of the void spaces is no longer critical in the void filling process. This is correspondingly reflected by the increased packing density of the small particles in the void spaces created by the matrix of large particles. Therefore as well as the packing structure dictating the critical spontaneous percolation diameter ratio, the relative size difference between particles that form a structure dictates a voidage geometry which can significantly influence this critical value. Therefore, when dealing with binary mixtures of size ratios less than 4:1 the shape as well as the size of the interstitial pore spaces should be considered.

Arteaga and Tüzün [60] also provided evidence of the difference in packing fractions for static and flowing particulate material structures. This was attributed to bed expansion during material movement that resulted in dilation of flow. The extent of this dilation as shown on Figure A.2.2. (b) was seen to be influenced by the diameter ratio of the mixture. The larger the diameter ratio of the mixture the greater the dissimilarity between static and flowing packing fractions. The maximum packing fraction value shifts to higher small particle fractions for mixtures with decreasing diameter ratio, which is comparable with the predicted maximum packing fractions, postulated on Figure A.2.2.(a).

APPENDIX A.3

ASSESSING STATIC MIXER PERFORMANCE

A.3.1. ASSESSING STATIC MIXER PERFORMANCE

A suitable mixer for inclusion in a proposed segregation test facility was required to meet a stringent set of criteria:

- The mixer was required to mix particles of different sizes to a similar quality of mixedness.
- There should be a proviso for the mixer to have an inherent flexibility to mix to an acceptable standard, free-flowing particulate materials that differ in other particle characteristics other than size.
- The mixer should not degrade the particles of a pre-selected size thus altering their size grading.
- A mixer should be of relatively low initial investment and have minimal operating costs.
- The mixer should achieve mixing to a required scale and scrutiny of segregation necessary for an investigation into heap segregation of this scale.
- The mixing process should be relatively instantaneous and consistent.
- The mixer should discharge a consistent quality of mixture as a continuous feed that is homogeneously radial in concentration.

In general, mixers can be categorised as those that are either static or dynamic. Dynamic mixing equipment can be broadly classified according to the mechanism of mixing that instigates the mixing of its contents i.e. diffusive, shear and convection as previously described in Section 2.2. The inherent disadvantage of dynamic mixers, which are often batch mixers, is the unknown deterioration of mixture quality during transition between mixer and intended use. The mixture quality cannot be guaranteed as a function of this transition period. Furthermore, a behavioural characteristic indicative of all these mixers is the variation in mixture quality as a function of mixing time. This is an undesirable complication for inclusion into an investigation into segregation and thus, dynamic mixers were not considered a satisfactory means of mixing materials for use in a segregation test facility. Consequently, a feasibility study into the applicability of a static mixer for mixing materials that have a propensity to segregate was conducted.

One criterion for the mixer's applicability was a requirement to discharge a consistent quality of mixture as a continuous feed that was homogeneously radial in concentration. This was necessary as this mixed material was to be used as a central point feed to a segregating heap. This homogeneity is essential, as any feed delivered to a conical heap will produce consistent non-preferential segregation down all the surface area of the heap as it is being built. It was therefore necessary to measure the radial mixedness of the discharging mixture and axial mixing performance. A subsequent two-stage mixing program was conducted in order to measure radial and axial mixture quality as a function of varying process conditions.

Ultimately an investigation into segregation during heap formation involved quantifying heap segregation with the knowledge that a guaranteed quality of mixture was consistently being discharged from the mixer.

Literature that documents investigations into the performance of static mixers has mostly been concerned with axial mixing performance, whereas investigations into radial mixing have received comparatively little attention. This may be attributed to practical situations in process plant that utilise static mixers which are more sensitive to axial deviations in mixture quality occurring rather than radial variations. However, conclusions drawn from axial investigations can be qualitatively compared to radial mixing due to their identical mechanisms of mixing. Although the dominant travel of the mixture is vertical, the process of static mixing is a volume process that occurs radially as well as axially. Favourable claims made in this literature as to the suitability of static mixers for axial mixing was used as corroborative evidence to justify the undertaking of a feasibility study into the appropriate radial mixing applicability of a static mixer.

A static mixer, the design of which is shown in Figure 52 was selected for investigation. In essence the number and spatial geometry between successive mixing elements is a predetermined design aspect of a static mixer and is unique to the particles characteristics of the mixture constituents required to be mixed. However, process and particle characteristics are to be altered throughout an investigation into segregation, therefore it is imperative that the mixer does not suffer any significant reduction in mixing performance as a result of these changes. In order to measure both radial and axial mixing performance two sample-extraction devices were designed and utilised in order to sample and measure the mixture produced. A device by which the mixed discharging stream from the mixer could be analysed with minimal disturbance to the physical state of the mixture was developed for both axial and radial investigations.

The experimental apparatus used to investigate both radial and axial mixing performance was similar. Variations concerned the method used to extract and analyse the mixture being discharged from the mixer. Before investigating radial or axial mixing it was immediately obvious that two apparatus affects could induce a misrepresentation of any mixing performance measured. Firstly, inconsistent feeding when initially starting the gravimetric vibratory feeders caused initial feed proportions to differ from pre-determined set values. A bottom fill pipe was therefore designed and connected to the base of the sampling device in order to contain this initial material and prevent it from being used in any subsequent analysis. Secondly, the geometry of the final element in the static mixer imposed a directional trajectory to the flowing mixture stream resulting in preferential radial flow discharging from the mixer. A pre-requisite of the mixers applicability stated that it should provide a homogeneously mixed discharging stream across the whole cross-section of the mixer outlet. This therefore prompted the inclusion of a flow diffusive section that was designed and attached to the base of the static mixer. This section helped to counteract any directional affects resulting from the geometry of the last mixing element and provide a discharging stream commensurate to the required specifications. However, any conclusions or assumptions made on the performance of the static mixer will have incorporated contributions made by the influence the discharged mixture undergoes as it passes through the flow centring diffusive section.

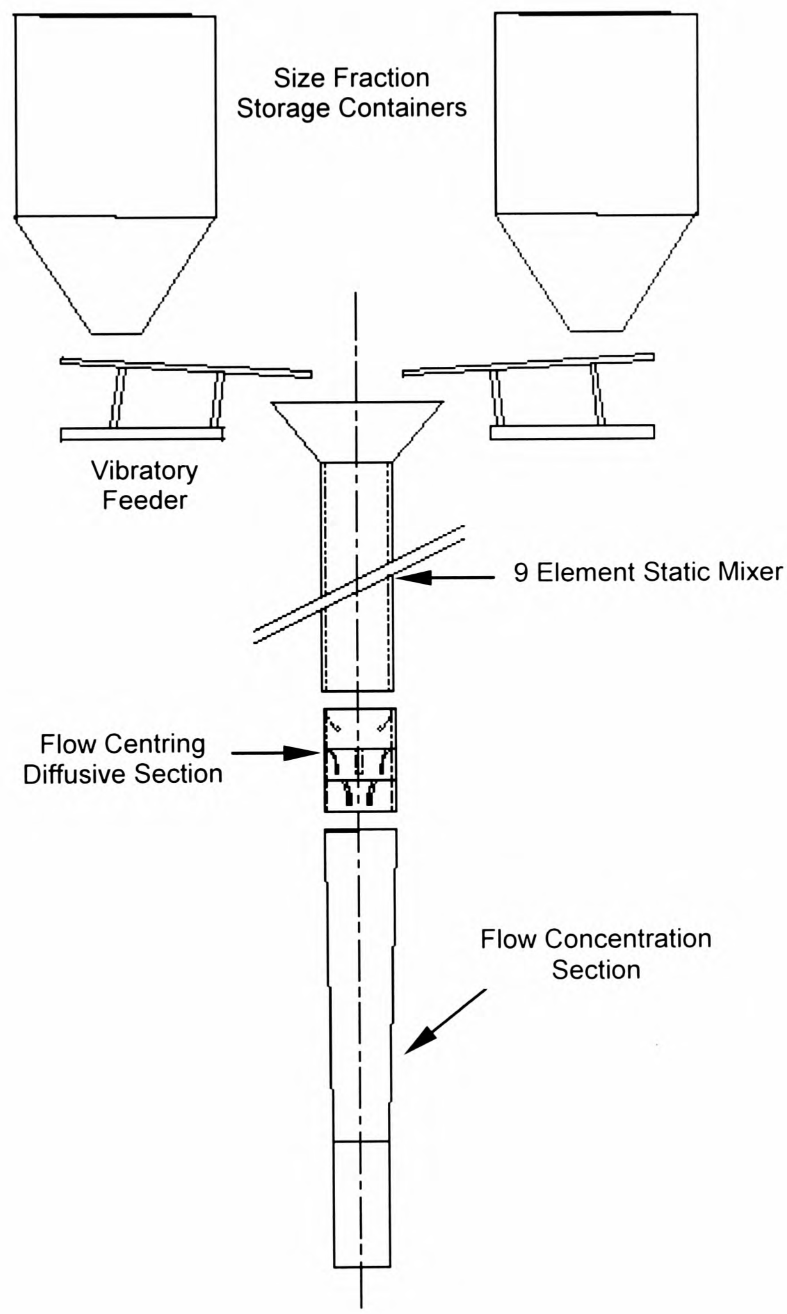
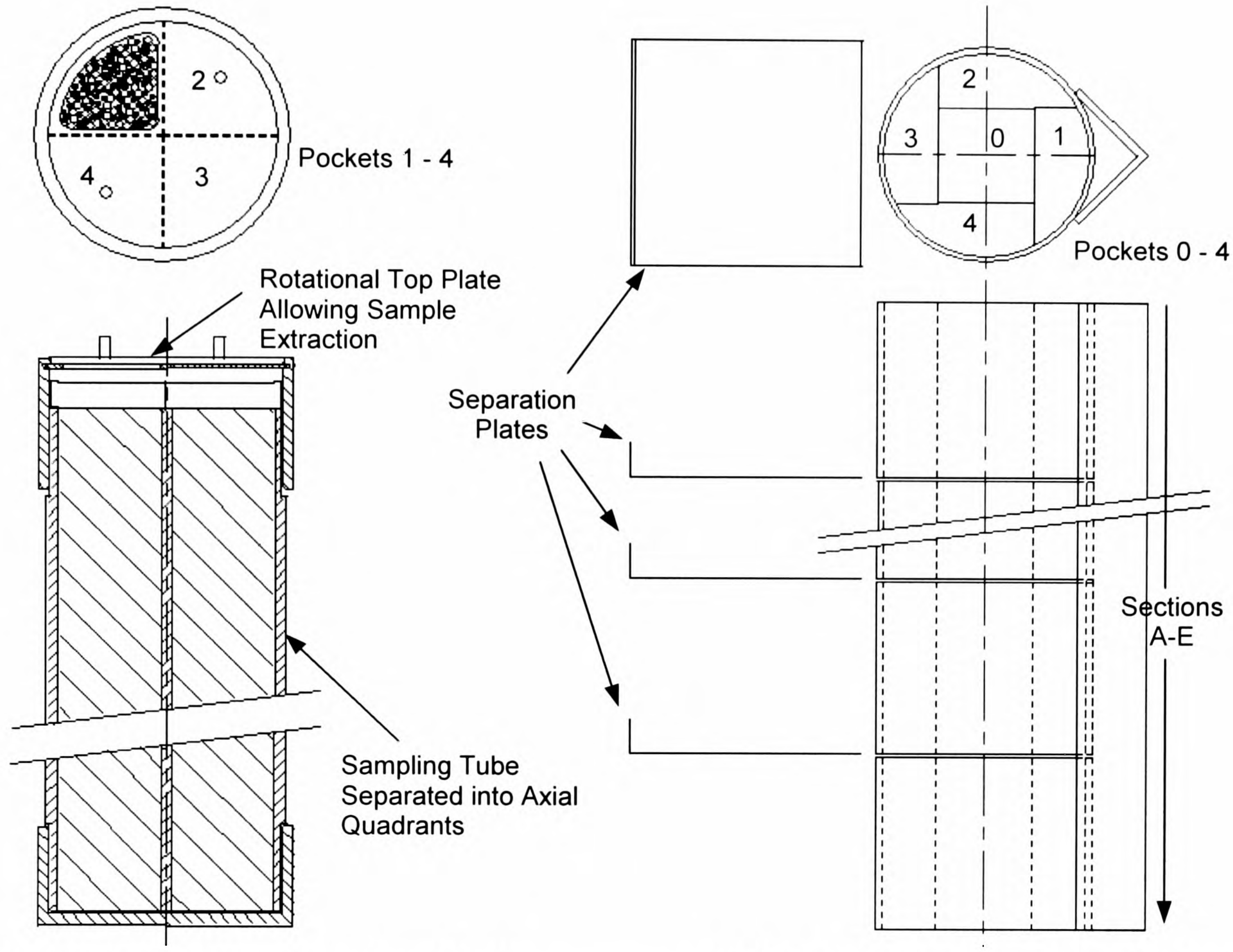


Figure A.3.1. Layout of Experimental Apparatus used to Assess Radial and Axial Performance of Static Mixer

Discharge of the condensed mixed material was subsequently fed into one of two devices connected to the bottom of the flow concentration device in order to measure radial or axial mixing.



(a) Radial Mixing Sampling Device (b) Axial Mixing Sampling Device

Figure A.3.2. Sampling Devices used to Ascertain Radial and Axial Mixing Performance

A.3.2. Measuring Radial Mixing Performance

The sampling device shown on Figure A.3.2.(a) was attached to the bottom of the concentration section that split the radially homogeneous flowing stream into four axial pockets. After a finite time of feeding sufficient to fill the sampling device the feed was stopped. Specially designed caps that allowed the separate extraction and analysis of mixture in each pocket were positioned on either end of the sampling device without disturbing the material in each pocket. The ratio of the mixed components in each quadrant was then analysed separately and compared to the initial feed conditions. Three feedrates, diameter ratios and feed proportions of small particles were selected as test variables to ascertain the mixing performance of the mixer.

Spherical Test Materials	Mean Particle Size (mm)	Mean Diameter Ratio
Small Aggregate/Large Aggregate	3.4 / 5.75	1.7 . 1

Large Aggregate/Plastic Pellets	5.75 / 2.8	2 : 1
Large Aggregate/Mustard Seed	5.75 / 2.0	3 : 1
Olivine Sand/ Plastic Pellets	0.33 / 2.8	8.5 : 1

Feedrate (kg/s)	0.1	0.25	0.3
Proportion of small particles	20	50	80

A series of tests were conducted using a 1.7:1 mean diameter ratio mixture to gauge the influence feedrate has on the performance of the mixer. Before every test a pre-calibration test was used to re-affirm the test feed condition settings. A complete list of mixing results is documented in Appendix A.4.

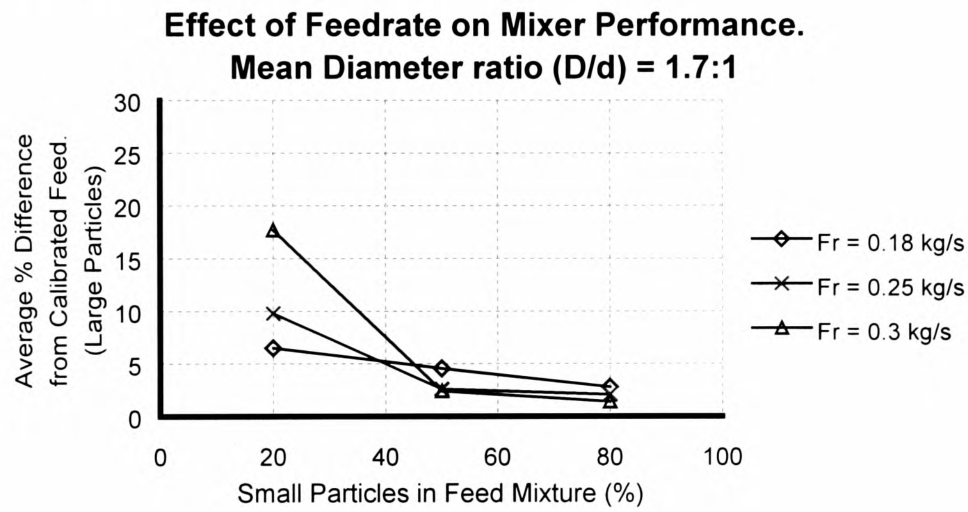


Figure A.3.3. Mixer Performance as a Result of Feedrate Variations

Graphical representation of the results shown on Figure A.3.3. indicate that the proportion of small to large particles in the mixture does produce a measurable change in mixing performance. Irrespective of feedrate tested, the mixing performance follows a similar trend. Individual pocket mixture quality associated with the extraction of samples is reliant on manual dexterity and familiarity of the mixing equipment. When testing a mixture that contains only 80% of small particles there would need to be a significant loss or measured pocket variation of small particles to yield a measurable percentage difference from the calibrated feed. Hence, for the 80% proportion small particle mixtures the percentage difference between pocket mixtures and calibrated feed mixture is small. Conversely, for mixtures containing a small proportion of small particles positional changes of a few small particles or losses during the sampling process would yield a measurable difference in pocket mixture quality. However, in conclusion, the changes shown on Figure A.3.3. indicate that there is not generally a significantly detrimental change in mixture quality for the tests undertaken and therefore does not negate the suitability of the mixer being tested.

Another pre-requisite of the applicability of the static mixer was its requirements to mix particulate materials to an acceptable level, irrespective of size differences. Consequently, mixtures that had very strong segregating tendencies i.e. diameter ratios of 8.5:1 were used to test mixer performance and help accentuate any failings of the mixer in its performance.

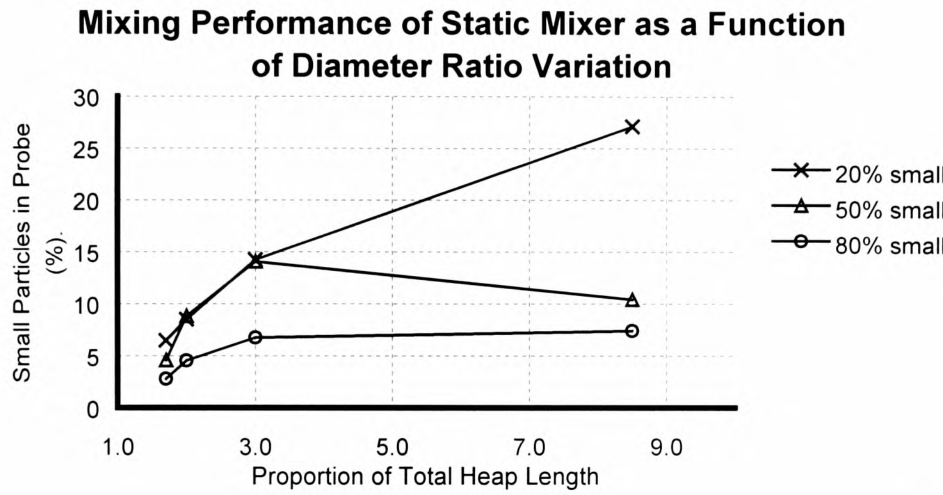
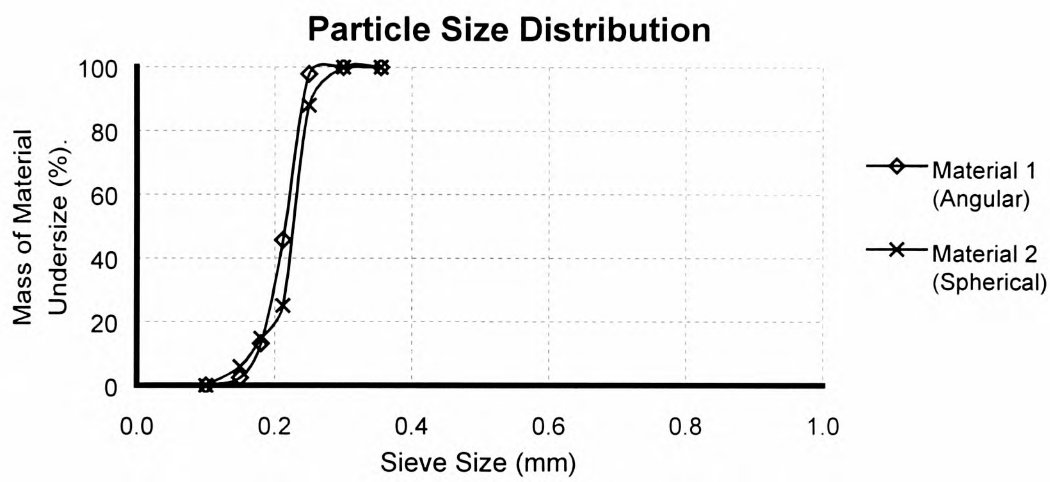


Figure A.3.4. Graphical Representation of Mixer Performance as a result of Increasing Particle Diameter Ratio

As shown on Figure A.3.4. the mixer produced mixtures that were approximately 27% from the desired settings when using a diameter ratio of 8.5:1. This was comparable to results documented in the relevant literature that tested material size differences of this order. The greatest dissimilarity of results occurred when using the combination of an 8.5:1 diameter ratio mixture with a proportion of small particles totalling 20%. As previously stated, losses of small numbers of small particles can greatly influence the measured pocket mixture quality when compared to the calibrated feed quality. Further more, static percolation of mixtures of this size order can exacerbate the mixing performance still further. In reality the mixer was unlikely to be required to mix such large differences in diameter ratio that would incur the influence of spontaneous percolation. It was a concern that static percolation, as defined in Section 3.5.2, associated with size differences of this type would significantly affect the validity of the mixing results taken using the experimental apparatus shown in Figure A.3.2.. However, when mixing performance for diameter ratio mixtures of 3.1:1 was analysed the percentage drop in mixture quality was not significant. This is a desirable facet of the mixers performance as according to the theoretical definitions of particle arrangements that induce spontaneous percolation, Appendix A.2, binary mixtures used in any ensuing investigation into heap segregation will not be greater than approximately 4:1. This was a positive indication that the static mixer was a viable option for mixing materials in order to investigate their segregation tendencies.

A.3.3. Measuring Axial Mixing Performance

A series of mixing investigations was undertaken as part of a confidential program of segregation work for a client of the University. Mixing work of relevance concerned the mixing performance of two particulate solids that were to be fed at three different proportions and three different feedrates. An attachment as shown in Figure A.3.2. (b) was used to sample the discharging mixture stream into a number of axial and radial segments. An electronic handheld 'colormeter' was used to quantify the luminescence and chromaticity of each sample. These results were then processed through a personal computer in order to convert the 'colormeter' readings into an actual proportion value representing the mixture of both materials for the sample tested.



Feedrate (kg/min)	6	11	16
Proportion of Material 2 (%)	50	70	80

Figure A.3.5. Test Materials and Conditions used To Assess the Axial Mixing Performance of the Static Mixer

Figure A.3.5. shows that although the two materials have similar particle size distributions they are significantly smaller in size than those used to ascertain the radial mixing performance of the mixer, Appendix A.4. Material 1 and 2 were similar in particle density but significantly different in shape. The two materials were mixed in differing proportions as shown on Figure A.3.5. Using materials of this size allowed the axial mixing performance to be ascertained for smaller material sizes than the mixer under investigation had been specifically designed to mix.

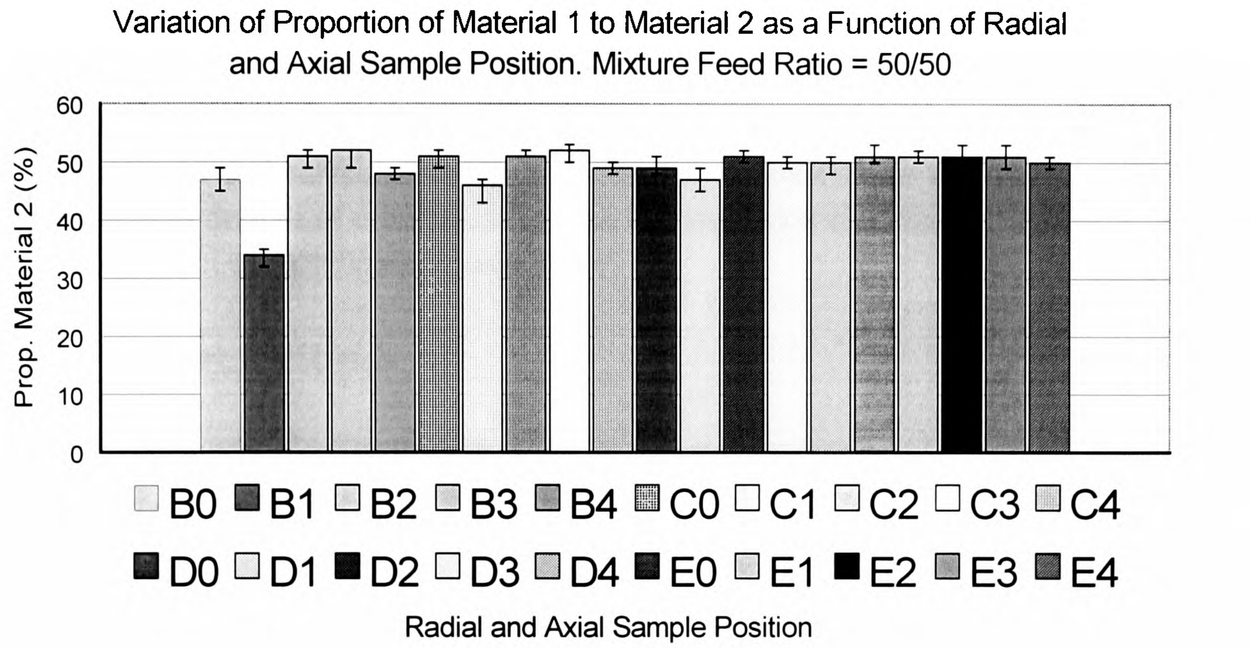


Figure A.3.6. Variation of Axial and Radial Mixture Quality for a 50/50 Mixture

Material extracted from each axial segment as shown on Figure A.3.2.(b) was measured five times in order to obtain the mean and standard deviation of mixture composition. Test results for these series of experiments are documented in Appendix A.4. Figure A.3.6. shows a graphical representation of results for a two component mixture mixed at proportions of 50/50. Mixing was successfully achieved both radially and axially.

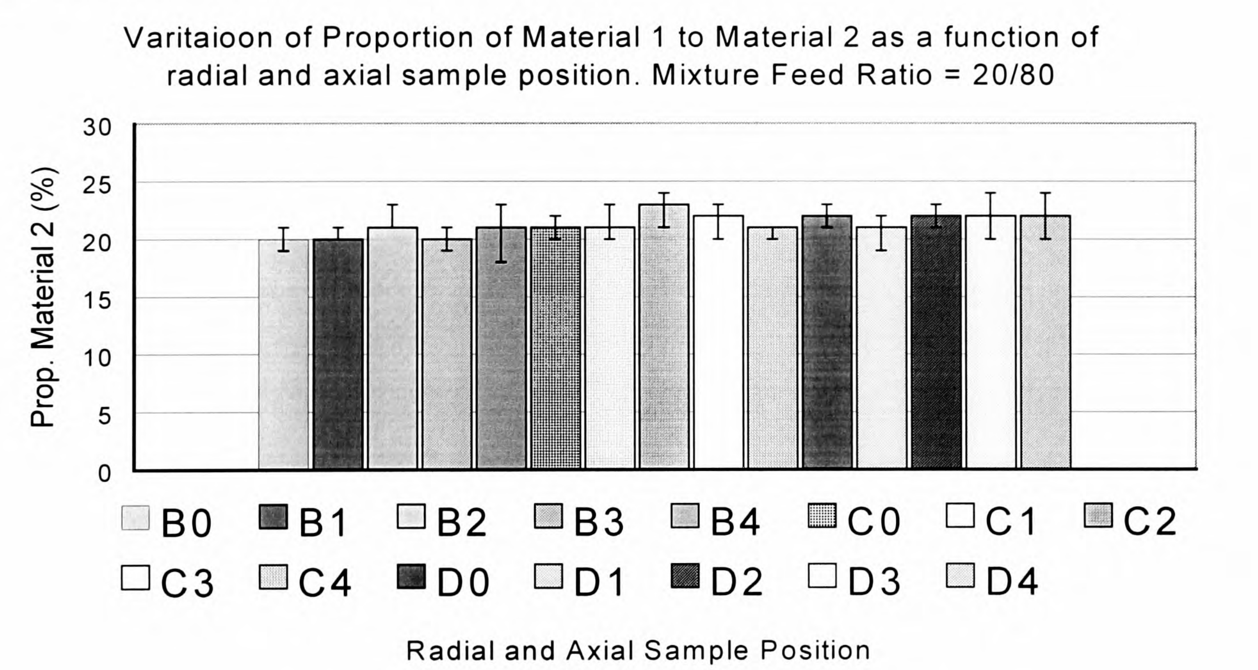


Figure A.3.7. Variation of Axial and Radial Mixture Quality for a 20/80 Mixture

Figure A.3.7. also shows that a high quality consistent mixture was produced even though the proportion of material 1 was only 20%. It was shown previously that the performance of the mixer reduces when small proportions of one component are required to be mixed. However, this is not the case when mixing these materials in similar proportions. Analysis of this study indicated that the mixer was able to attain a sufficiently high degree of mixedness across the spectrum of mixture proportions and feedrates used in this particular investigation.

A.3.4. Conclusions

Both radial and axial mixing results suggest that the feed proportions and the range of feedrates used throughout the test program did not significantly influence the mixing performance of the mixer. This therefore did not negate the static mixer being an appropriate means of mixing materials for use in a segregation testing facility. Investigation into mixer performance indicated that for the anticipated particulate material sizes proposed to be passed through the mixer in a segregation testing program, they will be mixed axially and radially to a satisfactory level.

APPENDIX A.4

TEST RESULTS FROM MIXER INVESTIGATIONS

A.4.1. Test Results From Mixer Investigations

Spherical Test Materials	Mean Particle Size (mm)	Mean Diameter Ratio
Small Aggregate/Large Aggregate	3.4 / 5.75	1.7 : 1
Large Aggregate/Plastic Pellets	5.75 / 2.8	2 : 1
Large Aggregate/Mustard Seed	5.75 / 2.0	3 : 1
Olivine Sand/ Plastic Pellets	0.33 / 2.8	8.5 : 1

Material	Particle Density (kg/m^3)
Small or Large Aggregate	1660
Plastic Polly-Pellets	800
Olivine Sand	2400
Mustard Seed	1120

Feedrate (kg/s)	0.1	0.25	0.3
Proportion of small particles	20	50	80

A.4.2. Radial Mixing Results (Apparatus Figure A.3.2.(a))

D/d = 1.7:1 Feedrate = 0.18kg/s Feed Proportion of Small Particles = 0.2

Ideal Split: 20/80

Calibration	feed kg/s	Split Ratio	% from Ideal
Sml	0.035	20.02	0.12
Lrg	0.139	79.98	0.03
	0.17	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total			
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. % diff.	
grams	104.0	390.0	108.0	387.0	100.0	396.0	93.0	401.0	405.0	1574.0		
ratio	21.1	78.9	21.8	78.2	20.2	79.8	18.8	81.2	20.5	79.5	Sml	Lrg
cal% diff	5.1	1.3	9.0	2.2	0.7	0.2	6.0	1.5	2.2	0.6	5.2	1.3
ideal% diff	5.3	1.3	9.1	2.3	0.8	0.2	5.9	1.5	2.3	0.6	5.3	1.3

Ideal Split: 20/80

Calibration	feed kg/s	Split Ratio	% from Ideal
Sml	0.034	19.47	2.65
Lrg	0.140	80.53	0.66
	0.17	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total			
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. % diff.	
grams	109.0	394.0	106.0	389.0	102.0	394.0	96.0	401.0	413.0	1578.0		
ratio	21.7	78.3	21.4	78.6	20.6	79.4	19.3	80.7	20.7	79.3	Sml	Lrg
cal% diff	11.3	2.7	10.0	2.4	5.6	1.4	0.8	0.2	6.5	1.6	6.9	1.7
ideal% diff	8.3	2.1	7.1	1.8	2.8	0.7	3.4	0.9	3.7	0.9	5.4	1.4

Ideal Split: 20/80

Calibration	feed kg/s	Split Ratio	% from Ideal
Sml	0.034	19.58	2.10
Lrg	0.138	80.42	0.52
	0.17	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total			
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. % diff.	
grams	110.0	389.0	106.0	387.0	103.0	396.0	99.0	398.0	418.0	1570.0		
ratio	22.0	78.0	21.5	78.5	20.6	79.4	19.9	80.1	21.0	79.0	Sml	Lrg
cal% diff	12.6	3.1	9.8	2.4	5.4	1.3	1.7	0.4	7.4	1.8	7.4	1.8
ideal% diff	10.2	2.6	7.5	1.9	3.2	0.8	0.4	0.1	5.1	1.3	5.3	1.3

D/d = 1.7:1 Feedrate = 0.18kg/s Feed Proportion of Small Particles = 0.5

Ideal Split: 50/50

Calibration	feed kg/s	Split Ratio	% from Ideal
Sml	0.089	49.44	1.12
Lrg	0.091	50.56	1.12
	0.18	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total			
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. % diff.	
grams	259.0	246.0	265.0	235.0	260.0	243.0	243.0	260.0	1027.0	984.0		
ratio	51.3	48.7	53.0	47.0	51.7	48.3	48.3	51.7	51.1	48.9	Sml	Lrg
cal% diff	4.4	4.3	7.9	7.6	5.2	5.1	1.6	1.6	4.0	3.8	4.8	4.6
ideal% diff	2.6	2.6	6.0	6.0	3.4	3.4	3.4	3.4	2.1	2.1	3.8	3.8

Ideal Split: 50/50

Calibration	feed kg/s	Split Ratio	% from Ideal
Sml	0.089	50.23	0.45
Lrg	0.088	49.77	0.45
	0.18	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total			
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. % diff.	
grams	263.0	241.0	261.0	239.0	253.0	250.0	238.0	265.0	1015.0	995.0		
ratio	52.2	47.8	52.2	47.8	50.3	49.7	47.3	52.7	50.5	49.5	Sml	Lrg
cal% diff	6.2	6.0	6.3	6.1	2.4	2.3	3.7	3.5	2.8	2.7	4.6	4.5
ideal% diff	4.4	4.4	4.4	4.4	0.6	0.6	5.4	5.4	1.0	1.0	3.7	3.7

Ideal Split: 50/50

Calibration	feed kg/s	Split Ratio	% from Ideal
Sml	0.089	49.12	1.76
Lrg	0.092	50.88	1.76
	0.18	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total			
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. % diff.	
grams	257.0	249.0	259.0	242.0	259.0	246.0	239.0	268.0	1014.0	1005.0		
ratio	50.8	49.2	51.7	48.3	51.3	48.7	47.1	52.9	50.2	49.8	Sml	Lrg
cal% diff	3.4	3.3	5.2	5.1	4.4	4.3	4.0	3.9	2.2	2.2	4.3	4.1
ideal% diff	1.6	1.6	3.4	3.4	2.6	2.6	5.7	5.7	0.4	0.4	3.3	3.3

D/d = 1.7:1 Feedrate = 0.18kg/s Feed Proportion of Small Particles = 0.8

Ideal Split: 80/20

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	396.6	111.3	398.5	106.8	393.7	112.6	380.0	127.3	1568.8	458.0		
Sml	0.143	78.69	1.64	ratio	78.1	21.9	78.9	21.1	77.8	22.2	74.9	25.1	77.4	22.6		
Lrg	0.039	21.31	6.55	cal% diff	0.8	2.8	0.2	0.8	1.2	4.4	4.8	17.8	1.6	6.0	1.7	6.4
	0.18	Total		ideal% diff	2.4	9.6	1.4	5.7	2.8	11.2	6.4	25.5	3.2	13.0	3.2	13.0

Ideal Split: 80/20

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	374.9	133.4	386.6	116.2	386.0	122.1	367.3	139.1	1514.8	510.8		
Sml	0.147	76.58	4.27	ratio	73.8	26.2	76.9	23.1	76.0	24.0	72.5	27.5	74.8	25.2		
Lrg	0.045	23.42	17.08	cal% diff	3.7	12.1	0.4	1.3	0.8	2.6	5.3	17.3	2.4	7.7	2.5	8.3
	0.19	Total		ideal% diff	7.8	31.2	3.9	15.6	5.0	20.2	9.3	37.3	6.5	26.1	6.5	26.1

Ideal Split: 80/20

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	402.3	106.0	404.5	100.0	400.6	104.0	387.2	119.2	1594.6	429.2		
Sml	0.148	75.69	5.39	ratio	79.1	20.9	80.2	19.8	79.4	20.6	76.5	23.5	78.8	21.2		
Lrg	0.048	24.31	21.56	cal% diff	4.6	14.2	5.9	18.5	4.9	15.2	1.0	3.2	4.1	12.8	4.1	12.8
	0.20	Total		ideal% diff	1.1	4.3	0.2	0.9	0.8	3.1	4.4	17.7	1.5	6.0	1.6	6.5

D/d = 1.7:1 Feedrate = 0.25kg/s Feed Proportion of Small Particles = 0.2

Ideal Split: 20/80

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	112.0	386.0	116.0	377.0	108.0	389.0	104.0	389.0	440.0	1541.0		
Sml	0.049	20.21	1.07	ratio	22.5	77.5	23.5	76.5	21.7	78.3	21.1	78.9	22.2	77.8		
Lrg	0.194	79.79	0.27	cal% diff	11.3	2.9	16.4	4.2	7.5	1.9	4.4	1.1	9.9	2.5	9.9	2.5
	0.24	Total		ideal% diff	12.4	3.1	17.6	4.4	8.7	2.2	5.5	1.4	11.1	2.8	11.1	2.8

Ideal Split: 20/80

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	112.0	385.0	113.0	380.0	110.0	388.0	100.0	394.0	435.0	1547.0		
Sml	0.047	19.41	2.96	ratio	22.5	77.5	22.9	77.1	22.1	77.9	20.2	79.8	21.9	78.1		
Lrg	0.196	80.59	0.74	cal% diff	16.1	3.9	18.1	4.4	13.8	3.3	4.3	1.0	13.1	3.2	13.1	3.2
	0.24	Total		ideal% diff	12.7	3.2	14.6	3.7	10.4	2.6	1.2	0.3	9.7	2.4	9.7	2.4

Ideal Split: 20/80

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	114.0	385.0	113.0	381.0	109.0	385.0	97.0	378.0	433.0	1529.0		
Sml	0.050	20.99	4.93	ratio	22.8	77.2	22.9	77.1	22.1	77.9	20.4	79.6	22.1	77.9		
Lrg	0.189	79.01	1.23	cal% diff	8.9	2.4	9.0	2.4	5.1	1.4	2.7	0.7	5.2	1.4	6.4	1.7
	0.24	Total		ideal% diff	14.2	3.6	14.4	3.6	10.3	2.6	2.1	0.5	10.3	2.6	10.3	2.6

D/d = 1.7:1 Feedrate = 0.25kg/s Feed Proportion of Small Particles = 0.5

Ideal Split: 50/50

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	263.2	240.0	271.0	225.0	257.5	248.1	255.1	249.1	1046.8	962.2		
Sml	0.124	50.47	0.94	ratio	52.3	47.7	54.6	45.4	50.9	49.1	50.6	49.4	52.1	47.9		
Lrg	0.122	49.53	0.94	cal% diff	3.6	3.7	8.3	8.4	0.9	0.9	0.3	0.3	3.2	3.3	3.3	3.3
	0.25	Total		ideal% diff	4.6	4.6	9.3	9.3	1.9	1.9	1.2	1.2	4.2	4.2	4.2	4.2

Ideal Split: 50/50

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	263.2	237.6	260.3	237.6	255.5	244.1	252.8	247.1	1031.8	966.4		
Sml	0.122	50.31	0.62	ratio	52.6	47.4	52.3	47.7	51.1	48.9	50.6	49.4	51.6	48.4		
Lrg	0.120	49.69	0.62	cal% diff	4.5	4.5	3.9	4.0	1.7	1.7	0.5	0.5	2.6	2.7	2.6	2.7
	0.24	Total		ideal% diff	5.1	5.1	4.6	4.6	2.3	2.3	1.1	1.1	3.3	3.3	3.3	3.3

Ideal Split: 50/50

	Calibration			D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
	feed kg/s	Split Ratio	% from Ideal	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Sml	Lrg
				grams	262.3	239.3	254.8	243.6	250.4	249.9	248.3	253.2	1015.8	986.0		
Sml	0.130	50.23	0.46	ratio	52.3	47.7	51.1	48.9	50.0	50.0	49.5	50.5	50.7	49.3		
Lrg	0.129	49.77	0.46	cal% diff	4.1	4.1	1.8	1.8	0.4	0.4	1.4	1.4	1.0	1.0	1.9	1.9
	0.26	Total		ideal% diff	4.6	4.6	2.2	2.2	0.1	0.1	1.0	1.0	1.5	1.5	2.0	2.0

D/d = 1.7:1 Feedrate = 0.25kg/s Feed Proportion of Small Particles = 0.8

Ideal Split: 80/20

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.197	78.38	2.03
Lrg	0.054	21.62	8.11
	0.25	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	407.0	99.0	408.0	94.0	407.0	99.0	387.0	116.0	1609.0	408.0		
ratio	80.4	19.6	81.3	18.7	80.4	19.6	76.9	23.1	79.8	20.2	Sml	Lrg
cal% diff	2.6	9.5	3.7	13.4	2.6	9.5	1.8	6.7	1.8	6.4	2.7	9.8
ideal% diff	0.5	2.2	1.6	6.4	0.5	2.2	3.8	15.3	0.3	1.1	1.6	6.5

Ideal Split: 80/20

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.186	78.04	2.45
Lrg	0.052	21.96	9.81
	0.24	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	389.0	119.0	406.0	97.0	395.0	113.0	380.0	128.0	1570.0	457.0		
ratio	76.6	23.4	80.7	19.3	77.8	22.2	74.8	25.2	77.5	22.5	Sml	Lrg
cal% diff	1.9	6.7	3.4	12.2	0.4	1.3	4.1	14.7	0.7	2.7	2.5	8.7
ideal% diff	4.3	17.1	0.9	3.6	2.8	11.2	6.5	26.0	3.2	12.7	3.6	14.5

Ideal Split: 80/20

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.194	78.24	2.20
Lrg	0.054	21.76	8.78
	0.25	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	397.0	112.0	403.0	103.0	396.0	109.0	387.0	120.0	1583.0	444.0		
ratio	78.0	22.0	79.6	20.4	78.4	21.6	76.3	23.7	78.1	21.9	Sml	Lrg
cal% diff	0.3	1.1	1.8	6.4	0.2	0.8	2.4	8.8	0.2	0.7	1.2	4.3
ideal% diff	2.5	10.0	0.4	1.8	2.0	7.9	4.6	18.3	2.4	9.5	2.4	9.5

D/d = 1.7:1 Feedrate = 0.30kg/s Feed Proportion of Small Particles = 0.2

Ideal Split: 20/80

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.051	16.96	15.18
Lrg	0.252	83.04	3.80
	0.30	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	112.0	381.0	103.0	386.0	106.0	385.0	98.0	394.0	419.0	1546.0		
ratio	22.7	77.3	21.1	78.9	21.6	78.4	19.9	80.1	21.3	78.7	Sml	Lrg
cal% diff	33.9	6.9	24.2	4.9	27.3	5.6	17.4	3.6	25.7	5.3	25.7	5.2
ideal% diff	13.6	3.4	5.3	1.3	7.9	2.0	0.4	0.1	6.6	1.7	6.8	1.7

Ideal Split: 20/80

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.054	18.19	9.06
Lrg	0.244	81.81	2.27
	0.30	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	105.0	389.0	103.0	388.0	99.0	392.0	99.0	394.0	406.0	1563.0		
ratio	21.3	78.7	21.0	79.0	20.2	79.8	20.1	79.9	20.6	79.4	Sml	Lrg
cal% diff	16.9	3.7	15.3	3.4	10.9	2.4	10.4	2.3	13.4	3.0	13.4	3.0
ideal% diff	6.3	1.6	4.9	1.2	0.8	0.2	0.4	0.1	3.1	0.8	3.1	0.8

Ideal Split: 20/80

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.056	18.50	7.50
Lrg	0.248	81.50	1.88
	0.30	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	105.0	391.0	109.0	384.0	103.0	391.0	100.0	393.0	417.0	1559.0		
ratio	21.2	78.8	22.1	77.9	20.9	79.1	20.3	79.7	21.1	78.9	Sml	Lrg
cal% diff	14.4	3.3	19.5	4.4	12.7	2.9	9.6	2.2	14.1	3.2	14.1	3.2
ideal% diff	5.8	1.5	10.5	2.6	4.3	1.1	1.4	0.4	5.5	1.4	5.5	1.4

D/d = 1.7:1 Feedrate = 0.30kg/s Feed Proportion of Small Particles = 0.5

Ideal Split: 50/50

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.154	50.33	0.65
Lrg	0.152	49.67	0.65
	0.31	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	256.0	242.0	256.0	237.0	252.0	245.0	241.0	255.0	1005.0	979.0		
ratio	51.4	48.6	51.9	48.1	50.7	49.3	48.6	51.4	50.7	49.3	Sml	Lrg
cal% diff	2.1	2.2	3.2	3.2	0.7	0.8	3.5	3.5	0.7	0.7	2.4	2.4
ideal% diff	2.8	2.8	3.9	3.9	1.4	1.4	2.8	2.8	1.3	1.3	2.7	2.7

Ideal Split: 50/50

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.141	49.58	0.84
Lrg	0.144	50.42	0.84
	0.29	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	251.0	251.0	253.0	243.0	254.0	247.0	237.0	261.0	995.0	1002.0		
ratio	50.0	50.0	51.0	49.0	50.7	49.3	47.6	52.4	49.8	50.2	Sml	Lrg
cal% diff	0.8	0.8	2.9	2.8	2.3	2.2	4.0	3.9	0.5	0.5	2.5	2.5
ideal% diff	0.0	0.0	2.0	2.0	1.4	1.4	4.8	4.8	0.4	0.4	2.1	2.1

Ideal Split: 50/50

	Calibration		
	feed kg/s	Split Ratio	% from Ideal
Sml	0.142	49.17	1.66
Lrg	0.147	50.83	1.66
	0.29	Total	

D/d	Pocket Number ONE		TWO		THREE		FOUR		Total		Av. % diff.	
1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL		
grams	244.0	255.0	255.0	242.0	248.0	250.0	238.0	264.0	985.0	1011.0		
ratio	48.9	51.1	51.3	48.7	49.8	50.2	47.4	52.6	49.3	50.7	Sml	Lrg
cal% diff	0.6	0.5	4.4	4.2	1.3	1.2	3.6	3.5	0.4	0.4	2.4	2.4
ideal% diff	2.2	2.2	2.6	2.6	0.4	0.4	5.2	5.2	1.3	1.3	2.6	2.6

D/d = 1.7:1 Feedrate = 0.30kg/s Feed Proportion of Small Particles = 0.8

Ideal Split: 80/20

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	398.0	108.0	399.0	103.0	397.0	106.0	392.0	113.0	1586.0	430.0	diff.	
Sml	0.244	78.57	1.79	ratio	78.7	21.3	79.5	20.5	78.9	21.1	77.6	22.4	78.7	21.3	Sml	Lrg
Lrg	0.067	21.43	7.14	cal% diff	0.1	0.4	1.2	4.2	0.5	1.7	1.2	4.4	0.1	0.5	0.7	2.7
	0.31	Total		ideal% diff	1.7	6.7	0.6	2.6	1.3	5.4	3.0	11.9	1.7	6.6	1.7	6.6

Ideal Split: 80/20

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	403.0	103.0	404.0	98.0	407.0	97.0	389.0	114.0	1603.0	412.0	diff.	
Sml	0.245	78.55	1.81	ratio	79.6	20.4	80.5	19.5	80.8	19.2	77.3	22.7	79.6	20.4	Sml	Lrg
Lrg	0.067	21.45	7.26	cal% diff	1.4	5.1	2.5	9.0	2.8	10.3	1.5	5.7	1.3	4.7	2.1	7.5
	0.31	Total		ideal% diff	0.4	1.8	0.6	2.4	0.9	3.8	3.3	13.3	0.6	2.2	1.3	5.3

Ideal Split: 80/20

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	1.7:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	404.0	101.0	403.0	101.0	402.0	102.0	385.0	118.0	1594.0	422.0	diff.	
Sml	0.239	79.22	0.98	ratio	80.0	20.0	80.0	20.0	79.8	20.2	76.5	23.5	79.1	20.9	Sml	Lrg
Lrg	0.063	20.78	3.90	cal% diff	1.0	3.8	0.9	3.6	0.7	2.6	3.4	12.9	0.2	0.7	1.5	5.7
	0.30	Total		ideal% diff	0.0	0.0	0.0	0.2	0.3	1.2	4.3	17.3	1.2	4.7	1.2	4.7

D/d = 2.0:1 Feedrate = 0.1kg/s Feed Proportion of Small Particles = 0.2, 0.5, 0.8

Ideal Split: 20/80

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	2.0:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	83.3	365.0	83.7	362.0	93.3	347.9	98.6	336.2	358.9	1411.1	diff.	
Sml	0.021	18.99	5.07	ratio	18.6	81.4	18.8	81.2	21.1	78.9	22.7	77.3	20.3	79.7	Sml	Lrg
Lrg	0.091	81.01	1.27	cal% diff	2.1	0.5	1.1	0.3	11.4	2.7	19.4	4.6	6.8	1.6	8.5	2.0
	0.11	Total		ideal% diff	7.1	1.8	6.1	1.5	5.7	1.4	13.4	3.3	1.4	0.3	8.1	2.0

Ideal Split: 50/50

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	2.0:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	176.4	187.8	199.2	175.4	161.2	197.8	147.7	203.7	684.5	764.7	diff.	
Sml	0.050	49.91	0.18	ratio	48.4	51.6	53.2	46.8	44.9	55.1	42.0	58.0	47.2	52.8	Sml	Lrg
Lrg	0.050	50.09	0.18	cal% diff	3.0	2.9	6.5	6.5	10.0	10.0	15.8	15.7	5.4	5.3	8.8	8.8
	0.10	Total		ideal% diff	3.1	3.1	6.4	6.4	10.2	10.2	15.9	15.9	5.5	5.5	8.9	8.9

Ideal Split: 80/20

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	2.0:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	248.4	60.6	242.2	69.5	255.6	49.1	260.0	38.6	1006.2	217.8	diff.	
Sml	0.089	79.58	0.53	ratio	80.4	19.6	77.7	22.3	83.9	16.1	87.1	12.9	82.2	17.8	Sml	Lrg
Lrg	0.023	20.42	2.11	cal% diff	1.0	4.0	2.4	9.2	5.4	21.1	9.4	36.7	3.3	12.9	4.6	17.7
	0.11	Total		ideal% diff	0.5	1.9	2.9	11.5	4.9	19.4	8.8	35.4	2.8	11.0	4.3	17.1

D/d = 2.9:1 Feedrate = 0.1kg/s Feed Proportion of Small Particles = 0.2, 0.5, 0.8

Ideal Split: 20/80

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	2.9:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	109.6	411.6	86.9	397.0	122.3	391.4	148.8	390.0	467.6	1590.0	diff.	
Sml	0.021	21.84	9.21	ratio	21.0	79.0	18.0	82.0	23.8	76.2	27.6	72.4	22.7	77.3	Sml	Lrg
Lrg	0.074	78.16	2.30	cal% diff	3.7	1.0	17.8	5.0	9.0	2.5	26.4	7.4	4.0	1.1	14.2	4.0
	0.09	Total		ideal% diff	5.1	1.3	10.2	2.6	19.0	4.8	38.1	9.5	13.6	3.4	18.1	4.5

Ideal Split: 50/50

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	2.9:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	233.6	229.1	215.7	257.2	261.7	184.1	264.8	176.2	975.8	846.6	diff.	
Sml	0.048	48.25	3.51	ratio	50.5	49.5	45.6	54.4	58.7	41.3	60.0	40.0	53.5	46.5	Sml	Lrg
Lrg	0.052	51.75	3.51	cal% diff	4.6	4.3	5.5	5.1	21.7	20.2	24.5	22.8	11.0	10.2	14.1	13.1
	0.10	Total		ideal% diff	1.0	1.0	8.8	8.8	17.4	17.4	20.1	20.1	7.1	7.1	11.8	11.8

Ideal Split: 80/20

					Pocket			Number					Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	2.9:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	307.4	106.0	301.9	110.0	340.8	48.0	333.6	57.7	1283.7	321.7	diff.	
Sml	0.076	82.85	3.57	ratio	74.4	25.6	73.3	26.7	87.7	12.3	85.3	14.7	80.0	20.0	Sml	Lrg
Lrg	0.016	17.15	14.26	cal% diff	10.3	49.5	9.6	9.6	4.8	4.8	2.4	2.4	2.9	2.9	6.8	16.6
	0.09	Total		ideal% diff	7.1	28.2	6.7	6.7	7.7	7.7	5.3	5.3	0.0	0.0	6.7	12.0

D/d = 8.5:1 Feedrate = 0.1kg/s Feed Proportion of Small Particles = 0.2

Ideal Split: 20/80

					Pocket				Number				Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	8.5:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	115.0	263.8	52.7	268.0	61.9	269.0	105.0	264.4	334.6	1065.2	diff.	
Sml	0.022	21.78	8.92	ratio	30.4	69.6	16.4	83.6	18.7	81.3	28.4	71.6	23.9	76.1	Sml	Lrg
Lrg	0.079	78.22	2.23	cal% diff	39.4	11.0	24.6	6.8	14.1	3.9	30.5	8.5	9.7	2.7	27.1	7.6
	0.10	Total		ideal% diff	51.8	12.9	17.8	4.5	6.5	1.6	42.1	10.5	19.5	4.9	29.6	7.4

D/d = 8.5:1 Feedrate = 0.1kg/s Feed Proportion of Small Particles = 0.5

Ideal Split: 50/50

					Pocket				Number				Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	8.5:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	300.3	237.8	124.3	262.1	163.9	262.9	332.0	225.7	920.5	988.5	diff.	
Sml	0.044	46.63	6.73	ratio	55.8	44.2	32.2	67.8	38.4	61.6	59.5	40.5	48.2	51.8	Sml	Lrg
Lrg	0.051	53.37	6.73	cal% diff	19.7	17.2	14.5	14.5	8.2	8.2	12.9	12.9	1.6	1.6	13.8	13.2
	0.10	Total		ideal% diff	11.6	11.6	17.8	17.8	11.6	11.6	9.5	9.5	1.8	1.8	12.6	12.6

Ideal Split: 50/50

					Pocket				Number				Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	8.5:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	186.5	249.5	139.1	262.5	218.4	253.1	267.2	229.5	811.2	994.6	diff.	
Sml	0.045	47.38	5.23	ratio	42.8	57.2	34.6	65.4	46.3	53.7	53.8	46.2	44.9	55.1	Sml	Lrg
Lrg	0.050	52.62	5.23	cal% diff	9.7	8.8	34.6	65.4	46.3	53.7	53.8	46.2	2.5	2.5	36.1	43.5
	0.10	Total		ideal% diff	14.4	14.4	15.4	15.4	3.7	3.7	3.8	3.8	5.1	5.1	9.3	9.3

Ideal Split: 50/50

					Pocket				Number				Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	8.5:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	146.3	129.2	52.8	129.6	84.5	153.1	159.8	123.1	443.4	535.0	diff.	
Sml	0.051	49.19	1.62	ratio	53.1	46.9	28.9	71.1	35.6	64.4	56.5	43.5	45.3	54.7	Sml	Lrg
Lrg	0.053	50.81	1.62	cal% diff	8.0	7.7	28.9	71.1	35.6	64.4	56.5	43.5	45.3	54.7	32.2	46.7
	0.10	Total		ideal% diff	6.2	6.2	21.1	21.1	14.4	14.4	6.5	6.5	4.7	4.7	12.0	12.0

D/d = 8.5:1 Feedrate = 0.1kg/s Feed Proportion of Small Particles = 0.8

Ideal Split: 80/20

					Pocket				Number				Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	8.5:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	640.9	108.2	456.4	165.2	546.5	151.8	672.5	88.0	2316.3	513.2	diff.	
Sml	0.071	76.34	4.57	ratio	85.6	14.4	73.4	26.6	78.3	21.7	88.4	11.6	81.9	18.1	Sml	Lrg
Lrg	0.022	23.66	18.28	cal% diff	12.1	38.9	3.8	12.3	2.5	8.1	15.8	51.1	7.2	23.3	8.6	27.6
	0.09	Total		ideal% diff	6.9	27.8	8.2	32.9	2.2	8.7	10.5	42.1	2.3	9.3	7.0	27.9

Ideal Split: 80/20

					Pocket				Number				Total			
	Calibration			D/d	ONE		TWO		THREE		FOUR					
	feed	Split	% from	8.5:1	m1S	m1L	m2S	m2L	m3S	m3L	m4S	m4L	mS	mL	Av. %	
	kg/s	Ratio	Ideal	grams	677.8	93.1	484.1	152.1	591.3	131.4	700.4	72.0	2453.6	448.6	diff.	
Sml	0.075	82.06	2.58	ratio	87.9	12.1	76.1	23.9	81.8	18.2	90.7	9.3	84.5	15.5	Sml	Lrg
Lrg	0.017	17.94	10.31	cal% diff	7.1	32.7	7.3	33.3	0.3	1.4	10.5	48.0	3.0	13.8	6.3	28.8
	0.09	Total		ideal% diff	9.9	39.6	4.9	19.5	2.3	9.1	13.3	53.4	5.7	22.7	7.6	30.4

A.4.3. Axial Mixing Results (Apparatus Figure A.3.2.(b))

Test No 1
50/50 Material 1 / Material 2
Sample Position

	B0	B1	B2	B3	B4
Mean of Five Readings	16.36	20.66	15.34	15.48	16.17
Std Dev	0.55	0.51	0.45	0.42	0.41
Mean + SD	16.92	21.16	15.79	15.90	16.57
Mean - SD	15.81	20.15	14.89	15.07	15.76
Equated Mean of Material 1. (%)	47	34	51	52	48
Equated Mean + SD (%)	49	35	52	52	49
Equated Mean - SD (%)	45	32	49	49	47

	Sample Position				
	C0	C1	C2	C3	C4
Mean of Five Readings	15.35	16.88	15.15	15.05	15.88
Std Dev	0.46	0.41	0.19	0.47	0.25
Mean + SD	15.80	17.29	15.34	15.52	16.14
Mean - SD	14.89	16.47	14.96	14.59	15.63
Equated Mean of Material 1. (%)	51	46	51	52	49
Equated Mean + SD (%)	52	47	52	53	50
Equated Mean - SD (%)	49	44	51	50	48

	Sample Position				
	D0	D1	D2	D3	D4
Mean of Five Readings	15.71	16.50	15.11	15.60	15.67
Std Dev	0.40	0.53	0.28	0.33	0.44
Mean + SD	16.11	17.03	15.39	15.93	16.11
Mean - SD	15.32	15.96	14.83	15.27	15.22
Equated Mean of Material 1. (%)	49	47	51	50	50
Equated Mean + SD (%)	51	49	52	51	51
Equated Mean - SD (%)	48	45	50	49	48

	Sample Position				
	E0	E1	E2	E3	E4
Mean of Five Readings	15.14	15.26	15.20	15.16	15.62
Std Dev	0.43	0.19	0.67	0.63	0.31
Mean + SD	15.57	15.44	15.87	15.79	15.93
Mean - SD	14.70	15.07	14.54	14.53	15.30
Equated Mean of Material 1. (%)	51	51	51	51	50
Equated Mean + SD (%)	53	52	53	53	51
Equated Mean - SD (%)	50	50	49	49	49

Test No 3
80/20 Material 1 / Material 2

	Sample Position				
	B0	B1	B2	B3	B4
Mean of Five Readings	25.31	24.98	24.97	25.38	25.06
Std Dev	0.26	0.18	0.32	0.43	0.82
Mean + SD	25.57	25.16	25.29	25.81	25.89
Mean - SD	25.05	24.80	24.65	24.96	24.24
Equated Mean of Material 1. (%)	20	20	21	20	21
Equated Mean + SD (%)	21	21	22	21	23
Equated Mean - SD (%)	19	20	20	19	18

	Sample Position				
	C0	C1	C2	C3	C4
Mean of Five Readings	24.99	24.91	24.39	24.77	25.10
Std Dev	0.30	0.47	0.51	0.43	0.27
Mean + SD	25.30	25.38	24.90	25.20	25.37
Mean - SD	24.69	24.44	23.88	24.34	24.83
Equated Mean of Material 1. (%)	21	21	23	22	21
Equated Mean + SD (%)	22	23	24	23	21
Equated Mean - SD (%)	20	20	21	20	20

	Sample Position				
	D0	D1	D2	D3	D4
Mean of Five Readings	24.65	25.05	24.60	24.73	24.65
Std Dev	0.26	0.55	0.47	0.73	0.57
Mean + SD	24.91	25.60	25.06	25.46	25.22
Mean - SD	24.39	24.50	24.13	23.99	24.08
Equated Mean of Material 1. (%)	22	21	22	22	22
Equated Mean + SD (%)	23	22	23	24	24
Equated Mean - SD (%)	21	19	21	20	20

APPENDIX A.5

SEGREGATION RESULTS FOR IN-LINE FEED

Test No.	Size One d50	Size Two d50	Median Diameter Ratio	Feed (g/s)	Prop. of Size One	Proportional Distance Down Heap Length From Feed Point / Small Particles in Probe Sample (% Mass)										
						0.14	0.17	0.31	0.33	0.48	0.5	0.64	0.65	0.8	0.81	0.95
41	4.4	6.1	1.4	100	0.2	41.0	36.4	25.8	26.2	18.2	14.4	6.9	6.8	4.1	2.6	2.3
108	4.4	6.1	1.4	100	0.4	73.9	75.7	62.0	72.0	57.7	47.3	33.3	29.6	13.0	10.4	6.1
109	4.4	6.1	1.4	100	0.6	82.6	92.4	78.6	87.4	74.2	64.6	57.0	50.9	38.6	34.6	10.8
43	4.4	6.1	1.4	100	0.8	95.5	92.9	93.0	92.6	81.8	81.2	73.3	70.5	60.6	67.6	1.8
110	4.4	6.1	1.4	300	0.2	38.9	42.0	33.1	32.6	21.5	20.1	12.8	10.1	6.6	3.4	1.8
111	4.4	6.1	1.4	300	0.4	71.7	62.8	56.0	60.5	47.2	42.8	30.3	30.6	13.0	9.0	2.5
112	4.4	6.1	1.4	300	0.6	82.1	85.8	79.3	78.5	67.6	65.1	49.9	51.5	30.5	30.7	6.2
113	4.4	6.1	1.4	300	0.8	95.0	94.3	92.7	91.7	85.1	83.3	72.8	75.7	60.3	60.7	40.6
114	4.4	6.1	1.4	500	0.2	35.2	33.5	29.7	31.5	23.0	21.7	13.2	14.1	6.2	4.7	1.4
115	4.4	6.1	1.4	500	0.4	62.2	60.3	55.9	57.5	43.5	42.4	31.9	28.0	15.5	13.9	3.6
116	4.4	6.1	1.4	500	0.6	80.3	79.1	74.4	79.2	61.7	63.7	52.0	50.3	33.6	33.9	10.2
117	4.4	6.1	1.4	500	0.8	92.1	93.1	90.6	90.6	81.8	84.0	70.2	74.6	64.5	61.3	40.4
45	4.4	6.1	1.4	700	0.2	29.6	33.1	30.0	28.1	22.7	19.7	12.1	14.3	8.9	5.4	1.8
118	4.4	6.1	1.4	700	0.4	55.5	56.4	50.1	55.4	46.6	43.3	30.4	31.2	19.0	17.9	5.2
119	4.4	6.1	1.4	700	0.6	76.3	77.0	69.6	74.3	66.2	63.5	56.5	54.9	37.5	37.6	12.5
47	4.4	6.1	1.4	700	0.8	85.7	87.5	84.2	81.8	74.0	78.5	63.0	66.6	52.5	52.8	28.6
92	4.4	8.1	1.85	100	0.2	54.9	45.6	25.2	27.7	9.0	9.3	3.6	4.7	1.5	1.4	1.9
93	4.4	8.1	1.85	100	0.4	88.5	80.7	66.8	67.4	42.7	41.7	13.8	20.3	2.8	6.7	1.9
94	4.4	8.1	1.85	100	0.6	96.7	96.9	90.5	96.3	75.8	70.8	54.2	51.3	33.7	38.3	3.9
95	4.4	8.1	1.85	100	0.8	99.7	100.0	98.9	99.7	87.5	86.2	69.9	68.7	64.0	64.8	40.5
96	4.4	8.1	1.85	300	0.2	53.0	51.3	33.5	36.0	14.6	11.8	3.2	5.1	2.0	0.9	0.8
97	4.4	8.1	1.85	300	0.4	82.0	73.2	69.4	60.7	45.8	46.2	31.6	22.4	11.0	5.0	3.5
98	4.4	8.1	1.85	300	0.6	93.1	92.9	84.9	88.7	62.3	63.0	37.6	46.9	14.4	10.7	1.4
99	4.4	8.1	1.85	300	0.8	98.8	98.4	99.4	98.5	90.3	92.0	71.1	75.0	56.7	60.9	23.7
100	4.4	8.1	1.85	500	0.2	43.7	44.0	31.3	32.7	15.2	17.0	4.3	5.8	1.7	1.4	0.6
101	4.4	8.1	1.85	500	0.4	79.5	67.8	70.5	64.4	54.4	48.1	30.6	22.2	6.8	2.7	0.3
102	4.4	8.1	1.85	500	0.6	91.0	91.3	86.6	90.0	68.0	67.8	52.6	50.2	26.1	22.5	1.3
103	4.4	8.1	1.85	500	0.8	99.3	98.4	98.6	96.9	88.3	91.2	73.1	78.4	68.5	63.5	22.1
104	4.4	8.1	1.85	700	0.2	37.6	41.0	30.0	30.1	17.7	18.0	5.3	5.6	1.3	1.8	0.9
105	4.4	8.1	1.85	700	0.4	67.2	68.8	62.0	58.5	45.9	45.0	25.4	23.1	4.6	4.5	0.9
106	4.4	8.1	1.85	700	0.6	83.9	91.5	82.3	84.4	71.4	67.1	52.7	52.3	29.2	25.9	2.4
107	4.4	8.1	1.85	700	0.8	97.1	97.4	95.8	97.8	87.1	87.6	74.4	73.6	58.0	60.4	22.9
62	2.6	6.1	2.36	100	0.2	62.8	64.8	26.2	42.2	3.6	4.3	1.5	2.3	0.7	1.0	0.5
78	2.6	6.1	2.36	100	0.4	86.6	93.3	67.3	62.6	35.3	37.4	7.2	6.9	0.8	0.6	0.5
79	2.6	6.1	2.36	100	0.6	99.7	100.0	91.3	92.7	67.7	67.9	50.0	55.2	26.3	32.1	0.5
80	2.6	6.1	2.36	100	0.8	100.0	100.0	97.5	99.5	76.8	78.6	66.4	70.6	67.4	78.4	48.9
81	2.6	6.1	2.36	300	0.2	76.0	65.5	32.5	27.3	4.1	4.2	0.5	2.1	0.3	0.3	0.3
82	2.6	6.1	2.36	300	0.4	92.0	89.4	73.2	74.8	42.5	38.3	6.5	7.9	0.4	1.3	0.2
83	2.6	6.1	2.36	300	0.6	99.2	99.9	89.2	87.0	68.1	69.4	49.1	50.4	13.2	11.7	0.1
84	2.6	6.1	2.36	300	0.8	99.7	100.0	95.6	95.6	81.2	79.3	72.1	72.6	62.1	68.4	42.5
85	2.6	6.1	2.36	500	0.2	66.8	66.3	32.4	30.8	4.2	5.1	1.1	2.5	0.3	0.5	0.4
86	2.6	6.1	2.36	500	0.4	84.9	90.9	70.2	69.7	41.6	43.5	17.2	13.0	0.6	0.5	0.3
87	2.6	6.1	2.36	500	0.6	97.5	98.8	85.4	86.6	66.1	66.6	50.7	50.5	21.7	15.9	0.1
88	2.6	6.1	2.36	500	0.8	99.6	100.0	97.4	94.2	80.0	83.9	71.5	74.1	64.2	65.0	24.8
63	2.6	6.1	2.36	700	0.2	69.3	70.9	37.8	37.8	5.4	5.5	0.9	2.2	0.2	0.4	0.1
89	2.6	6.1	2.36	700	0.4	81.2	84.8	71.2	70.6	41.5	43.9	18.4	16.3	0.7	0.5	0.1
90	2.6	6.1	2.36	700	0.6	95.0	94.2	85.5	81.6	65.9	65.9	53.8	47.5	41.5	21.7	9.3
91	2.6	6.1	2.36	700	0.8	100	99.5	97.35	98	85.5	86.5	73.2	70.2	61.2	53.8	11.5
51	2.6	8.1	3.1	100	0.2	66.2	86.3	56.7	45.4	9.4	24.9	0.8	2.4	0.2	0.6	0.2
66	2.6	8.1	3.1	100	0.4	86.6	88.3	64.8	64.4	35.6	32.6	2.9	3.0	0.5	0.9	0.6
67	2.6	8.1	3.1	100	0.6	100.0	100.0	98.3	100.0	74.7	66.5	47.1	45.4	16.5	15.6	0.2
53	2.6	8.1	3.1	100	0.8	100.0	100.0	99.9	100.0	97.6	88.0	87.8	82.1	49.3	62.5	1.0
68	2.6	8.1	3.1	300	0.2	63.1	62.5	31.4	27.8	1.5	2.9	0.7	3.1	0.4	0.5	0.2
69	2.6	8.1	3.1	300	0.4	88.0	86.9	83.3	66.0	37.4	41.1	0.6	2.3	0.3	0.4	0.2
70	2.6	8.1	3.1	300	0.6	99.7	100.0	94.5	93.2	69.7	68.9	42.3	42.6	12.7	1.1	0.2
71	2.6	8.1	3.1	300	0.8	100.0	99.7	99.4	98.1	83.8	84.7	67.0	70.0	62.3	70.1	16.7
72	2.6	8.1	3.1	500	0.2	67.5	64.5	25.4	19.9	1.1	3.1	0.4	1.5	0.2	0.4	0.2
73	2.6	8.1	3.1	500	0.4	89.6	96.8	72.8	71.1	38.4	43.1	7.8	9.8	0.1	0.3	0.1
74	2.6	8.1	3.1	500	0.6	99.4	100.0	92.7	91.6	66.4	66.8	43.6	42.5	7.2	5.6	0.1
75	2.6	8.1	3.1	500	0.8	100.0		100.0			92.1		74.1		62.9	
55	2.6	8.1	3.1	700	0.2	69.4	71.7	38.2	36.2	1.8	3.5	0.3	1.9	0.2	0.2	0.0
76	2.6	8.1	3.1	700	0.4	86.0	88.1	66.3	67.2	36.5	37.8	2.7	4.8	0.1	0.2	0.2
77	2.6	8.1	3.1	700	0.6	99.2	99.7	90.6	87.2	61.4	69.6	46.6	45.6	15.3	7.0	0.2
49	2.6	8.1	3.1	700	0.8	100.0	100.0	98.9	98.3	84.0	85.1	71.9	66.8	65.7	47.3	0.0

APPENDIX A.6

LINEAR MODEL DEVELOPMENT

A.6.1. Linear Model Development

The characteristic pattern of segregation produced when using the in-line feed configuration, Chapter 7, could be assumed linear in characteristic. Consequently, an empirical model was developed based on the equation representing a straight-line:

$$Y = m.X + c \qquad \text{Equation 22}$$

Where the variables are defined as:

Y Percentage of small particles (0 – 100).
X Position down heap surface. (0 – 1).
m Slope pattern of segregation. c Intercept of Y axis.

Ascertaining the relationship between the constants of Equation 22 would yield a model that could predict the segregation pattern of lytag aggregate within the range of particle, process characteristics tested

A.6.2. Determining Value of Constant 'c'

It was established in Chapter 7 that feedrate was insignificant in influencing the pattern of segregation produced in comparison to size differences and feed proportions of small particles. The intercept values for the results of in-line feeding were analysed in order to establish a relationship between these two variables.

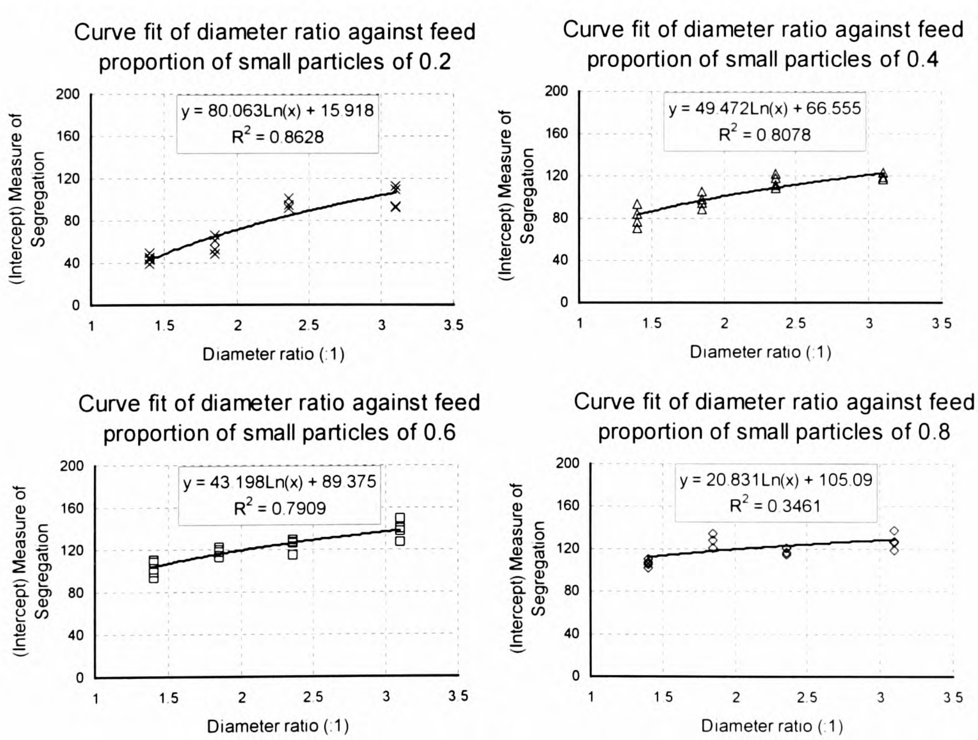


Figure A.6.1 Curve Fit of Values of Intercept for In-Line Feeding Results

The curves shown on Figure A.6.1. can be represented by the mathematical form:

$$c = a(Ln(x) +(b).$$

The relationship of the two constants 'a' and 'b' produced in the derivation of the curve fitting expressions shown on Figure A.6.1. could be predicted by the following two equations shown on Figure A.6.2..

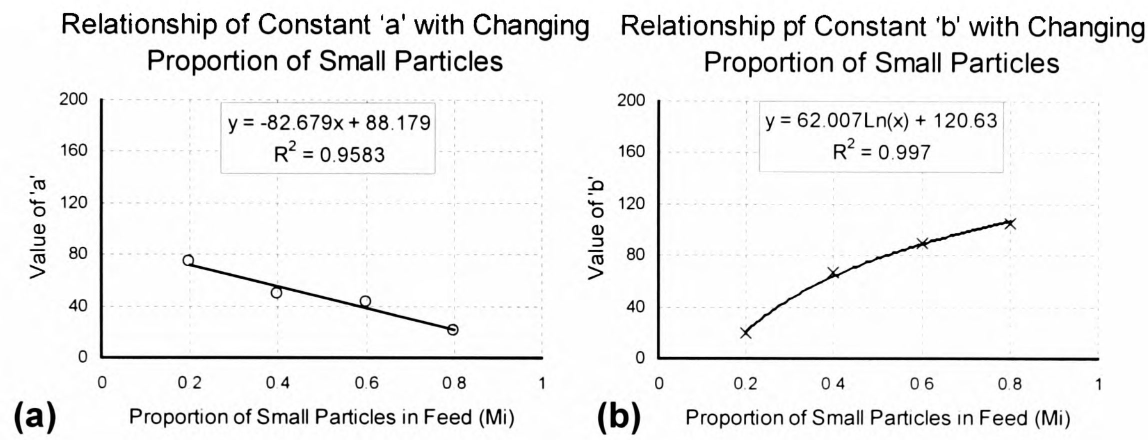


Figure A.6.2. Relationship of Two Constants that Form Expressions Derived in Figure A.6.1. that describe the Intercept Values of Linear Patterns

A.6.3. Determining Value of Constant 'm'

To ascertain the relationship that represented the slope value of the straight-line in Equation 22, it was necessary to measure the slope values of the entire results produced for in-line feeding. These results are shown on Figure A.6.3..

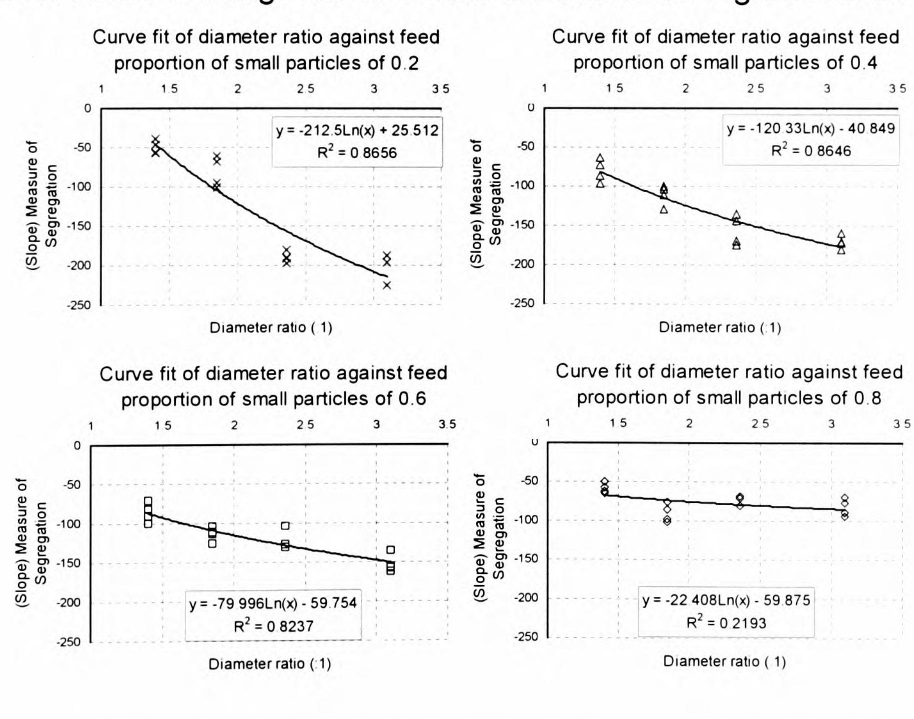


Figure A.6.3. Curve Fit of Values of Slope for In-Line Feeding Results

The curves shown on Figure A.6.3. can be represented by the mathematical form:

$$m = h(Ln(x) + (l).$$

The relationship of the two constants 'h' and 'l' produced in the derivation of the curve fitting expressions shown on Figure A.6.3. could be predicted by the following two equations shown on Figure A.6.4..

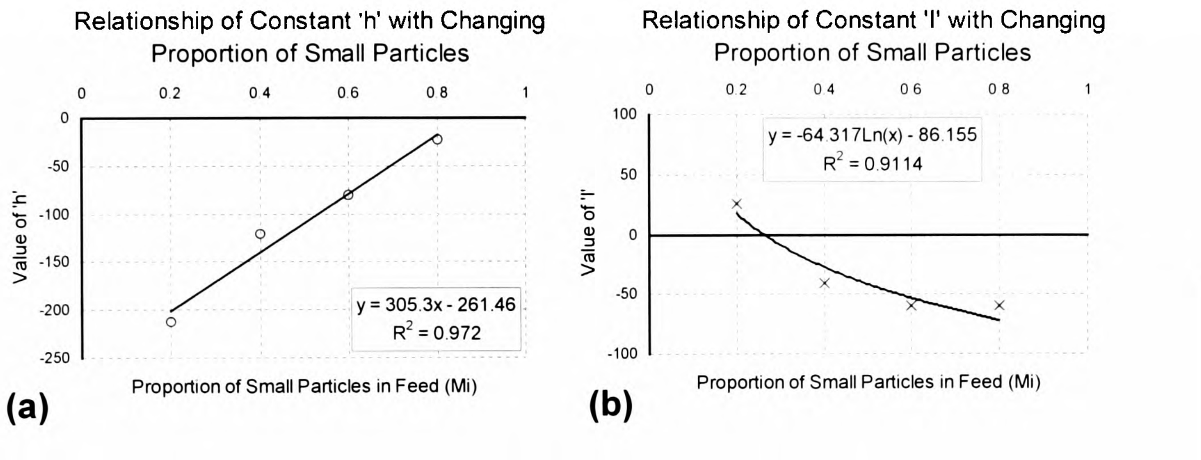


Figure A.6.4. Relationship of Two Constants that Form Expressions Derived in Figure A.6.3. that Describe the Slope Values of Linear Segregation Patterns

A.6.4. Governing Segregation Equation

Substituting the empirical expressions that model the relationship of slope and interception constants of Equation 22 yielded the governing segregation equation for predicting patterns of segregation within the range of variables tested.

GOVERNING SEGREGATION EQUATION

Y = mX + c

m = h*Ln(Dr)+l c = a *Ln(Dr)+b

h = J*(Mi)-k [Figure A.6.4. (a)]

l = L * Ln (Mi)+N [Figure A.6.4. (b)]

a = e *(Mi) + d [Figure A.6.2. (a)]

b = f *Ln(Mi) +g [Figure A.6.2. (b)]

J,K,L,N,E,D,F, & G = Material Dependant Constants

J	305.3	k	261.46	L	-64.317	N	-86.155
E	-82.679	D	88.179	F	62.007	G	120.63

Therefore:

$$Y = 305 \cdot l \cdot Ln\left(\frac{D}{d}\right) \cdot Mi - 261.5 \cdot l \cdot Ln\left(\frac{D}{d}\right) - 64.3 \cdot l \cdot Ln(Mi) - 86.2 \cdot l - 82.7 Ln\left(\frac{D}{d}\right) Ln(Mi) + 88.2 Ln\left(\frac{D}{d}\right) + 62 \cdot Ln(Mi) + 120.6$$

Equation 17

Where the variables are defined as:

Mi Proportion of Small particles in Mixture (0 – 1)
D Diameter of large particles
d Diameter of small particles
l Proportional distance down heap length (0 -1)
Y Percentage of small particles at position l down heap surface (0-100)

An example of the predictive ability of the empirically derived governing segregation equation is shown below:

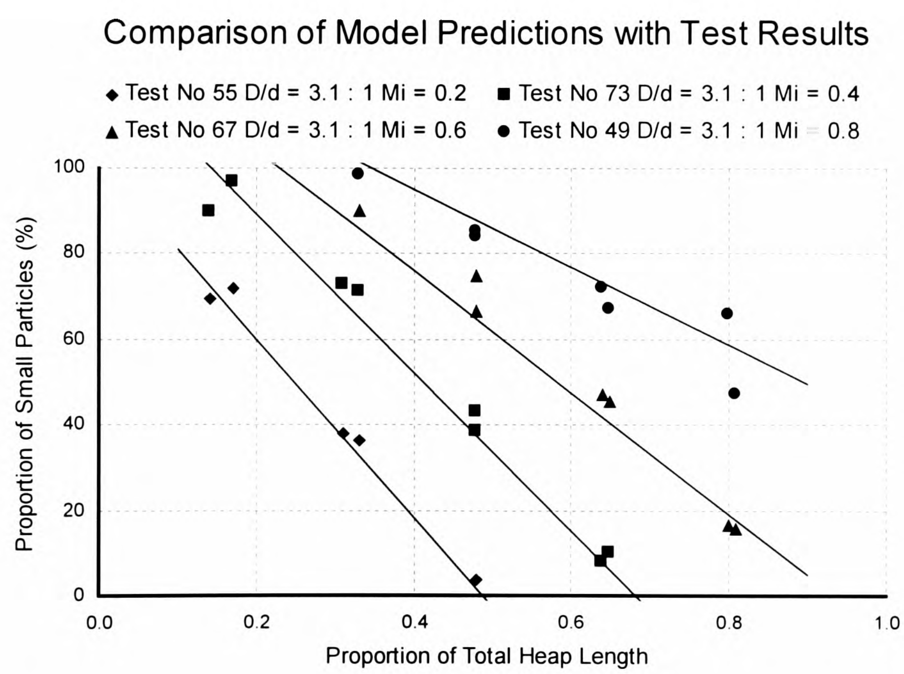


Figure A.6.5. Examples of the Predictive Ability of Equation 17.

APPENDIX A.7

MODELLING PROFILES FOR IN-LINE FEED

A.7.1. Modelling Profiles For In-Line Feed

Segregation model predictions compared to experimental test data for in-line feeding of plane-flow test vessel.

A.7.2. Median Diameter Ratio = 1.85:1

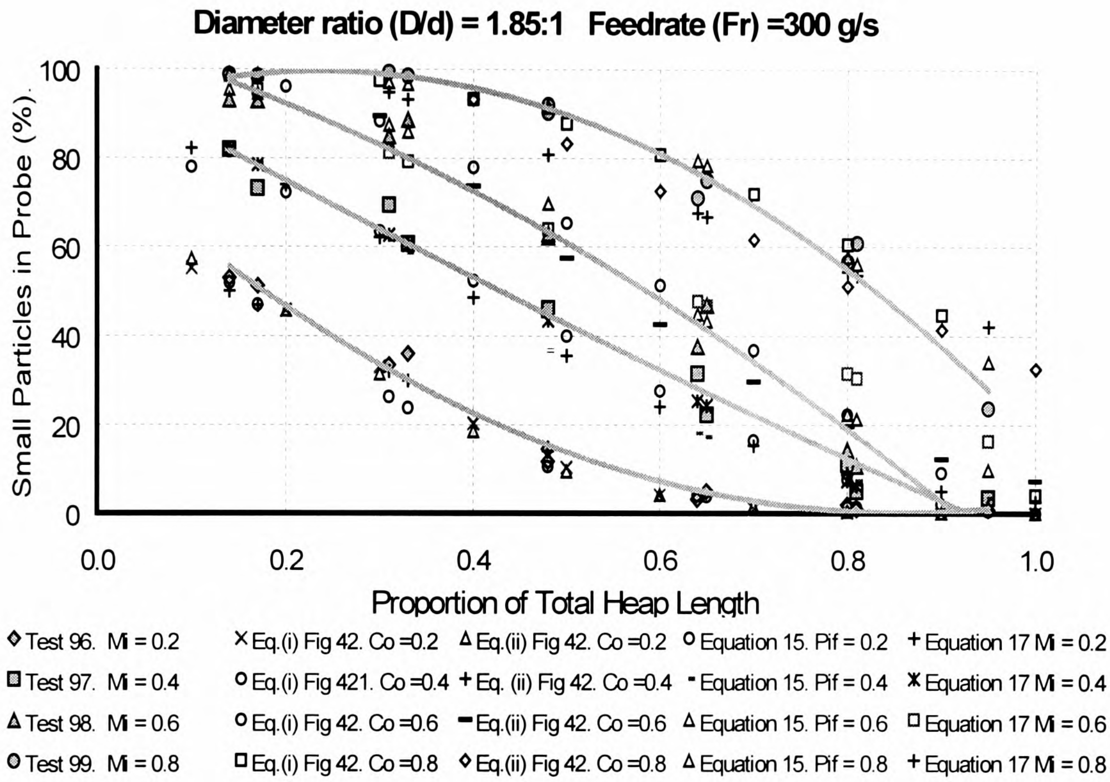
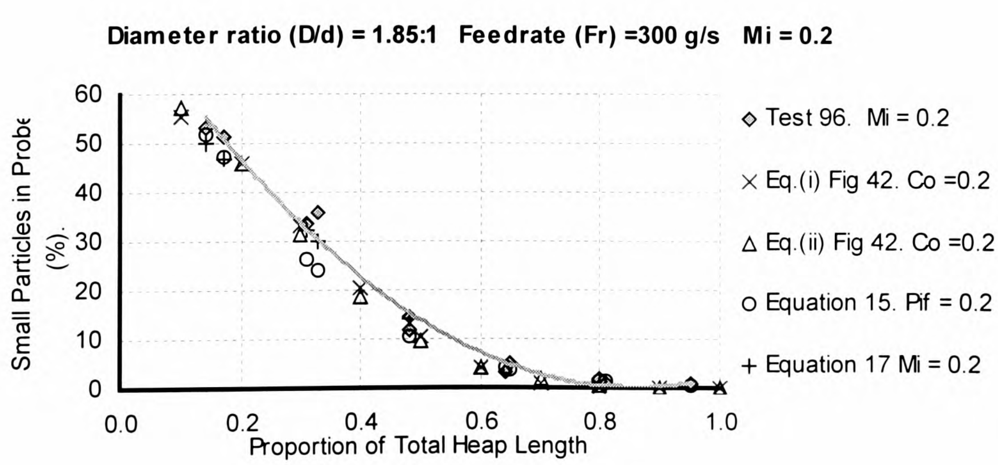
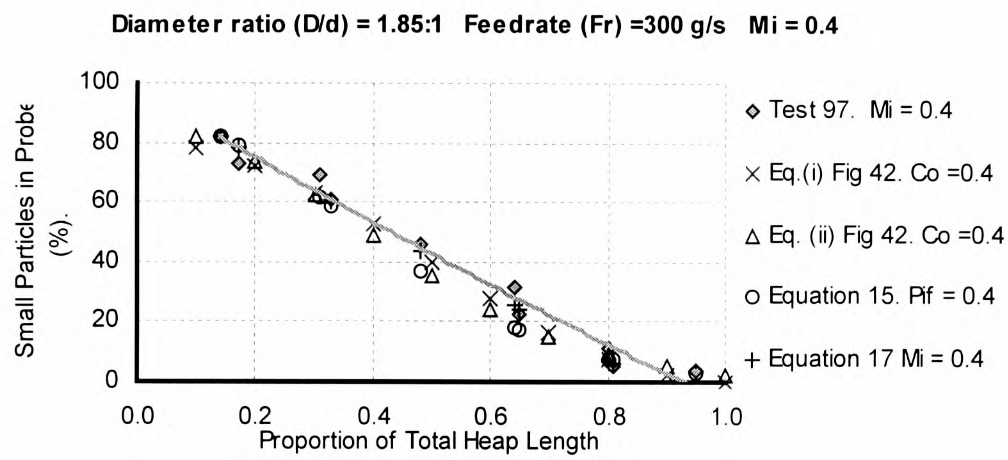
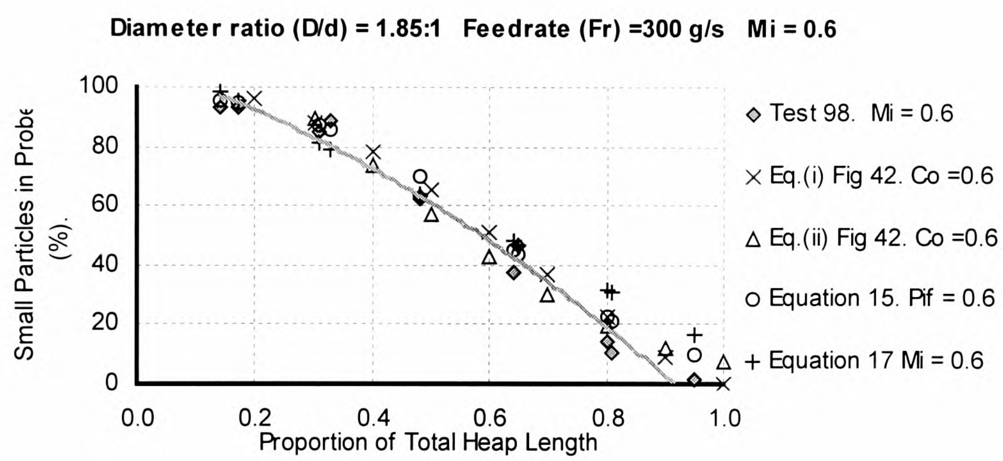


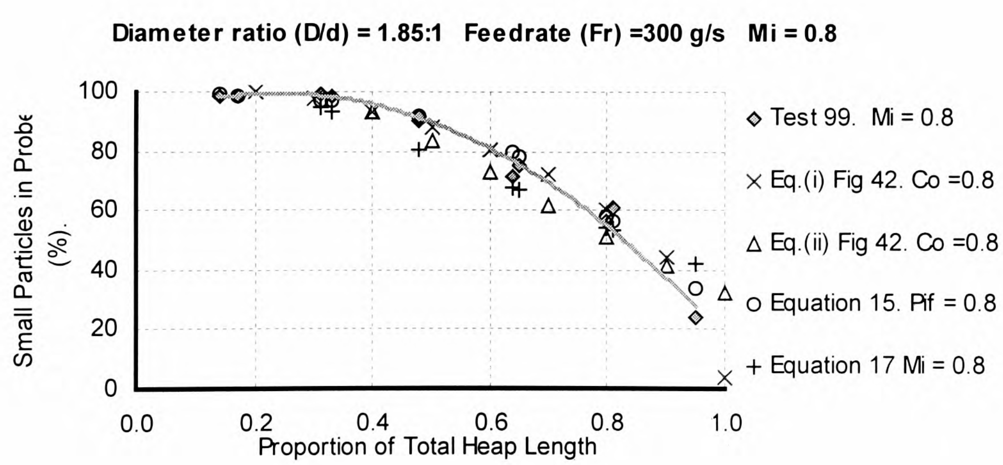
Figure A.7.1. Predictive Model Comparisons with Experimental Results for a 1.85:1 Diameter Ratio Binary Mixture for a Feedrate of 300 g/s

Each of the four experimental lines shown in Figure A.7.1. are shown individually below in order to provide a clearer picture of their ability to predict segregation.




Diameter ratio (D/d) = 1.85:1 Feedrate (Fr) =300 g/s Mi = 0.4
Small Particles in Probe (%).
Proportion of Total Heap Length
Test 97. Mi = 0.4
Eq.(i) Fig 42. Co =0.4
Eq. (ii) Fig 42. Co =0.4
Equation 15. Pif = 0.4
Equation 17 Mi = 0.4


Diameter ratio (D/d) = 1.85:1 Feedrate (Fr) =300 g/s Mi = 0.6
Small Particles in Probe (%).
Proportion of Total Heap Length
Test 98. Mi = 0.6
Eq.(i) Fig 42. Co =0.6
Eq.(ii) Fig 42. Co =0.6
Equation 15. Pif = 0.6
Equation 17 Mi = 0.6


Diameter ratio (D/d) = 1.85:1 Feedrate (Fr) =300 g/s Mi = 0.8
Small Particles in Probe (%).
Proportion of Total Heap Length
Test 99. Mi = 0.8
Eq.(i) Fig 42. Co =0.8
Eq.(ii) Fig 42. Co =0.8
Equation 15. Pif = 0.8
Equation 17 Mi = 0.8

A.7.3. Median Diameter Ratio = 2.36:1

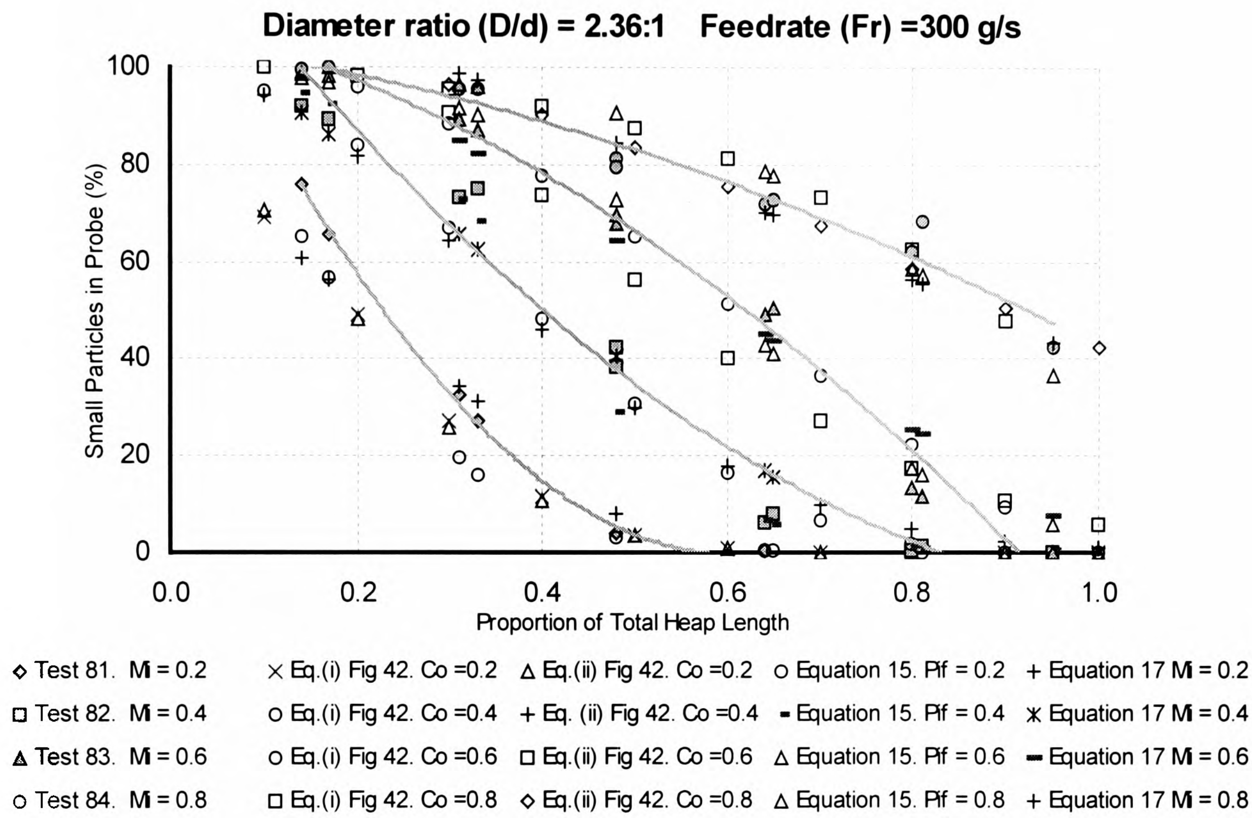
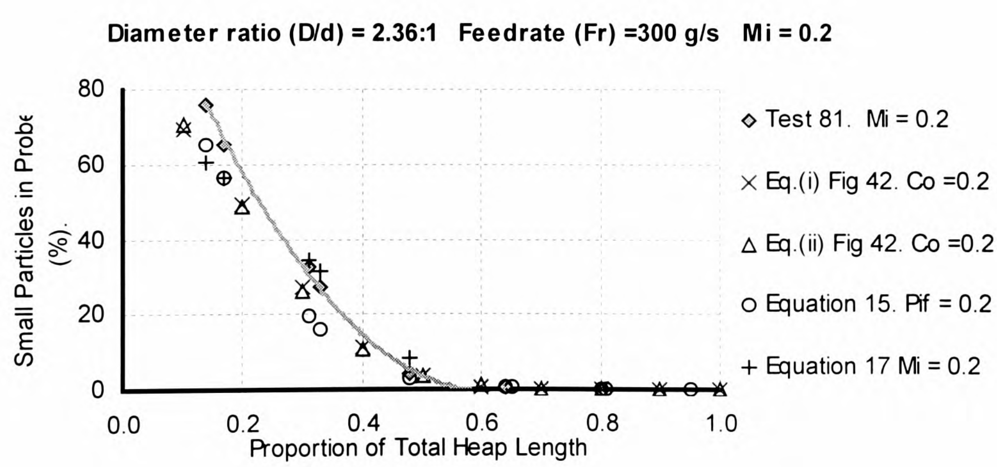
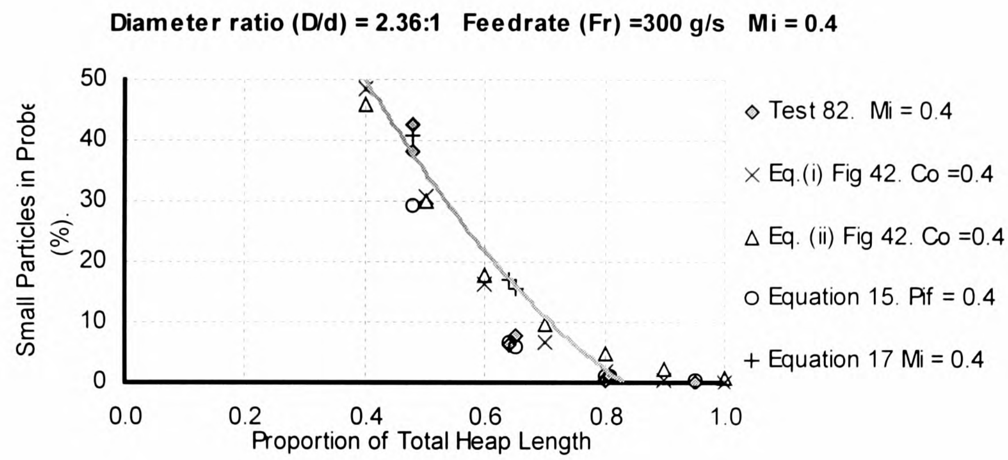
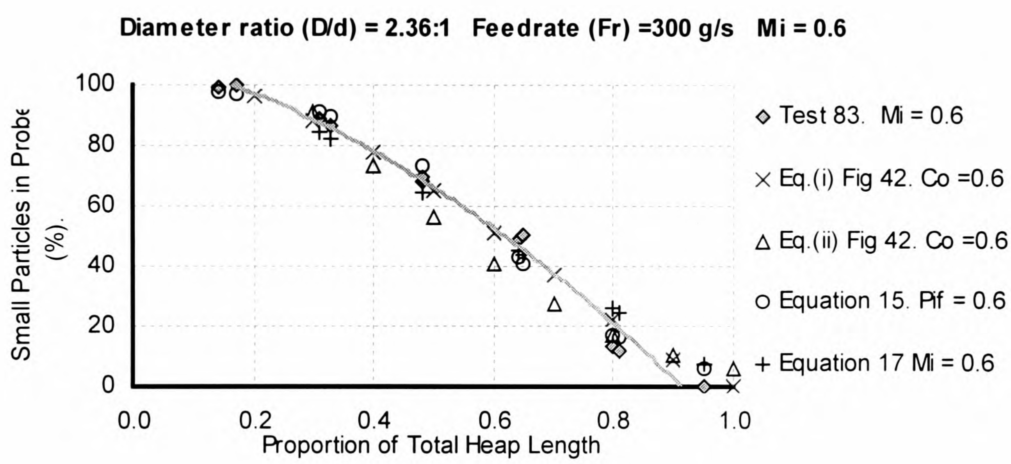


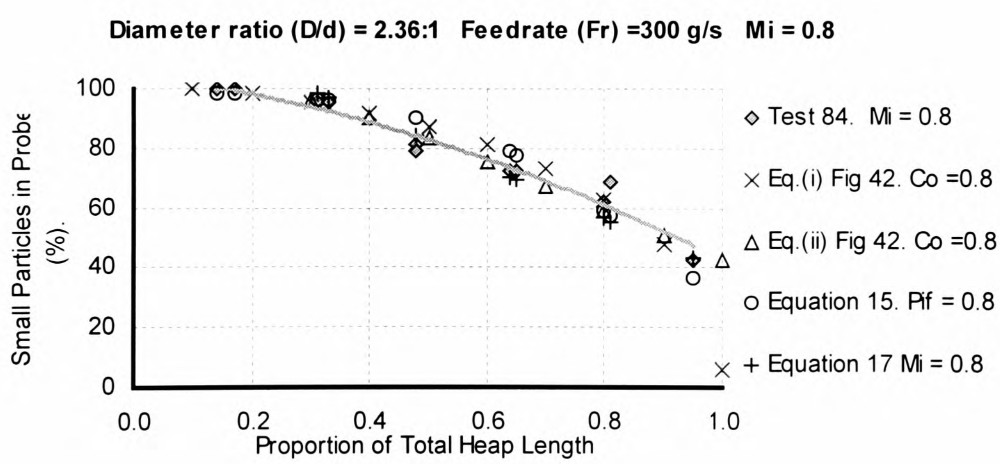
Figure A.7.2. Predictive Model Comparisons with Experimental Results for a 2.36:1 Diameter Ratio Binary Mixture for a Feedrate of 300 g/s.

Each of the four experimental lines shown in Figure A.7.2. are shown individually below in order to provide a clearer picture of their ability to predict segregation.




Diameter ratio (D/d) = 2.36:1 Feedrate (Fr) =300 g/s Mi = 0.4
Small Particles in Probe (%).
Proportion of Total Heap Length
0
10
20
30
40
50
0.0
0.2
0.4
0.6
0.8
1.0
◇ Test 82. Mi = 0.4
× Eq.(i) Fig 42. Co =0.4
△ Eq. (ii) Fig 42. Co =0.4
○ Equation 15. Pif = 0.4
+ Equation 17 Mi = 0.4


Diameter ratio (D/d) = 2.36:1 Feedrate (Fr) =300 g/s Mi = 0.6
Small Particles in Probe (%).
Proportion of Total Heap Length
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
◇ Test 83. Mi = 0.6
× Eq.(i) Fig 42. Co =0.6
△ Eq.(ii) Fig 42. Co =0.6
○ Equation 15. Pif = 0.6
+ Equation 17 Mi = 0.6


Diameter ratio (D/d) = 2.36:1 Feedrate (Fr) =300 g/s Mi = 0.8
Small Particles in Probe (%).
Proportion of Total Heap Length
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
◇ Test 84. Mi = 0.8
× Eq.(i) Fig 42. Co =0.8
△ Eq.(ii) Fig 42. Co =0.8
○ Equation 15. Pif = 0.8
+ Equation 17 Mi = 0.8

A.7.4. Median Diameter Ratio = 3.1:1

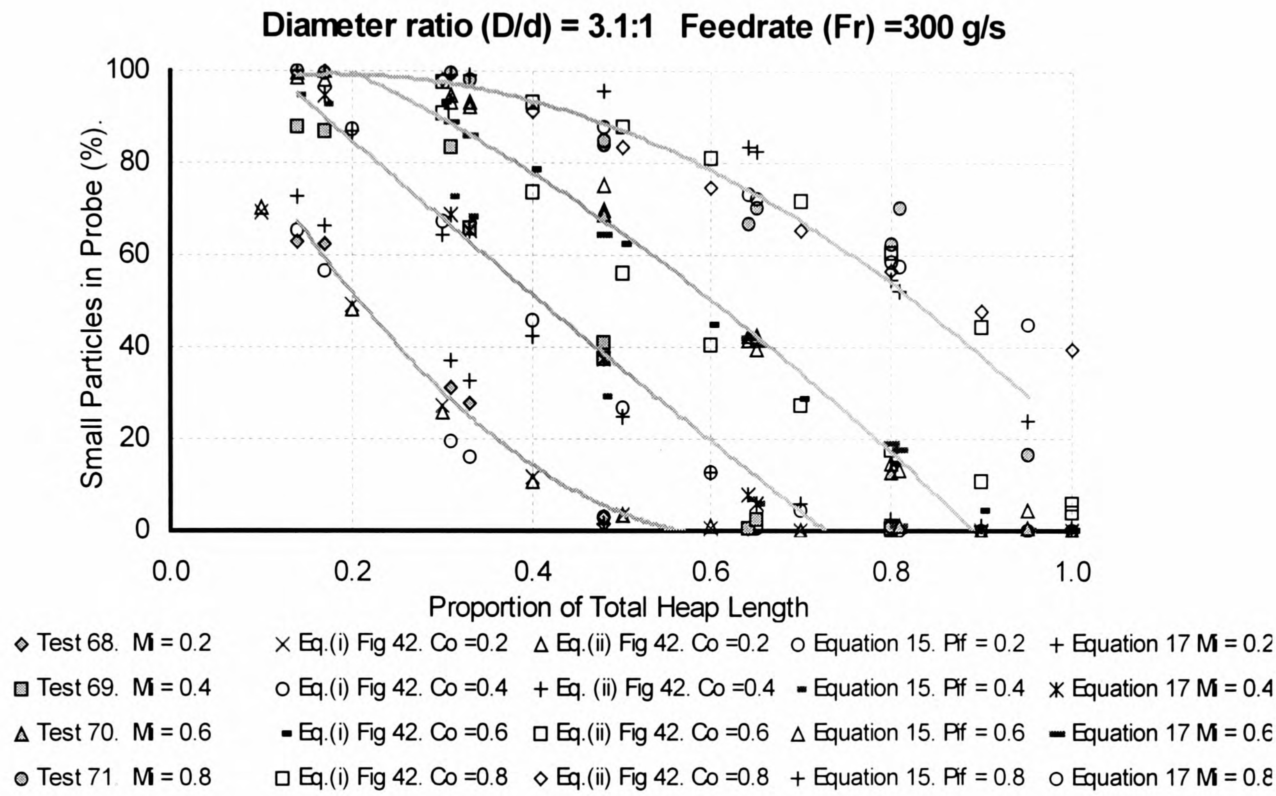
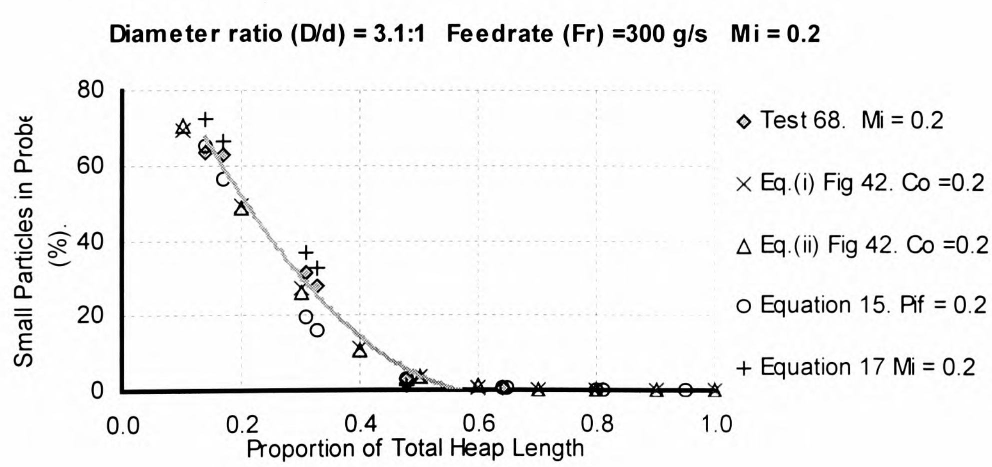
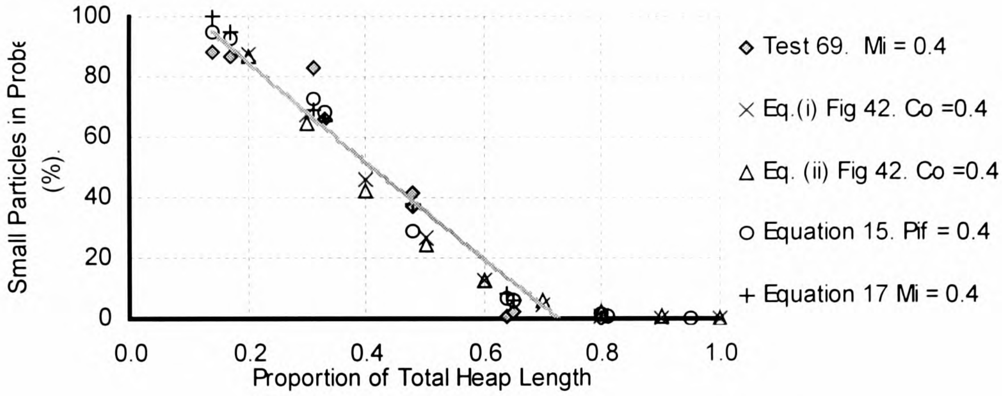


Figure A.7.3. **Predictive Model Comparisons with Experimental Results for a 3.1:1 Diameter Ratio Binary Mixture for a Feedrate of 300 g/s.**

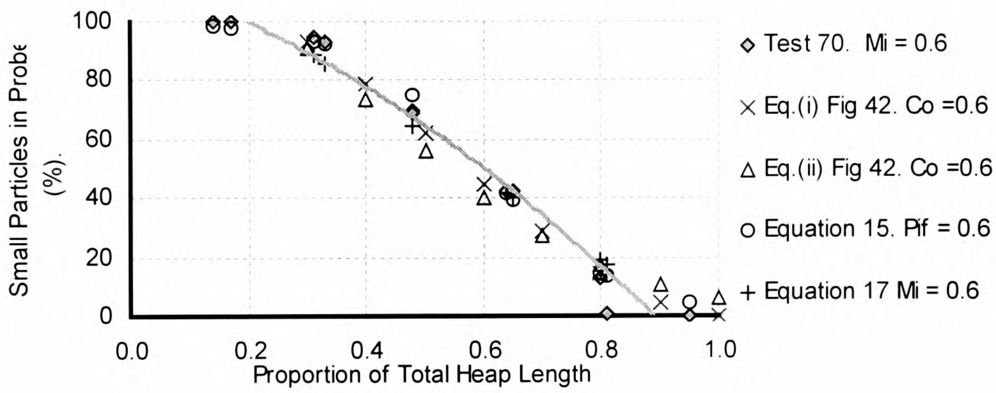
Each of the four experimental lines shown in Figure A.7.3. are shown individually below in order to provide a clearer picture of their ability to predict segregation.



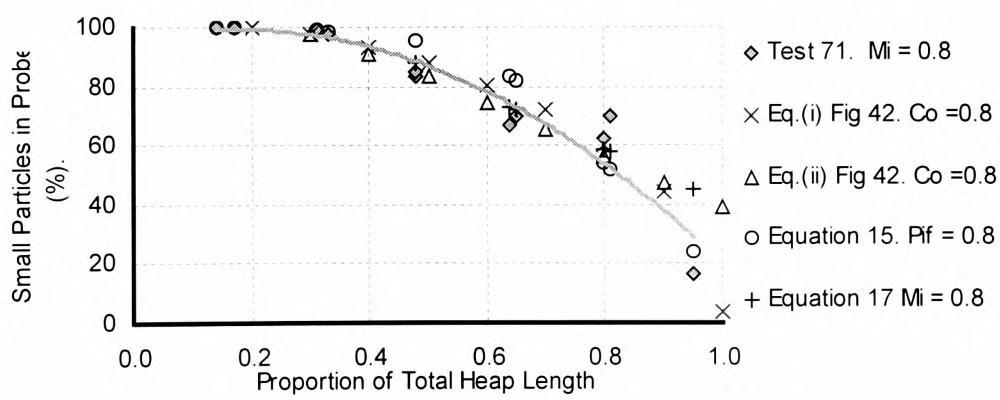
Diameter ratio (D/d) = 3.1:1 Feedrate (Fr) =300 g/s Mi = 0.4



Diameter ratio (D/d) = 3.1:1 Feedrate (Fr) =300 g/s Mi = 0.6



Diameter ratio (D/d) = 3.1:1 Feedrate (Fr) =300 g/s Mi = 0.8



APPENDIX A.8

TEST RESULTS FOR VERTICAL FEED

Test No	Size One d50	Size Two d50	Median Diameter Ratio	Feed (g/s)	Prop. of Size One	Proportional Distance Down Heap Length From Feed Point 0.04	0.08	0.21	0.25	0.38	0.43	0.55	0.6	0.72	0.78	0.89	0.95
						Small Particles in Probe Sample (% Mass)											
157	4.4	6.1	1.4	100	0.2	39.3	44.5	49.0	41.4	33.8	27.3	18.5	11.7	6.7	4.5	2.6	3.5
159	4.4	6.1	1.4	100	0.4	69.3	70.2	74.7	73.5	67.1	61.8	50.1	40.2	28.2	17.8	7.1	3.7
174	4.4	6.1	1.4	100	0.6	82.6	84.0	86.5	85.8	87.0	77.7	67.3	61.3	50.0	36.8	23.9	8.2
161	4.4	6.1	1.4	100	0.8	89.2	93.3	93.9	93.4	92.8	89.2	80.0	74.6	67.6	63.4	55.9	35.7
163	4.4	6.1	1.4	300	0.2	40.3	38.8	32.8	34.2	27.4	28.3	20.5	13.9	7.8	6.5	2.9	2.8
165	4.4	6.1	1.4	300	0.4	63.8	63.5	62.5	58.7	57.2	51.9	43.1	35.4	23.2	16.5	6.2	3.9
175	4.4	6.1	1.4	300	0.6	76.5	76.7	79.0	79.2	77.1	68.0	64.9	55.9	42.9	34.0	15.7	6.9
167	4.4	6.1	1.4	300	0.8	88.3	92.3	91.4	92.4	92.6	89.9	82.5	79.7	69.5	63.7	58.8	34.2
176	4.4	6.1	1.4	500	0.2	38.0	37.0	37.2	33.8	29.3	27.7	19.6	16.2	9.5	7.8	3.4	2.5
177	4.4	6.1	1.4	500	0.4	61.5	61.5	60.0	57.6	55.0	51.2	41.0	36.0	24.0	18.0	8.0	4.5
178	4.4	6.1	1.4	500	0.6	82.0	83.0	82.0	81.0	80.0	75.0	66.0	61.0	45.0	40.0	25.0	10.0
179	4.4	6.1	1.4	500	0.8	87.9	88.0	87.0	88.0	89.0	85.0	77.0	76.0	65.0	60.0	50.0	32.0
169	4.4	6.1	1.4	700	0.2	36.8	36.3	34.8	33.3	28.5	27.7	20.1	18.3	10.7	9.1	3.4	2.1
171	4.4	6.1	1.4	700	0.4	60.5	60.5	59.2	56.7	51.9	49.5	39.4	37.2	25.4	20.6	9.5	5.1
180	4.4	6.1	1.4	700	0.6	80.7	80.6	76.5	74.2	74.3	68.2	63.9	60.0	46.2	42.1	29.4	13.9
173	4.4	6.1	1.4	700	0.8	87.7	84.9	84.8	86.5	86.2	82.9	73.4	73.5	61.0	58.1	43.2	30.4
195	4.4	8.1	1.85	100	0.2	42.7	44.0	48.8	41.9	27.8	22.0	7.3	5.9	2.9	2.6	1.1	4.3
196	4.4	8.1	1.85	100	0.4	71.6	75.7	85.1	81.0	65.9	61.4	38.4	30.5	11.0	5.7	2.5	4.1
197	4.4	8.1	1.85	100	0.6	90.1	94.1	95.5	97.6	90.2	84.3	63.4	62.5	37.2	42.3	5.1	4.4
198	4.4	8.1	1.85	100	0.8	93.3	97.7	95.7	100.0	96.8	97.7	88.1	79.3	77.2	71.3	59.9	36.4
199	4.4	8.1	1.85	300	0.2	49.4	51.0	49.6	48.0	35.1	27.2	16.5	8.7	4.9	3.6	1.9	2.3
200	4.4	8.1	1.85	300	0.4	63.9	69.6	76.4	73.5	63.8	61.2	36.7	28.8	8.3	5.6	1.1	2.9
201	4.4	8.1	1.85	300	0.6	82.2	82.2	88.8	89.7	85.6	79.6	58.6	52.9	27.9	23.7	3.5	2.9
202	4.4	8.1	1.85	300	0.8	95.1	97.3	98.9	98.8	99.1	98.7	88.2	86.4	68.4	68.1	45.5	19.2
203	4.4	8.1	1.85	500	0.2	46.0	48.0	45.0	43.0	32.0	25.0	13.0	7.0	3.5	3.0	1.5	1.7
204	4.4	8.1	1.85	500	0.4	70.0	72.0	70.0	68.0	62.0	55.0	38.0	29.0	15.0	6.0	1.5	2.3
205	4.4	8.1	1.85	500	0.6	85.0	86.0	86.0	85.0	82.0	79.0	62.0	55.0	35.0	28.0	8.0	2.3
206	4.4	8.1	1.85	500	0.8	94.0	96.0	96.0	96.0	94.0	95.0	84.0	81.0	65.0	60.0	38.0	17.0
207	4.4	8.1	1.85	700	0.2	43.8	41.8	41.2	36.9	30.5	24.3	11.3	10.7	3.2	3.4	0.7	1.4
208	4.4	8.1	1.85	700	0.4	68.5	70.3	64.0	62.9	60.0	51.2	40.3	28.7	16.3	7.5	2.0	1.9
209	4.4	8.1	1.85	700	0.6	86.6	87.7	84.7	82.7	78.3	79.1	66.1	56.9	44.2	34.1	12.0	3.5
210	4.4	8.1	1.85	700	0.8	95.3	93.7	93.7	95.7	91.2	97.2	79.6	85.3	53.4	68.5	32.3	14.1
139	2.6	6.1	2.36	100	0.2	48.3	54.5	62.1	56.5	13.9	9.3	5.5	5.1	2.8	2.2	1.1	1.6
141	2.6	6.1	2.36	100	0.4	66.9	79.7	94.2	84.1	68.9	53.9	29.6	13.2	2.9	2.5	1.4	1.5
188	2.6	6.1	2.36	100	0.6	93.0	99.0	100.0	100.0	86.1	79.0	60.9	57.2	46.9	31.8	2.5	2.1
143	2.6	6.1	2.36	100	0.8	96.0	99.2	99.6	99.6	93.8	88.2	77.1	74.9	74.0	70.6	65.0	12.5
145	2.6	6.1	2.36	300	0.2	51.9	55.4	62.9	46.7	21.9	10.0	4.5	3.9	1.9	1.7	0.7	1.1
147	2.6	6.1	2.36	300	0.4	70.2	79.5	85.0	85.1	66.1	53.7	33.0	18.6	2.3	2.5	1.1	1.1
189	2.6	6.1	2.36	300	0.6	85.7	94.1	96.4	96.9	87.8	79.9	66.5	60.7	39.7	24.3	1.4	1.3
149	2.6	6.1	2.36	300	0.8	94.0	98.0	100.0	99.8	96.3	93.9	82.7	82.8	68.9	66.6	46.4	3.9
190	2.6	6.1	2.36	500	0.2	48.0	54.0	57.0	44.7	20.9	12.3	4.5	4.5	1.3	1.6	0.6	0.9
191	2.6	6.1	2.36	500	0.4	66.0	76.0	80.0	78.2	63.1	52.5	35.5	23.7	5.6	2.8	0.8	0.9
192	2.6	6.1	2.36	500	0.6	83.0	92.0	95.5	95.5	90.0	83.0	67.0	60.0	35.0	22.0	1.2	0.8
193	2.6	6.1	2.36	500	0.8	90.0	96.0	97.8	98.0	94.0	91.3	78.8	77.7	65.9	62.8	27.1	3.1
151	2.6	6.1	2.36	700	0.2	47.9	53.4	50.2	43.5	19.8	14.2	4.7	4.6	1.4	1.6	0.6	0.9
153	2.6	6.1	2.36	700	0.4	64.5	74.5	74.5	75.8	62.4	51.6	36.7	28.1	6.6	2.8	0.9	0.9
194	2.6	6.1	2.36	700	0.6	80.0	90.0	95.0	95.0	93.0	85.0	70.0	60.0	30.0	20.0	1.0	0.5
155	2.6	6.1	2.36	700	0.8	87.09	95.1	96.44	98.24	94.39	90.78	75.8	75.83	63.86	59.41	18.54	1.9
121	2.6	8.1	3.1	100	0.2	38.5	52.5	44.2	42.4	10.0	9.4	5.7	5.6	3.0	2.2	1.4	1.9
123	2.6	8.1	3.1	100	0.4	68.8	78.3	83.2	76.4	58.0	43.3	26.1	11.8	2.5	2.7	1.3	2.7
181	2.6	8.1	3.1	100	0.6	92.3	98.6	100.0	100.0	91.8	82.6	63.1	55.3	41.7	34.4	1.0	2.1
125	2.6	8.1	3.1	100	0.8	96.1	99.7	99.7	100.0	98.1	100.0	92.9	87.9	84.8	73.3	42.4	1.4
127	2.6	8.1	3.1	300	0.2	49.1	57.0	57.7	48.8	16.9	8.4	3.2	4.3	1.6	1.5	0.9	1.0
129	2.6	8.1	3.1	300	0.4	70.6	84.1	86.1	83.6	59.5	62.2	26.7	25.1	1.8	4.1	0.8	1.7
182	2.6	8.1	3.1	300	0.6	85.6	90.1	99.1	95.7	91.7	81.6	60.9	58.6	31.6	15.0	0.9	1.0
131	2.6	8.1	3.1	300	0.8	96.3	100.0	100.0	100.0	100.0	96.8	84.7	77.1	70.0	67.3	44.1	3.5
183	2.6	8.1	3.1	500	0.2	47.0	53.0	55.0	48.0	18.3	13.1	4.9	9.0	1.0	1.0	0.1	0.2
184	2.6	8.1	3.1	500	0.4	65.0	76.0	78.0	78.3	65.0	59.0	35.4	22.5	2.0	1.5	1.0	1.0
185	2.6	8.1	3.1	500	0.6	83.0	88.0	97.0	92.0	92.0	78.0	58.0	57.0	43.0	25.0	5.0	1.0
186	2.6	8.1	3.1	500	0.8	90.0	98.0	97.0	98.0	98.0	95.0	85.8	80.0	67.1	59.0	16.7	1.0
133	2.6	8.1	3.1	700	0.2	44.8	51.9	54.9	46.9	18.6	17.5	1.8	7.4	0.6	1.0	0.3	0.5
135	2.6	8.1	3.1	700	0.4	63.1	74.1	77.3	78.3	70.6	58.0	40.9	27.3	4.0	2.6	0.9	1.2
187	2.6	8.1	3.1	700	0.6	81.0	89.0	91.0	87.0	87.0	74.0	55.0	47.0	35.0	18.0	5.0	1.0
137	2.6	8.1	3.1	700	0.8	86.0	96.6	98.5	98.0	98.1	94.2	81.5	75.6	59.9	58.3	12.8	0.8

APPENDIX A.9

CONICAL HEAP SEGREGATION RESULTS

Test No.	Size One d50	Size Two d50	Median Diameter Ratio	Feed (g/s)	Prop. of Size One	Radial Samplig Position	**Proportional Distance Down Heap Length From Feed Point** 0	0.225	0.45	0.675	0.9
							Small Particles in Probe Sample (% Mass)				
223	4.4	6.1	1.4:1	300	0.4	0	51.7	53.1	62.6	71.1	43.5
224	4.4	6.1	1.4:1	300	0.4	0	45.5	52.7	62.2	65.4	37.4
225	4.4	6.1	1.4:1	300	0.4	120	53.3	54.3	54.7	56.2	33.8
226	4.4	6.1	1.4:1	300	0.4	120	54.5	53.7	56.5	53.2	32.1
227	4.4	6.1	1.4:1	300	0.4	240	52.1	58.4	62.2	68.1	48.3
228	4.4	6.1	1.4:1	300	0.4	240	51.5	57.0	61.7	67.7	47.5
233	4.4	8.1	1.85:1	300	0.4	0	52.1	63.8	73.3	84.4	27.8
216	2.6	6.1	2.36:1	100	0.4	0	86.0	97.8	99.5	92.3	16.1
211	2.6	6.1	2.36:1	300	0.4	0	75.5	83.3	95.0	94.9	12.0
212	2.6	6.1	2.36:1	300	0.4	0	73.2	82.8	92.8	91.2	18.6
213	2.6	6.1	2.36:1	300	0.4	0	70.7	79.3	93.6	94.3	15.9
214	2.6	6.1	2.36:1	300	0.4	0	73.5	83.3	94.0	97.9	19.9
215	2.6	6.1	2.36:1	300	0.4	0	73.4	83.7	94.5	96.7	17.6
218	2.6	6.1	2.36:1	500	0.4	0	69.2	79.0	90.0	89.4	12.4
217	2.6	6.1	2.36:1	700	0.4	0	62.6	74.7	83.0	78.5	5.7
231	2.6	6.1	2.36:1	300	0.4	60	72.3	80.7	91.8	80.4	5.6
232	2.6	6.1	2.36:1	300	0.4	60	71.5	78.5	89.3	79.8	3.4
219	2.6	6.1	2.36:1	300	0.4	120	68.3	71.0	80.6	45.3	4.3
220	2.6	6.1	2.36:1	300	0.4	120	66.2	74.9	85.7	41.8	3.7
229	2.6	6.1	2.36:1	300	0.4	180	76.5	83.0	89.5	77.6	4.8
230	2.6	6.1	2.36:1	300	0.4	180	75.8	81.5	88.7	76.5	4.3
221	2.6	6.1	2.36:1	300	0.4	240	62.5	75.9	87.4	86.3	5.7
222	2.6	6.1	2.36:1	300	0.4	240	62.6	73.6	88.2	69.7	4.8
234	2.6	6.1	2.36:1	300	0.4	300	69.9	77.6	87.3	72.4	5.1
235	2.6	6.1	2.36:1	300	0.4	300	68.7	78.3	85.8	73.5	4.9

APPENDIX A.10

CONICAL HEAP SCALING TECHNIQUE

A.10.1. Conical Heap Scaling Technique

Example of Scaling Probe Position 7 from Plane-Flow to Conical Heap

L_{PF} = Original Plane Flow Vessel, Distance from Heap Apex to Position of Probe

L_{Ch} = Distance From Heap Apex to Periphery of a Conical Heap

Angle = Poured Angle of Repose of Material (Degrees from the Horizontal)

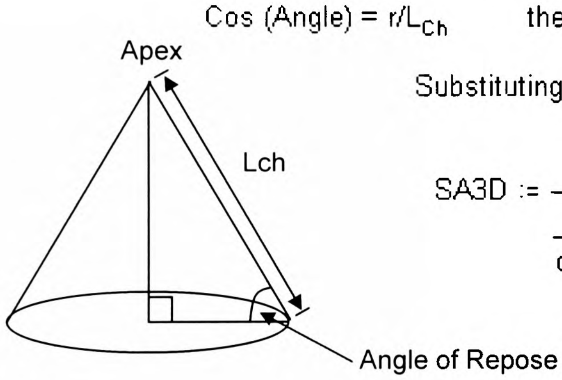
Lpf := 0.043 m pi := 3.14159 AngleofRepose := 35 degrees Lch := 0.6 m

Angle of Repose converted from Degrees into Radians: Angle (degrees) * (pi/180) = Angle (Radians)

$$\text{Repose} := \text{AngleofRepose}\cdot\left(\frac{pi}{180}\right) \qquad \text{Repose} = 0.611 \quad \text{Radians}$$

Surface Area of a conical heap (SA3D) = 1/3 *pi*r*lcheap - - - - - - - - - - - - - - - (i)

Cos (Angle) = r/L_{Ch} therefore $r = L_{Ch}/(1/\text{Cos (Repose)})$



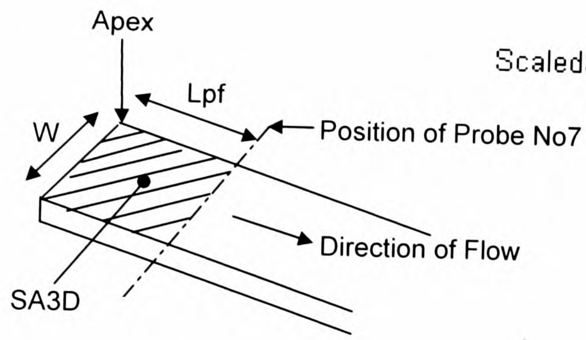
Substituting r into (i) gives

$$SA3D := \frac{Lch^2\cdot pi}{\dfrac{1}{\cos(\text{Repose})}} \qquad \text{therefore } SA3D = 0.926 \quad m^2 \text{ - - -(ii)}$$

Width of Plane-Flow Vessel that would have same surface area & heap length as conical heap

$$W := \frac{SA3D}{Lch} \qquad \text{therefore} \quad W = 1.544 \quad m$$

What is Surface Area in Plane Flow Rig from Apex to Probe Position using scaled width (W) and original length from apex to probe position (LD)



$$ScaledSA := W \cdot Lpf$$

therefore $ScaledSA = 0.066\ m^2$

What is new scaled length from Conical Heap Apex to Pobe Position using the value of ScaledSA. To achieve this, swap SA3D value for ScaledSA in equation (ii). By doing this the length term (originally L_{CH}) in equation (ii) has now changed to the desired Scaled Length which we wish to determine. Re-arranging equation (ii) to make ScaledLength the subject of the expression gives:

$$ScaledLength := \sqrt{\left[\frac{\left(\dfrac{1}{\cos(Repose)}\right) \cdot \left[\dfrac{\dfrac{pi \cdot Lch^2}{\left(\dfrac{1}{\cos(Repose)}\right)}}{Lch}\right] \cdot Lpf}{pi}\right]} \qquad \text{------ (iii)}$$

Equation (iii) simplifies to: $ScaledLength := \sqrt{Lch} \cdot \sqrt{Lpf}$

$ScaledLength = 0.161 \quad m^2$

Expressed as a percentage of conical heap length = $\% := \left(\dfrac{ScaledLength}{Lch}\right) \cdot \dfrac{100}{1}$

therefore new scaled position of probe 7 $= 26.771\ \%$

APPENDIX A.11

PUBLICATIONS

Mixing of Particulate Solids Using Static Mixers

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Summary: Static mixers are finding increasing application in the process industries for mixing particulate solids. The versatility of static mixers lend themselves to many advantages compared to dynamic mixers but the exact mixing process which can influence static mixer performance is not well understood. Various investigations into assessing the performance of static mixers are reviewed along with a more general overview of the area of mixing in terms of mixing mechanisms and equipment. In this article, pilot investigations into the radial mixing of binary mixtures in a static mixer with respect to size utilising a novel sampling method are presented. It was concluded that the static mixer under investigation fulfilled the necessary requirements to be included as an integral part of a segregation testing facility, based on test results which indicated the mixer's ability to mix highly segregating materials to a satisfactory degree of mixedness.

1 INTRODUCTION

1.1 Work Objectives

The radial mixing ability of a static mixer was investigated in order to assess its applicability to be used as an integral part of a segregation testing facility being developed at The Wolfson Centre, University of Greenwich, London, England.

Evaluation of the static mixer was based upon its ability to mix to a desired degree of mixedness, components, that varied in particle size. The mixer was required to achieve this mixing efficiently in terms of mixing time, minimal external energy input and with little or no alteration to the physical structure of the mixture components.

Prerequisites for the mixer's application required it to discharge a consistent quality of mixture as a continuous feed which is homogeneously radial in concentration. It was deemed necessary to measure the mixedness of the discharging mixture as it is to be used as a central point feed to a segregating heap. The subsequent segregation during heap formation is to be measured and used in comparison with the quality of mixture discharging from the mixer.

1.2 Mechanisms Of Mixing

In recent times there has been considerable effort directed at the description, qualitative in most cases, of the basic mechanisms which act when mixing particulate solids. For a particular process, the predominant mechanism by which mixing is progressed is a function of the flow pattern of the material within the mixer. This in turn is dependant on the physical characteristics of the material and the characteristics of the mixing environment which itself is dictated by the type of mixing equipment used.

There are three generally recognised mechanisms of mixing:-

- Diffusive mixing; independent movement of particles within a mixture, the extent of this movement being dependant on their individual particle characteristics.
- Shear mixing; prominent when shearing layers of a powder mixture
- Convective mixing; the movement of groups of particles within a mixture

These mechanisms have been documented by a number of authors including Williams (1) (2), and Lacey (3) who have recognised that the predominance of the three mechanisms during a mixing process will differ, depending on the particle characteristics of the material to be mixed and the type of mixing equipment used.

2 MIXING EQUIPMENT

2.1 Types Of Dynamic Mixing Equipment

In general, dynamic mixers can be classified according to their mechanism used to progress the mixing process. Such mixers can therefore be classified into three broad categories, i.e.,

- Tumbler mixers:- These rely on the diffusive mechanism of mixing and in general are not recommended for mixing materials which are highly prone to segregation.
- Convective mixers:- Groups of particles are moved from one part of the mixer to another.
- High shear mixers:- Useful for mixing agglomerating materials. Can cause degradation of friable materials resulting from the relatively high forces present in such mixers.

The classification of commercially available mixers, categorised according to their mechanism of operation, have been well documented by Williams (2) and Harnby (4) together with more detailed descriptions of the mechanisms of mixing.

Mixing segregating particulate solids to a high degree of mixedness is restricted when utilising any one of the categories of dynamic mixers available. Also, dynamic mixers are generally batch mixers, therefore segregation of the mixture upon mixer discharge, may result. This has prompted the current investigation into the applicability of using static mixers for mixing materials that are highly prone to segregation .

2.2 Static Mixing And The Mixing Process

Static mixing has been a long established method of mixing in a variety of industrial applications which include blending of high or low viscosity fluids, gas streams, heat and mass transfer operations and intimate dispersion and contacting reaction applications. More recently static mixers are finding an increasing variety of applications in the solids processing industry due to their inherent advantages over dynamic mixers for mixing free flowing materials. These advantages include low investment costs resulting from no moving mixer parts, gentle processing of solids due to low shear rates, a continuous mixing process which can be fitted in line with a variety of processes and energy demands and operating costs which are relatively low in comparison with dynamic mixers.

Static mixers utilise flow under gravity to mix material components as they pass down through a series of baffle elements fixed to the inside of a pipe as shown in Figure 1.

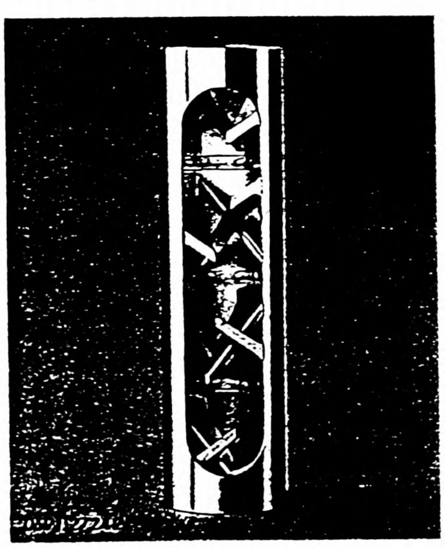


Figure 1: Static Mixer of the Type used in the Experimental Investigations. (Picture Courtesy of Sulzer Chemtech (13))

The arrangement of the baffle elements induces the flowing material stream to be split into sub-streams. When these sub-streams come into contact with the next element they are separated again with their direction of movement being altered. This continuous process ensures that the flowing material is split into an increasing number of sub-streams, the particles of which, are continuously being mixed with their neighbours. The shearing forces in the material as a result of the mixing process are small in comparison to a majority of the dynamic mixing processes. The static mixing process culminates in discharging a mixture which has suffered minimal degradation and is generally homogenised radially and axially in terms of the component particle characteristics present in the mixture.

3 A REVIEW OF METHODS USED TO MEASURE MIXING PERFORMANCE

3.1 Defining Terms Associated With Mixture Quality

Assessment of mixing performance can only be achieved when terms associated with the mixing process have been defined. The mixing process could be undertaken using either a dynamic or static mixer, each with its own characteristic mechanism of mixing. These mechanisms will induce movement of particles within a mixture which is fundamental in progressing the mixing process. However, movement of individual particles which differ in characteristics can cause the mixture to segregate, as well as mix, during the mixing cycle, therefore preventing the consistent attainment of a perfectly mixed mixture. As mixing progresses, the resulting mixture quality will reside at a position of equilibrium somewhere between two extremes, one extreme defined as the perfectly mixed state, while the other, a completely segregated state as shown in Figure 2(a).

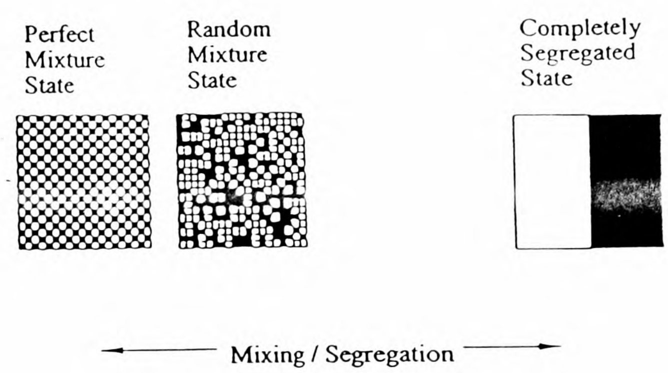
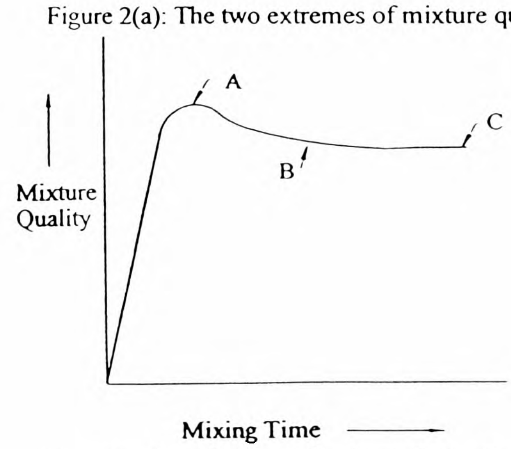


Figure 2(a): The two extremes of mixture quality



A. Highest Quality of Mixture During Mixing Process.

B. Mixture Quality Reducing Due to Chaotic Segregation and Mixing.

C. Equilibrium Degree of Mixing.

Figure 2(b): A Graph Showing How Segregation and Mixing Effects the Ultimate Equilibrium Degree of Mixing Achieved.

A perfect binary mixture could be assumed to resemble the appearance of a chess board, where any group of particles taken from the mixture would consist of the same proportions, even when a small sample size of two particles is selected. Nevertheless, the aforementioned mechanisms of mixing associated with various mixing equipment cannot consistently attain a perfect mixture at equilibrium for a variety of materials of differing particle characteristics, and therefore mixing is undertaken in order to produce a high quality random mixture. Williams (2) defined a random mixture as a mixture in which the probability of finding a particle of any component is the same at all positions in the mixture and is equal to the proportion of that component in the mixture as a whole.

As stated, the particle characteristics of a mixture and the mixing environment will influence the ultimate position of equilibrium between the two extremes. Boss et al. (10) showed that this equilibrium position could be considered as the most sustainable degree of mixedness that can be achieved for a particular set of mixing circumstances. However, the equilibrium position is not the highest degree of mixedness of mixture produced at any one instance for the set of mixing circumstances as shown in Figure 2(b). This is due to the segregating/mixing behaviour of a mixture during the mixing process as mixing time progresses. Excessive mixing time can cause considerable depreciation in mixture quality.

Williams (1) stated that an inappropriate match of mixer to a material which has a high propensity to segregate can result in a very poor degree of mixing at equilibrium being achieved. When mixing a non-segregating mixture the degree of mixing at equilibrium will generally approach the desired random state, whereas, a mixture highly susceptible to segregation will not achieve such a high state of equilibrium.

3.2 Assessing Mixing Performance

Often the random nature of various mixing processes has resulted in researchers using statistical analysis to express the quality or degree of mixedness of a mixture. This has involved measuring the standard deviation or variance of spot samples taken from a mixture and utilising the values in various forms of mixing indices.

Lacey (5) expressed two statistical limiting values for a binary mixture:-

σ_R The standard deviation for a fully randomised mixture, where the value is calculated from a knowledge of the proportion of component in the mix.

σ_O The standard deviation for a completely segregated mixture.

Rose (6), Lacey (3), Jeck (8) and Poole et al. (7) have accommodated one or both of these extremes into various indices of mixing. These indices often incorporate the experimentally determined standard deviation from samples analysed with other statistical quantities to produce a numerical value, which is usually expressed as a dimensionless ratio. The ratio is generally represented as zero for a fully segregated mixture and unity for a fully randomised mixture. Williams (1) and Harnby (4) point to the fact that some indices based on the aforementioned forms of standard deviation become insensitive to small changes in mixedness of the mixture as the index approaches unity. Lacey's (5) mixing index was utilised by Poole et al. (7) in processing experimental results obtained using a centrifuge type batch blender. Whilst mixing indices based on binary mixtures provide a useful insight into the mixedness of the mixture, they are limited in their application to industrially relevant materials.

Industrially relevant materials are generally multi-component mixtures having a range of particle characteristics. This does not effect the process of obtaining the experimental standard deviation from mixture samples but does complicate the determination of an optimum value of σ_R. Harnby (4) states that the original assumption made in order to determine the optimum value of σ_R for a binary mixture is no longer valid because the number of particles in every sample taken does not remain the same. Poole et al. (7) has therefore developed an expression which allows the determination of a limiting value of σ_R for a two-component multi-sized particulate mixture. Also an expression for a limiting value of σ_R for a fully randomised mixture has been developed by Stange (9) to cover multi-component mixtures, provided that particle characteristics of the mixture components are known. Whilst expressions for obtaining values of the best randomised mixture may prove impossible to achieve in practice when mixing materials highly prone to segregation, they can provide an indication of the best possible mixture limits.

3.3 Static Mixing Investigations

Of the literature available which relates to the performance of static mixers, most are concerned with axial mixing performance, whereas investigations into radial mixing has received comparatively little attention. More often than not this is as a result of the fact that practical situations in process plant, for which the use of static mixers are being applied, are more sensitive to axial deviations in mixture quality occurring rather than radial variations. However, conclusions drawn from axial investigations can be qualitatively compared to radial mixing due to their identical mechanisms of mixing. Also, although the dominant travel of the mixture is vertical, the process of mixing is a volume process which occurs radially as well as axially.

Boss et al. (10) conducted investigations into axial mixing of heterogeneous mixtures for four commercially available designs of mixing element. Test results were analysed using Roses's 'mixing theory' (6) in order to study the distribution of pre-selected particles at different positions in a mixture, as mixing progressed, for the different mixing elements under investigation. The experimental apparatus consisted of a ten segment, feed cassette and receiver cassette positioned on either end of the mixing element being examined. The test material was placed in pre-selected segments of the feeder cassette. The feed was then allowed to discharge through the mixing element and into the receiver cassette. One pass of the material through the mixing element was considered a step. The receiver then became the new feeder by changing positions and vice versa. This process was repeated for a variety of steps up to a maximum of sixty before the concentration of the particles in each of the ten segments was measured in order to establish the degree of mixing at equilibrium for the particular test element. Further tests were conducted to assess what effect the initial placing of size fractions at different positions in the feed cassette prior to mixing had on the degree of mixing achieved at equilibrium. In conclusion the authors stated that the initial position of size fractions does not affect the degree of mixing reached at equilibrium, and that a measurable improvement in mixing equilibrium was found to occur as the diameter of the mixing element increased. The degree of mixing at equilibrium was reached after approximately 25 35 steps and when the size ratio of the material to be mixed increased the degree of mixing at equilibrium was subsequently reduced by an amount which was dependant on the element type under investigation. It is evident, from their investigations, that the four different types of mixing element under investigation each yielded a mixture which had a different degree of mixing at equilibrium.

Boss et al. (10) were concerned in investigating the effect of particle size difference on the resulting degree of mixing at equilibrium achieved, where it was assumed that there was no distribution in sizes for each of the two size fractions used in tests. For industrially relevant materials there would be considerable diameter differences in either of the two size fractions used. Therefore, Boss and Wegrzyn (11) investigated the effects of altering the size distribution in one of the two size fractions being tested and assessing what effect it had on the resulting degree of mixing at equilibrium achieved. An identical experimental apparatus was used to that of Boss et al. (10), however, only three different mixing elements were examined. Throughout the experiments, the size fraction under investigation, consisting of selected proportions of various sieve fractions was pre-mixed and placed in the first five segments of the feeder cassette. The remaining material which formulated the mixture to be tested was placed into the second five segments. As was the case with Boss et al. (10), the degree of mixing at equilibrium was established after approximately thirty steps. The results obtained from their experimental work was used in conjunction with *Bartletts* statistical test to verify a null hypothesis. The null hypothesis, stated as 'all the equilibrium states of the mixture for the particular mixer are the same', was set against the alternative hypothesis which states that 'all the equilibrium states of the mixture are not the same'. The authors conclude that variations in proportions of various sieve fractions which made up the size fraction under investigation produced different degrees of mixing at equilibrium which were statistically insignificant, therefore indicating that the rejection of the null hypothesis could not be undertaken. The authors highlighted the fact that from analysing the particle size fraction under investigation in each segment of the receiver cassette analysed, segregation of sieve fractions within the size fraction under investigation was found to vary longitudinally, thus indicating some inhomogeneity of the mixture axially.

Herbig and Gottschalk (12) also investigated axial mixing of segregating solid particles in a static mixer. The static mixer consisted of poles arranged in two layers positioned perpendicular to each other to form a grid. Materials to be tested were formulated to give size ratios up to 1:10 and density ratios up to 1:3.6. The performance of the mixer was assessed by employing an electromagnetic induction sensing test method using ferromagnetic iron as one of the key components in a mixture. This allowed direct measurement of the amount of the component in the mixture as it discharged from a funnel positioned beneath the static mixer. Again, as with Boss et al. (10) & (11), a number of passes through the mixer was required before the degree of mixing at equilibrium was reached. The authors concluded that the large differences in size and density ratios investigated made only a small difference to the performance of the mixer which was in general agreement with the work Boss et al. (10). Experiments to assess the effects that initial arrangements of particles in the feeder prior to mixing had on the degree of mixing at equilibrium achieved was investigated. Their results indicated that initial positioning of mixture components does influence the progression of mixing, but had no significant influence on the ultimate degree of mixing achieved at equilibrium, a point well made by Boss et al. (10).

4 EXPERIMENTAL INVESTIGATIONS

4.1 Objective

The performance of a nine element static mixer, which was of a proprietary type supplied by Sulzer Chemtech (13), was scrutinised in terms of its radial mixing capabilities using binary mixtures that varied in particle size. A device by which the mixed discharging stream from the mixer could be analysed with minimal disturbance to the physical state of the mixture was developed.

4.2 Apparatus

The static mixer and sampling device formed the major elements of the testing facility which is shown in Figure 3. The static mixer is nominally 100mm in diameter and approximately 800mm in length. The facility consisted of two gravimetric resonant vibratory feeders of a novel design by Barnes (14) which fed pre-selected binary mixture streams, the nine element static mixer under investigation, the sampling device, flow centring section, flow concentration section and bottom fill pipe. The flow centring section and bottom fill pipe were designed and included as part of the experimental testing facility as a result of two problematic areas which were highlighted from initial test runs.

One was concerned with the geometry of the final element in the static mixer which imposed a directional trajectory to the flowing mixture stream resulting in preferential radial flow discharging from the mixer. A pre-requisite of the mixers applicability states that it should provide a homogeneously mixed discharging stream across the whole cross-section of the mixer outlet. This therefore prompted the inclusion of a flow centring section which was designed and attached to the base of the static mixer. The section helped to counteract any directional effects resulting from the geometry of the last mixing element and provided a discharging stream commensurate to the required specifications. However, any subsequent measurements made on the performance of the static mixer has incorporated into it the effects contributed by the flow centring section.

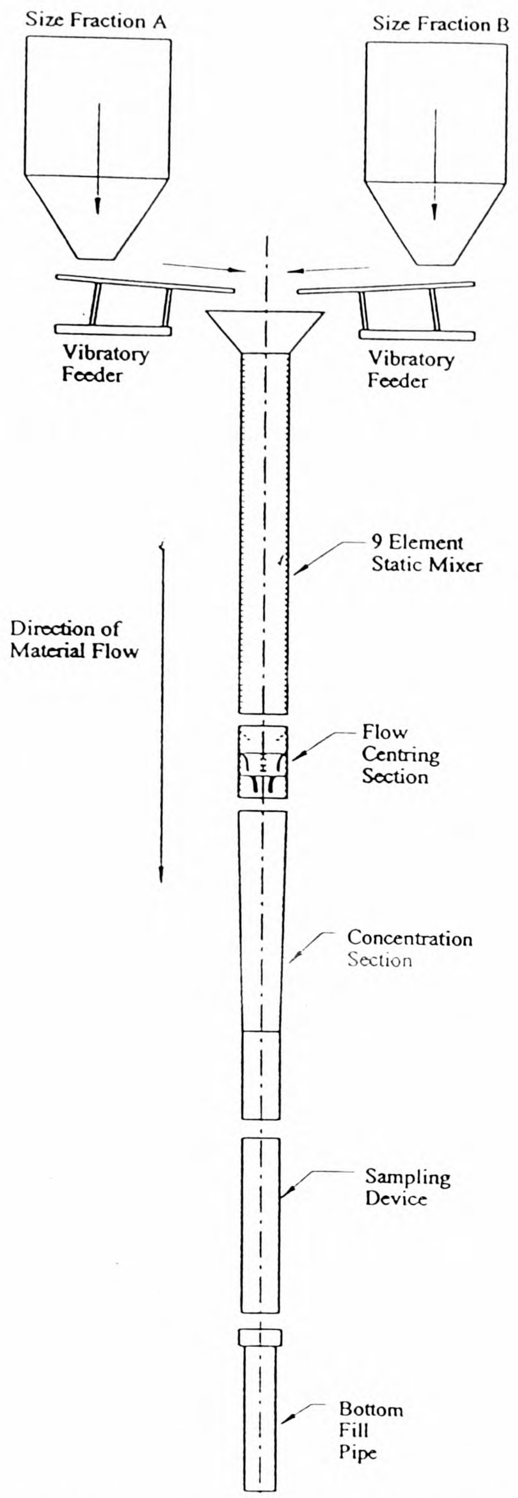


Figure 3: A Schematic Layout of the Experimental Apparatus

The second problem was caused by inconsistent feeding when initially starting the gravimetric vibratory feeders. This caused initial feed proportions to differ from pre-determined set values. A bottom fill pipe was designed and connected to the base of the sampling device in order to contain this initial material and prevent it from being used in any subsequent analysis. The pipe was also measurably smaller in diameter to that of the sampling device which resulted in the surface of the collected material to rise rapidly up through the pipe and sampling device and into the flow concentration pipe. This rapid filling of the sampling device resulted in reducing to a minimum, any time for segregation of the discharging stream resulting from heap formation when filling the sampling device.

A section of pipe which radially concentrated the discharging stream was connected to the base of the flow centring section. The sampling device which is shown in Figure 4 was attached to the bottom of the concentration section which split the radially homogeneous flowing stream into four axial pockets.

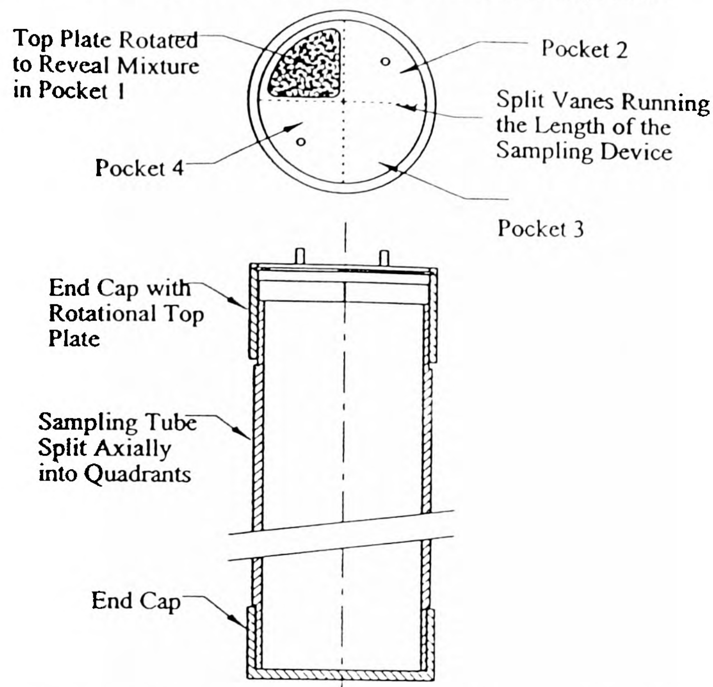


Figure 4: The Sampling Device with End Caps in Position

After a finite time of feeding, when the sampling device had filled with mixed material the feeding was stopped. Specially designed caps which allowed the separate extraction of material in each pocket were positioned on either end of the sampling device without disturbing the material in each pocket. The ratio of the mixed components in each quadrant was then measured and compared to the initial feed conditions.

4.3 Mixture Component Materials

Binary mixtures were compiled from different test materials used and are tabulated in Table 1. Narrow size fractions as a result of sieving were used as a single binary fraction. Even though these fractions contained some small distribution in particle size they were considered narrow enough to be assigned a numerical value based on the mean size of the fraction without any detrimental effects to subsequent mixing performance analysis.

Spherical Test Materials	Mean Particle Size (mm)	Diameter Ratio
Aggregate Small Size/ Aggregate Large Size	3.4 / 5.75	1.7:1
Non-Spherical Olivine Sand / Plastic Pellets	0.33 / 2.8	8.5:1
Aggregate Large Size / Mustard Seed	5.75 / 2.0	3:1
Aggregate Large Size / Plastic Pellets	5.75 / 2.8	2:1

Table 1: A Table Indicating Materials used in Test Program

5 DISCUSSION

Initial tests were conducted to assess the performance of the flow centring section in counteracting any abnormal directional flow from the static mixer and provide a radially homogenous discharging mixture stream. Visual indications of the discharging stream indicated that it was functioning as intended. Further confidence of its inclusion in the test facility was attained by conducting tests to ascertain whether there was an even fill rate in each quadrant of the sampling device. This was achieved by feeding mixture components for a definitive amount of time to allow the sampling device to be filled part way.

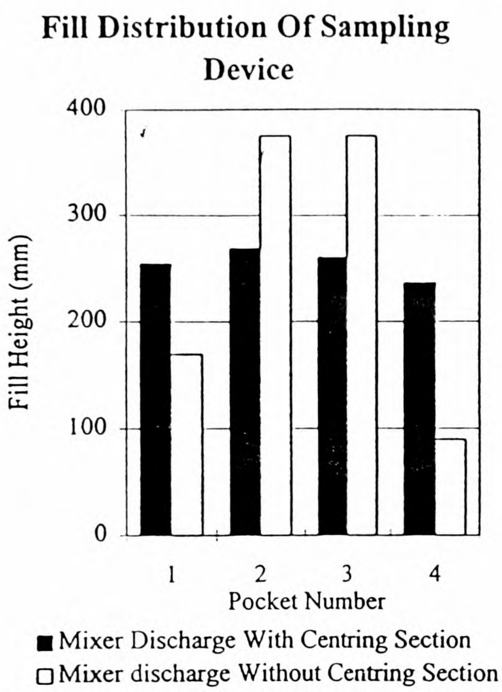


Figure 5: A Graph Indicating an Even Radial Discharge From the Mixer using the Flow Centring Section.

Figure 5 provides evidence that an even fill of the sampling device was not being achieved when the flow centring section was missing but was filling evenly when used, thus indicating that the flow centring section was functioning as intended and could be used permanently as part of the experimental testing facility. An even fill of the sampling device allowed tests to be conducted to ascertain radial homogeneous mixing of binary mixtures discharging from the mixer for different diameter and feed proportion ratios.

Prior to every mixing test run, the feed from the vibratory metering system was measured to ensure consistent feed was being achieved. Each mixing test condition was repeated three times. This revealed a high level of repeatability of the test runs and also highlighted little or no detrimental effects to mixture quality using the sampling method for extracting the test mixture was found. After each test run the mixture contained in each of the four pockets was extracted separately from the sampling device and analysed with respect to the calibrated feed proportion ratio as well as the ideal feed proportion ratio.

Results are expressed in terms of the average difference in proportions in each pocket compared to the feed proportions and are shown in Figure 6.

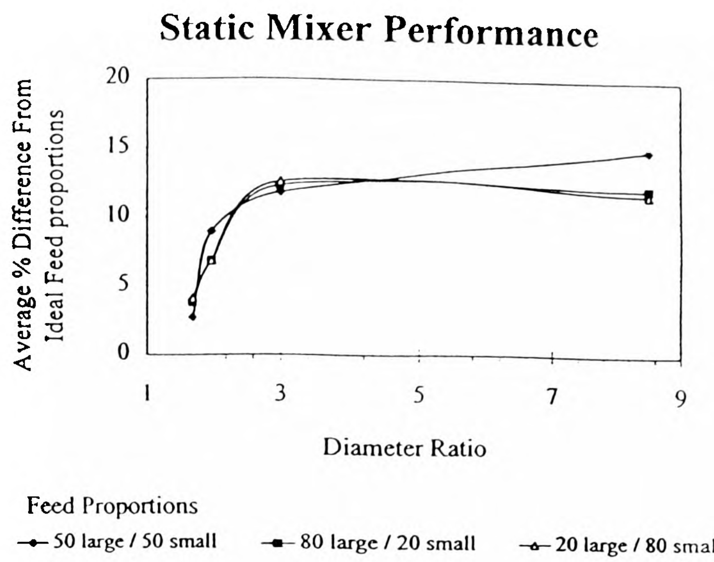


Figure 6: A Graph Indicating the Effect that Particle Diameter Ratio has on Mixer Performance.

Figure 6 provides an indication of what effect the particle diameter ratio had on the resulting average degree of radial mixing. As can be seen, the mixer performed well when mixing diameter ratios up to around 2:1 where the percentage difference from the split was limited to around 5%. There is a steady drop in mixer performance as the diameter ratio increases but the performance of the mixer is not significantly further effected for particle diameter ratios in-excess of 4:1. However, further tests are required using diameter ratios between 4:1 and 8.5:1 to give an indication of the characteristic pattern of the curves between these two ratios for the different feed proportions tested.

A pre-requisite of the applicability of the static mixer states that it was required to mix mixtures which have very strong segregating tendencies to a reasonable level, hence the use of diameter ratios of 8.5:1 in the test program which helped to accentuate any failings of the mixer in its performance. In general the mixer fluctuated at worst around 15% from the desired settings when using a diameter ratio of 8.5:1 which is comparable to Herbig and Gottschalk (12) who recognised a depreciation in the equilibrium position of mixture quality as the diameter ratio approached 10:1. Boss et al. (10) also observed a measurable reduction in mixture quality when using larger diameter ratios but considered the amount of de-mixing negligible.

Nevertheless, with this said, if the mixer is to be incorporated into a subsequent segregation testing facility, it is unlikely to be required to mix such large differences in diameter ratio as segregation test materials will involve third and fourth size fractions inserted in between the upper and lower size fractions which formulated the 8.5:1 diameter ratio binary mixture in these tests. This will reduce the magnitude of size ratio difference between neighbouring size fractions considerably. A

15% difference in mixture proportions radially is not deemed significant enough to reject the mixer in terms of its performance in mixing radially but indicates that the mixer can successfully progress radial mixing of materials which are highly prone to segregation.

It was a concern that static percolation, that is the sifting of the fines through the voids of the matrix of larger particles in a stationary material, would significantly affect the validity of the mixing results taken using the experimental apparatus in conjunction with larger diameter ratio binary mixtures. Results suggest that static percolation may well be a contributory factor to the reduction in mixture quality but did not render the mixing tests invalid.

Mixing performance was comparable for binary mixtures of similar size ratios to those used by Boss et al. (10). However, one significant factor which will affect the overall mixing performance in the tests undertaken is the mixer geometry in terms of its diameter. Jeck (8) comments on the fact that the ideal mixer diameter for high performance mixing is influenced by the size of material particles which are to be passed through it and work undertaken by Boss et al. (10) indicates that the performance of the mixer is effected by mixer diameter. It is therefore inappropriate to expect the static mixer under investigation to perform to the same high degree of mixing for a variety of different sized materials when the mixer geometry is fixed.

Visual indications for the smallest of the particle sizes used indicated that it was far easier for some small particles to pass through the gaps in-between mixer elements without their direction being significantly altered by any elements or larger particles which would contribute to a highly efficient radial homogenisation of the mixture. This, in conjunction with static percolation, is probably some of the main causes for the reduction in mixer performance as the diameter ratio increases and is analogous to the depreciation in mixture quality previously outlined in section 3.1.

Mixing results suggest that the feed proportions and the range of feedrates used throughout the test program did not significantly effect the mixing performance of the mixer but served to indicate that for the anticipated size of material particles to be passed through the mixer in a segregation testing program the mixer can be regarded as being able to radially mix to a desirable level.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

1. WILLIAMS J.C., 'The Mixing of Dry Powders', Powder Technology, 2, 1968/69, 13-20.

2. WILLIAMS J.C., 'Mixing and Segregation in Powders', Principles of Powder Technology, Edited by M.J.Rhodes, Published by John Wiley and Sons Ltd, Chapter 4, 1990, 71-90.

3. LACEY P.M.C., 'Developments in the theory of particulate mixing', J. Appl. Chem., London., 4, May, 1954, 257.

4. HARNBY N., 'Characterisation of powder mixtures', Mixing in the process industries, second edition, Published by Butterworth-Heinemann Ltd, Chapter 2, 1992, 25-41.

5. LACEY P.M.C., 'The mixing of solid particles', Trans. Instn Chem. Engrs, 21, 1943, 53.

6. ROSE H.E., 'A suggested equation relating to the mixing of powders and its application to the study of the performance of certain types of machine', Trans. Instn Chem. Engrs, 37, 1959, 47.

7. POOLE K.R., TAYLOR R.F., WALL G.P., 'Mixing powders to fine-scale homogeneity: Studies of batch mixing', Trans. Instn Chem. Engrs, Vol 42, 1964, 305-315.

8. JECK N.R., 'Processing of Solids in Static Mixers', Powder handling and Processing. Vol 4, No 3, September 1992, 313-317.

9. STANGE K., Chem., Ing. Tech., 35, 1963, 580.

10. BOSS J., KNAPIK A.T., WEGRZYN M., 'Segregation of Heterogeneous Grain Systems during Mixing in Static Mixers', Bulk Solids Handling, Vol 6, No 1, February 1986, 145-149.

11. BOSS J., WEGRZYN M., 'The Effect of the Tracer Particles Distribution on the Equilibrium Degree of Mixture', Powder handling and processing, Vol 3, No 3, September 1991, 253-255.

12. HERBIG R., GOTTSCHALK I., 'Mixing of segregating solid particles in a static mixer', Journal of Powder and Bulk Solids Technology, 10, 1986, 2, 7-12.

13. Personal correspondence with Mr T Mallett, Sulzer Chemtech, Sulzer (UK) Ltd, Sulzer-Chemtech Division, Westmead, Farnborough, Hampshire GU14 7LP

14. BARNES R.N., 'Resonant Vibratory Feeders', Int'l Conf. on Bulk Materials Handling and Transportation and Symposium on Freight Pipelines, Wollongong, Australia, 6-8 July, 1992, 321-326.

Segregation of Particulate Solids - A Review

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Summary: Particulate solids segregation is a very broad and complex phenomenon which occurs in various areas of process plant. One such area that has seen an increase in research is the segregation process present when charging storage vessels, where several phenomena have important roles to play. It is now widely understood that the feedrate, the angle of charge, bin geometry and particle characteristics will all influence the extent to which a material will segregate within this area. However, the knowledge of the interaction and extent to which each phenomenon acts is not advanced enough at present to allow engineers to predict in a quantitative sense the magnitude of this potential problem. This paper includes a review and comparison of research based on experimental investigations undertaken to date utilising both industrial and bench sized types of segregation equipment. It is concluded that none of the mathematical models so far derived to predict the extent of potential segregation have proved general enough to be used for all scenarios.

1 INTRODUCTION

1.1 Material Segregation.

In a bulk solid material it is common to find many constituents, each of which will exhibit a different propensity to segregate when subjected to various processing operations. Since most unit operations in solids handling technology involve bulk movement, inter-particulate movement of particles within the bulk are inevitable. Free flowing mixtures having differing particle characteristics such as size, density and shape etc. tend to easily segregate due to individual particles having the freedom to move independently with respect to their neighbours. However, a cohesive mixture will generally resist segregation to an extent due to the cohesive nature of such materials preventing the movement of particles with respect to each other. With this said, it is conceivable in the extreme, that a relatively free-flowing and highly mixed material could become completely un-mixed at the end of its journey through process plant.

1.2 Where in Bulk Solids Handling Operations does Segregation Occur?

It is unlikely that a material highly prone to segregation will encounter unit operations such as mixing, storage, feeding and transport that will not cause inter-particulate movement of the material. Different segregating mechanisms can be associated with the aforementioned facets of process plant. These have been established and documented by a number of authors including Johanson (1) and Williams (2) & (3) which has culminated in documented research being undertaken by a number of authors into areas such as vibration; Williams and Shields (4), fluidised beds; Schouten et al. (5), Garcia-Ochoa et al. (6), Peeler and Huang (7) and rotating cylinders i.e. kilns, driers, mixers and blenders etc. by authors including Williams and Khan (8) and Pollard and Hencin (9). It is evident that research effort has been directed into solving problems associated with various operations in process plant.

1.3 The Implications of Material Segregation

Since resources will have been committed to mixing a material to an appropriate specification, it is essential to ensure that segregation as a result of any subsequent handling operations does not significantly reduce the mixedness of the material. Quality assurance problems as a result of material segregation can lead to out of specifi-1Xcation products which can result in ai unknown reduction in process efficiency if segregated material, for example, is used as feed to a process.

1.4 Understanding Where the Problem Lies

Industrially driven research into the area of segregation has generally centred around prevention of a particular problem, rather than defining the causes, and hence, developing an understanding of the phenomena controlling the situation. Segregation in storage vessels where retrofitting of existing vessels has been undertaken in pharmaceutical and food processing applications to minimise the segregation resulting from charging and discharging is a specific example. Intrusive devices designed to reverse the extent of segregation suffered upon charging are fitted to existing problematic storage vessels in order to change the mode of discharge to mass flow which can result in some re-mixing of the segregated components on discharge. Examples of these devices include anti-segregation distribution cones, inserts and multi-point feeding techniques which have been documented by Johanson (10) & (11).

These methods, coupled with research into segregation on discharge, provides evidence which suggests somewhat similar mechanisms are acting when storage vessels are being charged and discharged. However, retrofitting existing vessels or analysing segregation on discharge does not provide enough information for a full understanding and hence resolution of the segregation process as a whole. If the segregation process when charging storage vessels could be better understood and reduced to a minimum, then by the nature of their similar mechanisms, segregation problems occurring on discharge will also decrease significantly.

2 DEFINING THE PROBLEM

Before the overall problem of segregation associated with charging storage vessels can be determined, it is important to address and clarify definitions associated with quantifying the segregation phenomenon.

2.1 Quantifying Segregation

Before any meaningful measurements of segregation can be undertaken, two aspects of quantification require clarification in order to provide a complete description of the segregation process:-

- Quantification of a material's propensity to segregate with respect to defining a numerical value.
- To use the method outlined above to quantify the degree of segregation of a material as it progresses through a solids handling system.

However, the major difficulty with quantifying the segregation phenomenon is the fact that particle characteristics such as size, density and shape, which are known to be contributory factors, are also difficult to quantify. Researchers have often tried to simplify the problem by utilising binary mixtures. The resulting research into the quantification of segregation associated with binary mixtures is reviewed and documented in sections 3.2 & 3.3. Unfortunately, real life materials handled in process industries are often multi-component mixtures which have a continuous distribution of particle characteristics. This has resulted in a small amount of information being available on quantifying segregation associated with multi-component mixtures in comparison to that of binary mixtures but has been documented in section 3.3.4

2.2 Defining Segregation Terminology

Danckwerts (12) has provided a basis for defining various terms which relate to segregation. He has shown that important features of mixtures can be described by two statistically-defined quantities termed the 'scale' and 'intensity' of segregation.

- 'Scale of Segregation' is defined as the measure of the size of regions of segregation within a mixture Hence, smaller regions define higher mixture quality.
- 'Intensity of Segregation' is defined as the amount of variation within these regions e.g. a region can be completely absent of, or lacking in, the desired quantity of a constituent.

Hamby (13) documented that whilst the mixedness of a mixture can be assessed as a whole or in part, a means of selecting a representative size of mixture for analysis was required. Danckwerts (35) and Hamby (13) define this as the 'Scale of Scrutiny' which is the maximum size or number of segregated regions in the mixture which would render the mixture unsuitable for its intended purpose. The scale of scrutiny chosen is a pre-requisite for fixing the scale or sample size at which the mixture should be inspected. Care must be taken when selecting a scale to avoid unnecessarily high mixing time and expenditure, which could be incurred in mixing a material to a high degree of scrutiny when the subsequent segregation suffered during the process is deemed insignificant to cause rejection of the material for its intended use.

2.3 Segregation Mechanisms Associated with Charging Storage Vessels

When charging storage vessels, the behaviour of the material is influenced by its environment and method of charging. Two methods of charging can result in quite pronounced differences in segregation pattern, caused by different functioning mechanisms which have been documented by Johanson (1) and Williams (2). Fine sized materials, pneumatically charged at high velocities will segregate differently than larger, mechanically charged materials. With the former, there is the likelihood of attaining an inverse segregation pattern as documented by Arnold (14), Figure 1(a), resulting in the distribution of fines at the wall and coarse particles centralised around the charge point of the vessel. A similar inverse segregation pattern was observed by Lawrence and Beddow (15) for mixtures containing a high percentage of fines when charging dies. The exact pattern of fill will be further dictated by the charging angle at inlet to the vessel which is a point well made by Arnold.

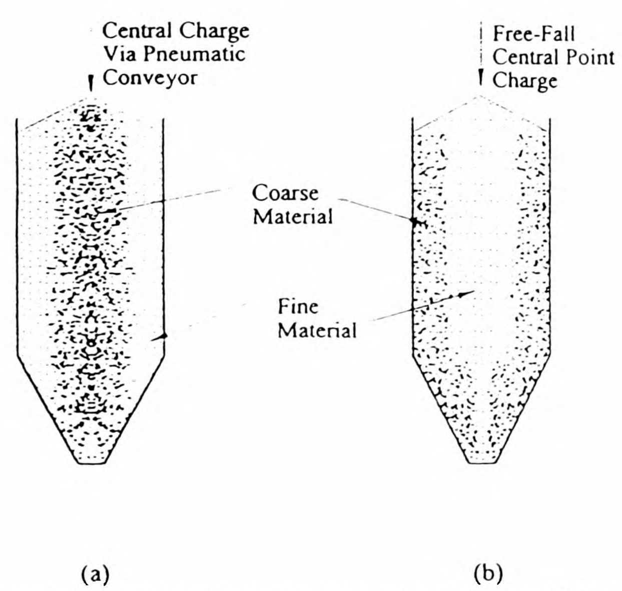


Figure 1: Segregation Patterns Associated with Different Forms of Charging Storage Vessels

Generally, with mechanical central point charging, the more recognised segregation behaviour is encountered where a heap is formed, initiating the free surface segregation phenomenon as shown in Figure 1(b)

Research has shown that the rate at which the heaping process is carried out affects the amount of segregation a material experiences. Lawrence and Beddow (15) state that from their experiments the amount of segregation observed was reduced by increasing the rate of fill. Further evidence to support this view was provided by the experimental work undertaken by O'Dea and Waters (16) and Shinohara et al. (17).

3 DETAILED INVESTIGATIONS

The majority of background, empirically based research work, has been undertaken using binary mixtures as the segregating medium. This has accelerated the development of more simplistic predictive models, to assess the effects of individual segregation mechanisms which occur within the general area of free surface segregation. However, modelling the effects that multi-component materials will have on the same segregation mechanisms have received comparatively little attention. The possibility that a mechanism's contributory effect to the segregation process as a whole will be altered by the quantity and variance of multi-component particle characteristics, has currently not been quantified satisfactorily.

3.1 General Segregation Research

In order to facilitate an understanding of the segregation process, various experimental techniques have been utilised. Most attempts to quantify segregation have centred around using binary mixtures with two general methods of assessment:-

- Classifying a mixture into a coarse and a fine fraction
- Monitoring the behaviour of tracer particles which differ in characteristic to the majority of the bulk.

Williams and Shields (4) developed a coefficient of segregation which was determined from a binary mixture which had segregated in a vibrated bed. The bed was separated into two halves and the coarse and fine content of each was measured. The coefficient of segregation was then defined as:-

$$C_s = \frac{W_{CT} - W_{CB}}{W_{CT} + W_{CB}} \times 100\,\% \qquad 1$$

where

C_S Coefficient of segregation
W_{CT} Proportion of coarse particles in top half of bed
W_{CB} Proportion of coarse particles in bottom half of bed

Advantages of using this coefficient of segregation include, the experimental simplicity of determining a value, and also the fact that the equation takes into account the mixture as a whole, not just a sample.

A similar variation of the equation developed by Williams and Shields (4) was used by Williams and Khan (8) in the analysis of the segregation in an inclined rotating drum. Donald and Roseman, (19) and Campbell and Bauer, (20) also investigated binary mixture segregation in terms of size and density in a horizontal rotating drum and concluded that measurable segregation occurred for only slight differences in particle size.

Williams and Shields (4) equation 1 was used in comparison with a theoretical segregation index proposed by Popplewell et al. (21). Claimed advantages of Popplewell's index was that it could predict the vertical concentration profile of the segregating component at various depths of a vibrated bed and was more sensitive to the effects of small concentration profiles. This differed from the equation proposed by Williams and Shields (4), which was limited to recognising changes in concentration in only the top and bottom halves of the bed. Computer simulations of various concentration profiles provide the basis from which the author makes his claims. Experimental verification of the concentration profiles is needed in order to validate the assumptions on which the segregation index is based.

3.2 Initial Research into 'Free Surface' Segregation

Specific investigations into free surface segregation are limited, which is partly due to research work being directed at solving segregation on discharging rather than charging, as outlined in section 1.4.

Harris and Hildon (22) defined a degree of segregation for a binary mixture in terms of the presence of one of the components at various positions in a segregated heap. The degree of segregation was subsequently defined as S. If the percentage compositions of one component in the four samples are α_1, α_2, α_3 and α_4 where $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 100$, then

$$S = \sum_{n=1}^{n=4} (\alpha_n - 25) \qquad 2$$

A direct comparison between the author's test data and free surface segregation test data is not advisable. This is due to the design of the author's experimental test apparatus, which consisted of a core flow feed hopper which was charged and then discharged to form a heap from which samples were taken. Therefore there are three distinct segregation phases contributing to the overall segregation of the material.

Lawrence and Beddow (15) conducted experiments to study the amount of segregation when binary mixtures were charged into a die. Their results compare favourably to Campbell and Bauer (20) who stated that a small difference in particle size was enough to cause measurable segregation.

Drahun and Bridgwater (23) conducted test work which involved studying the distribution of tracer particles as a consequence of free surface segregation when forming a heap. A more precise understanding of how process or geometrical variables contributed and influenced the mechanisms of segregation, was possible using the test facility constructed. Results from experimental work were expressed in dimensionless form and indicated that particle characteristics, such as size and density, made a significant contribution to the free surface segregation phenomenon.

The authors concluded that size and density did have a significant effect on the distribution of tracer particles in a segregating bed. They also recognised that throughout the majority of relevant segregation literature available, there were conflicting views from authors as to the extent to which particle characteristics such as size and density contributed to the segregation phenomena. Whilst there is little doubt that size is the predominant characteristic, the contribution of density is not so clearly defined, with authors Harris and Hildon (22) and Lawrence and Beddow (15) stating that it has some or no effect. As Drahun and Bridgwater (23) have stated, this is probably due in part to the fact that if density was documented in papers, it was often considered as an afterthought to the main test program conducted.

3.3 Detailed Analysis of Free Surface Segregation

The phenomenon of free surface segregation has been recognised as the major reason for the separation of binary mixtures into characteristic elements when charging storage vessels. Some of the more relevant work has already been outlined in section 3.2 where Lawrence and Beddow (15) qualitatively stated that the predominant free surface segregation mechanism can be described as the fine component in a binary mixture filtering down through the moving mass, sometimes referred to as sifting. The experimental results documented in their paper were consistent with this statement. However, this still remains only a qualitative explanation of the process. Very few quantifiable attempts have been made to describe the path between the two physical states of a mixed and segregated material.

3.3.1 Shinohara's Segregation Research

A significant amount of work by Shinohara et al. has focused on free surface segregation for over 20 years which has been documented in a variety of published articles (17), (18), (24), (25), (26) & (27). The overall aim of the work has been to produce a definitive model which could quantify the free surface segregation process when charging storage vessels.

The initial work originated back to investigations using a screening model developed to analyse the segregation and blending of particles discharging from a storage vessel (24). The model was formulated with reference to Shinohara's hypothesis outlined in section 3.3.2 which states that there are mainly three predominant mechanisms acting within the scope of free surface segregation. From this hypothesis he developed a screening layer model which could predict the segregation of a binary mixture as it flowed down the free surface of a stationary heap. Various derivatives of the model have been developed to analyse segregation relating to individual particle characteristics such as size (17), density (25) and shape (26). From the information that this work produced, Shinohara progressed further to formulate two screening layer models which describe the segregation process in both two-dimensional (18) & (25) and axi-symmetric (27) geometry storage vessels. Computing techniques have since been employed to predict the segregation of a binary mixture for given geometries of such storage vessels.

In developing the theoretical model there was a need to include certain material dependent characteristic variables, the value of which had to be determined experimentally. A knowledge of these variables is essential before the model can be used as a predictive tool.

3.3.2 Shinohara's Modelling Hypothesis

Pouring a particulate mixture onto a heap causes a flowing layer to descend over the inclined heap surface. The segregating component, by virtue of the acting segregating mechanisms, propagates its way to the bottom of the flowing layer as it descends over the stationary heap surface. When the flowing layer reaches the storage vessel wall it ceases to flow and becomes the new static heap surface, the top surface of which is predominantly made up of the non segregating component. This then presents an opportunity for the segregating component of the next flowing layer to be trapped in the protuberances on the top surface of the new static layer. The whole cycle then repeats itself as the storage vessel fills.

The free surface segregation process between the upper flowing layer and the lower stationary layer for particle characteristics such as size, density and shape was classified into three stages and is shown schematically in Figure 2:-

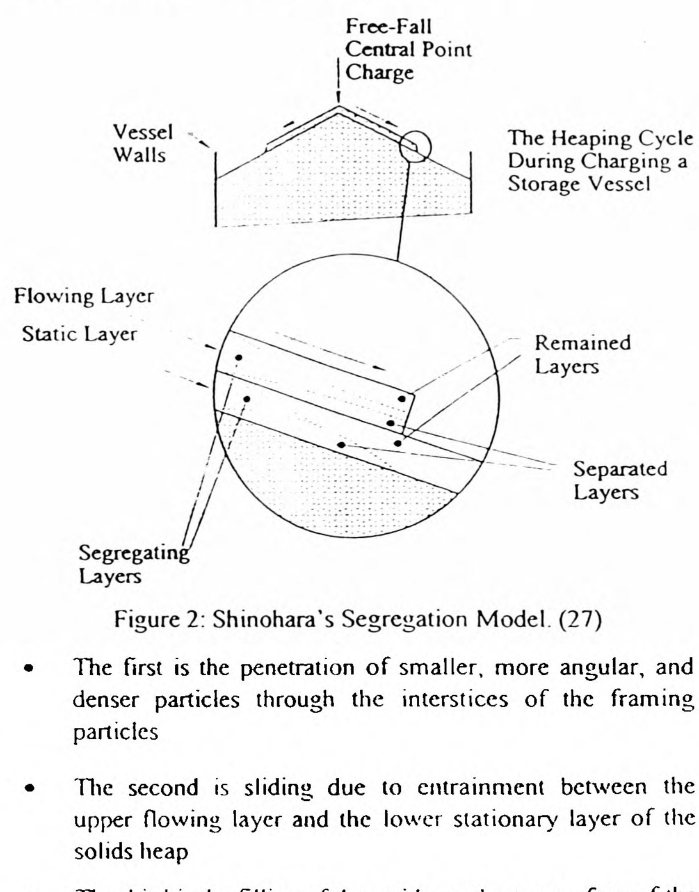


Figure 2: Shinohara's Segregation Model. (27)

- The first is the penetration of smaller, more angular, and denser particles through the interstices of the framing particles
- The second is sliding due to entrainment between the upper flowing layer and the lower stationary layer of the solids heap
- The third is the filling of the voids on the top surface of the stationary layer with the separated particles.

Constructive argument as to the extent to which each particle characteristic is involved in each of the three stages is documented throughout the research undertaken. For shape segregation, the first two stages appear to predominate, whilst size segregation is described by the first and third stages. Density segregation can be described in a similar way. i.e. the denser component behaves just like smaller particles in size segregation or angular ones in shape segregation.

3.3.3 Discussion on the Work of Shinohara

The work undertaken by Shinohara et al., has produced a predictive model which describes free surface segregation to a higher degree of accuracy than has previously been available. However, the predictive model does not represent a complete description of the free surface segregation process.

Consideration of the following phenomena, which experience has shown does occur, cannot be ignored:-

- The effect of excessive free fall height has been recognised by the author but has not been included in the model. This can cause the segregating particles to be deposited, un-characteristically, further towards the periphery of the bin.
- If the size of the larger framing particle is too large in relation to the smaller segregating component then static percolation can result without the need of material movement.
- The model does not take into consideration any rolling effects of particles and is only fairly representative of the free surface segregation process for high feedrates, resulting in a thick layer flowing down the heap surface. It is restricted for circumstances involving single particles moving down the heap which has been observed to occur in practice.
- The occurrence and frequency of avalanching resulting in a layer of the segregating component being un-characteristically deposited towards the periphery.
- The model cannot be used with multi-component materials and is restricted to binary mixtures varying in a particular particle characteristic.
- In order to make a quantifiable statement of the segregation that a material has undergone in a process it is imperative that an initial assessment is made of the mixedness of the pre-segregated material. This is by no means an easy undertaking, but only when this has been achieved can the measurable effect of processes be made.

Avalanching of a layer of material over a heap surface has been given consideration by a number of authors.

Drahun and Bridgwater (23) state that avalanches disturbed the segregating layer to around seven particles in depth and caused uncharacteristic displacement of segregated particles towards the periphery of the heap. They present an equation which suggests that the distribution of avalanche size is in proportion to the slope length. This avalanching process is known to continue throughout the heaping cycle and will produce the 'Christmas tree' segregation effect noted by Forberg (28) as shown in Figure 3. Jaeger and Nagel (29) have researched into the area of avalanching by studying the behaviour of sand piles. They are in agreement with Drahun and Bridgwater (23) when they state that upon avalanching all the motion occurs in the top few layers of a heap surface. They also state that the motion of particles down a heap surface involves a balance of gravitational forces connected with the particle inertia and friction forces resulting from dissipation. On observing experiments they argue that both forces are comparable in magnitude.

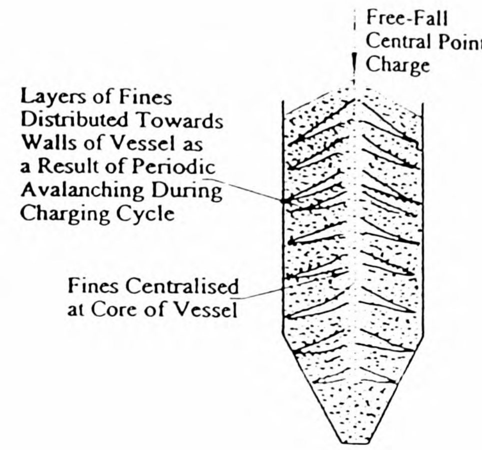


Figure 3: The 'Christmas Tree' Segregation Pattern

3.3.4 Quantifying Segregation Using a Continuous Distribution of Particle Characteristics.

O'Dea and Waters (16) have developed a mechanistic model which can provide an index of the degree of segregation of a material possessing a continuous distribution of sizes. The work centred around adopting the analogy of research conducted by Miwa (30) and Subashinge et al. (31) who considered continuous screening as a first-order process and showed it to be a good approximation. O'Dea and Waters (16) assumed that percolation and rolling were the two predominant mechanisms in free surface segregation and considered each mechanism to be a first-order process, following an exponential relationship. Experimental results from their segregation equipment are documented which show a good relationship between theoretical and experimental results. They propose that the model is capable of being adapted to predict stockpile and storage vessel segregation. Likewise it can be utilised to provide a technical understanding of how segregation of feed influences the performance of sintering operations as documented by O'Dea and Waters (32).

As was the case with Shinohara, the O'Dea and Waters segregation model includes material dependant parameters, the determination of which are obtained empirically. With this said the model does have the ability to predict the segregation characteristics of industrially relevant materials containing a continuous size distribution.

4 RESEARCH IN PROGRESS AT UNIVERSITY OF GREENWICH

4.1 Objectives

A research programme into the segregation of particulate materials when charging storage vessels is being undertaken at

The Wolfson Centre for Bulk Solids Handling Technology, University of Greenwich. The main objective of this research program is to aid industry by producing an easily workable method by which the degree of segregation a bulk material will suffer in various environments, can be determined with a sufficient degree of accuracy. If and when this is achieved it should be possible to predict the geometrical locations of elements in a bulk material which has segregated upon charging a storage vessel, without the need to construct a pilot sized test facility.

4.2 Experimental Apparatus

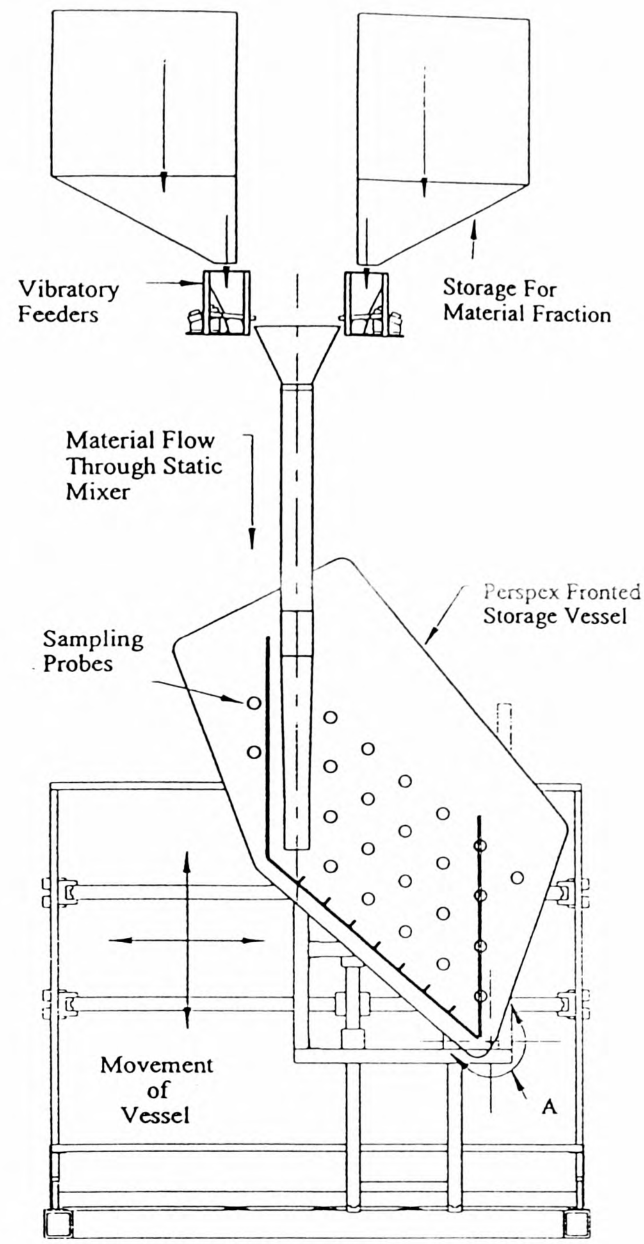
From the aforementioned review of segregation research, it is clear that there is a need for an experimental apparatus which is capable of isolating the recognised mechanisms of segregation. This will then allow mechanisms to be analysed singularly or in combination so as to assess their associated contributions to the overall segregation phenomenon encountered when charging storage vessels.

An experimental rig has been designed which allows similar control of independent variables to that of Drahun and Bridgwater (23), the major differences being in the method of mixture preparation and subsequent charging. The experimental rig will allow the heap slope length, feedrate of charged material, free fall height and angle of repose of heaping to be varied independently.

The experimental rig, as depicted in Figure 4, consists of several vibratory feeders of a novel design by Barnes (33) which can be used to formulate and feed industrially representative mixture compositions and/or characteristic distributions. The feed is passed through an in-line static mixer which serves to mix the incoming element streams and concentrate the flow to provide a highly mixed charging stream of material. The static mixer, by its nature will provide mixing under the influence of gravity, with minimal degradation. The material discharged from the static mixer can be assessed for its mixedness, radially prior to charging a storage vessel. This assessment is essential if consistent segregation on each side of a centrally charged heap is to be achieved.

The mixture segregates as it charges a plane flow storage vessel. The orientation of the vessel can be altered to facilitate two effects; it will allow the thief probes to be aligned parallel with the heap surface being formed which itself is characteristic to the angle of repose formed by the material, and also it is hoped the phenomenon of avalanching can be controlled and investigated by varying the angle at which the charging stream contacts the heap being formed.

The free fall height, which can be defined as the distance between the discharge from the static mixer and the heap apex being formed, can be controlled. This therefore allows the free fall height to be set at a predetermined distance to assess its influence on the segregation process. Similarly, the free fall height can be kept constant throughout the heaping process during storage vessel charging to eliminate free fall height effects.



A: Rotational Movement Allowing Alignment of Sampling Probes with Angle of Repose Formed by Material.

Figure 4: Schematic Diagram of Segregation Testing Facility

Alongside this work a comparative study of the predictive power of current segregation models will be carried out. Investigations into the variation of segregation with change in free fall height, bulk solid characteristics and feedrate variation will also be undertaken. By analysing results from the developed experimental test facility it is hoped that an improved understanding of the free surface segregation process in charging storage vessels will be achieved.

5 REFERENCES

1. JOHANSON J.R., 'Solids Segregation: Causes and solutions', Powder and Bulk Engineering, August 1988, 13-19.

2. WILLIAMS J.C., 'The segregation of Particulate Materials. A Review', Powder Technology, 15, 1976, 245-251.

3. WILLIAMS J.C., 'Mixing and Segregation in Powders', Principles of Powder Technology, Edited by M.J.Rhodes, John Wiley and Sons Ltd, Chapter 4, 1990, 71-90.

4. WILLIAMS J.C., SHIELDS G., 'The segregation of granules in a vibrated bed', Powder Technology, 1, 1967, 134-142.

5. SCHOUTEN J.C., VALKENBURG P.J.M., VAN DEN BLEEK C.M., 'Segregation in a slugging FBC large-particle system', Powder Technology, 54, 1988, 85-98.

6. GARCIA-OCHOA F., ROMERO A., VILLAR J.C., BELLO A., 'A study of segregation in a gas-solid fluidised bed: particles of different density', Powder Technology, 58, 1989, 169-174.

7. PEELER J.P.K., HUANG J.R., 'Segregation of wide size range particle mixtures in fluidised beds', Chemical of Engineering Science, Vol 44, No 5, 1989, 1113-1119.

8. WILLIAMS J.C., KHAN M.I., 'The mixing and segregation of particulate solids of different particle size', The Chemical Engineer, January 1973, 19-25.

9. POLLARD B.L. HENEIN H., 'Kinetics of radial segregation of different sized irregular particles in rotary cylinders', Canadian Metallurgical Quarterly, Vol 28, No.1, 1989, 29-40.

10. JOHANSON J.R., 'Controlling flow patterns in bins by use of an insert', Bulk Solids Handling, September 1982, Vol.2, No.3.

11. JOHANSON J.R., 'Solids segregation - case histories and solutions', Bulk Solids Handling, Vol 7, No2, April 1987, 205-208.

12. DANCKWERTS P.V., 'The definition and measurement of some characteristics of mixtures', Appl.Sci.Res. Section A, Vol 3, 1952, 279-296.

13. HARNBY N., 'Characterisation of powder mixtures', Mixing in the process industries, second edition, Published by Butterworth-Heinemann Ltd, Chapter 2, 1992, 25-41.

14. ARNOLD P.C., 'On the influence of segregation on the flow pattern in silos', Bulk Solids Handling, Vol 11, No 2, May 1991, 447-449.

15. LAWRENCE L.R., BEDDOW J.K., 'Powder segregation during die filling', Powder Technology, 2, 1968/69, 253-259.

16. O'DEA D.P., WATERS A.G., 'Quantifying segregation in a bulk solids handling system', Int'l Conf. on Bulk Materials Handling and Transportation, Symposium on Freight Pipelines, Wollongong, Australia, 6-8 July, 1992, 413-417.

17. SHINOHARA K., SHOJI K., TANAKA T., 'Mechanism of size segregation of particles in filling a hopper', Ind. Eng. Chem. Process. Des. Develop., Vol.11, No.3, 1972, 369-376.

18. SHINOHARA K., Aufbereitungs-Technik, 26, 1985, 116.

19. DONALD M.B., ROSEMAN B., Br. Chem. Eng, 7, 1962, 749.

20. CAMPBELL H., BAUER C., Chem. Eng., 73, 1966, 179.

21. POPPLEWELL L.M., CAMPANELLA O.H., SAPRU V., PELEG M., 'Theoretical comparison of two segregation indices for binary powder mixtures', Powder Technology, 58, 1989, 55-61.

22. HARRIS J.F.G., HILDON A.M., 'Reducing segregation in binary powder mixtures with particular reference to oxygenated washing powders', Ind. Eng. Chem. Process. Des. Develop., Vol.9, No.3, 1970, 363-367.

23. DRAHUN J.A., BRIDGWATER J., 'The mechanisms of free surface segregation', Powder Technology, 36, 1983, 39-53.

24. SHINOHARA K. SHOJI., TANAKA T., Ind. Eng. Chem. Process. Des. Develop., 9, 174, 1970.

25. SHINOHARA K., MIYATA S., 'Mechanism of density segregation of particles in filling vessels', Ind. Eng. Chem. Process. Des. Develop., Vol 23, No. 3, 1984, 423-428.

26. SHINOHARA K., 'Mechanism of segregation of differently shaped particles in filling containers', Ind. Eng. Chem. Process. Des. Develop., Vol 18, No. 2, 1979, 223-227.

27. SHINOHARA K., ENSTAD G.G., 'Segregation mechanism of binary solids in filling axi-symmetric hoppers', Proc. of second World Congress, Particle Technology, September 19-22, 1990. Kyoto, Japan, 45-52.

28. FORBERG H., 'Modern Mixing- theory and praxis', Powder Handling and Processing., Vol 4, No. 3, September 1992, 318-321.

29. JAEGER H.M., NAGEL S.R., Physics of the granular state', Science, the American Association for the Advancement of Science, 20th March 1992, Vol 255, 1523-1531.

30. MIWA S., Report of Powder Technology, Soc. of Japan (Funtai Kogaku Kenkyukai), No 26, 1960.

31. SUBASHINGE G.K.N.S., SCHAAP W., KELLY E.G., 'Modelling screening as a conjugate process', Int. J. Min. Proc., 28, 1990, 289.

32. O'DEA D.P., WATERS A.G., 'Modelling strand segregation and the benefits to sintering operations', 52nd ISS Ironmaking conference, Dallas, 1993.

33. BARNES R.N., 'Resonant Vibratory Feeders', Int'l Conf. on Bulk Materials Handling and Transportation, Symposium on Freight Pipelines, Wollongong, Australia, 6-8 July, 1992, 321-326.

34. SALTER G.F., PITTMAN A.N., REED A.R., BARNES R.N. Mixing of particulate solids using static mixers', For presentation at 5th Int'l Conf. on Bulk Materials Storage and Handling and Transportation, Newcastle, N.S.W., Australia, 9-12 July 1995.

35. DANCKWERTS P.V., 'Theory of mixtures and mixing', Research, (London), Vol 6, 1953, 355-361.

APPENDIX A.12

REFERENCES

1 Carson, J.W, Royal, T.A, and Goodwill, D.J,. 'Understanding and Eliminating Particle Segregation Problems', Bulk Solids Handling, Vol. 6, No. 1, February 1986. 139-144.

2 Goodwill, D.J,: 'Solving Particle Segregation Problems in Bins', Engineering Digest, April 1985.

3 Goodwill, D.J, and Jenkyn R.T,: 'Particle Segregation Upsets Metallurgical Processes', Materials Handling in Pyrometallurgy, 1991. 67-74.

4 Johansen, H, Andersen, I.S, and Leedgaard, H,: 'Segregation and Continued Mixing in an Automatic Capsule Filling Machine', Drug Development and Industrial Pharmacy. Vol. 15(4), 1989. 477-488.

5 Fujimoto, M, Kubo, S, and Shimozawa, E,: 'Development of a New Type of Feeding Method for Homogenisation of Sintering Reaction', Proceedings of 49th ISS Ironmaking Conference. London, U.K. 1990. 589-601.

6 O'Dea, D, and Waters, A, 'Modelling Strand Segregation and the Benefits to Sintering Operations', Proceedings of 52nd ISS Ironmaking Conference. Dallas. USA. 1993.

7 British Materials Handling Board,: 'User Guide to Segregation' 1st Edition, Bartham Press Ltd

8 Harnby, N,: 'The mixing of cohesive powders' Mixing in the Process Industries, 2nd Edition, Butterworth-Heinemann Ltd. Chapter 5, 79-98.

9 Barbosa-Canovas, G, Malave-Lopez, J, and Peleg, M,. 'Segregation in Food Powders', Biotechnology Progress. Vol. 1, No. 2, 1985. 140-146.

10 Lacey, P,M,C,. 'Developments in the Theory of Particle Mixing', Journal of Applied Chemistry, No. 4, 1954. 257-268.

11 Poole, K,R, Taylor, R,F, and Wall, G,P,. 'Mixing Powders to Fine-Scale Homogeneity: Studies of Batch Mixing', Trans. Instn. Chem. Engineers. Vol. 42, 1964. 305-315.

12 Stange, K,: 'Die Mischgüte einer Zufallsmischung aus drei und mehr Komponenten', Chemie-Ing. Techn. No. 35. 1963. 580-582.

13 Rollins, D,K, Faust, D L, and Jabas, D,L,: 'A Superior Approach to Indices in Determining Mixture Segregation', Powder Technology, Vol. 84, 1995. 277-282.

14 Danckwerts, P V,: 'The Definition and Measurement of Some Characteristics of Mixtures', Appl. Sci. Res. Section A, Vol. 3, 1952. 279-296.

15 Danckwerts, P V,. 'Theory of Mixtures and Mixing', Research. London. Vol. 6, 1953. 355-361.

16 Mosby, J, De Silva, S, & Enstad, G.G,: 'Segregation of Particulate Materials – Mechanisms and Testers', Kona. No. 14. 1996. 31-43.

17 Williams, J.C,: 'The Segregation of Powders and Granular Materials', Fuel Society Journal. Vol. 14, 1963. 29-34.

18 Fiske, T.J, Railkar, S.B, and Kalyon, D.M,: 'Effects of segregation on the packing of spherical and non spherical particles', Powder Technology, Vol. 81, 1994. 57-64.

19 Johanson, J.R.,: 'Solids Segregation: Case Histories and Solutions', Bulk Solids Handling, Vol. 7, No. 2, April 1987 205-208.

20 Johanson, J.R.,: 'Solids Segregation: Causes and Solutions', Powder and Bulk Engineering, August 1988. 13-19.

21 De Silva, S.R, and Enstad, G.G.: 'Bulk Solids Handling in Scandinavia: A Case Study in the Aluminium Industry', Bulk Solids Handling, Vol. 11, No. 1, March, 1991. 65-68.

22 Arnold, P.C,: 'On the Influence of Segregation on the Flow Pattern in Silos', Bulk Solids Handling. Vol. 11, No. 2, May 1991. 447-449.

23 Arnold, P.C.. 'Storage Bin Reliability' Proc. Bulk Handling Conference, Asia. Singapore. September 19-21, 1995. 173-184.

24 Fürll, G,. 'Investigation of the Segregation in Big Bins', Powder Handling and Processing. Vol. 6, No. 4, October/December, 1994. 395-397

25 O'Dea, D, and Waters, A,. 'Quantifying Segregation in a Bulk Solids Handling System', 4th International Conference. On Bulk Materials Handling and Transportation, Wollongong, Australia. July 6-8, 1992, 413-417.

26 Standish, N, Yu, A, and He, Q,. 'An Experimental Study of the Packing of a Coal Heap', Powder Technology. Vol. 68, 1991. 187-193.

27 Yu, A, and Standish, N,: 'Estimation of the Bulk Density of a Coal Stockpile', Bulk Solids Handling. Vol. 11, No. 3. August, 1991. 605-612.

28 Yu, A, Cowgill, D, Wong, P, Standish, N, and He, Q,: 'Stockpiling Behaviour as Observed in a Model Experiment', Proceedings of 5th International Conference on Bulk Materials Storage, Handling and Transportation. Newcastle, Australia. 10-12 July, 1995. 451-455.

29 Williams J.C,. 'The Mixing of Dry Powders', PowderTechnology 2. 1968/69. 13-20.

30 Makse, H, Havlin, S, King, P and Stanley, H,. 'Spontaneous Stratification in Granular Mixtures', Nature. Vol. 386, 27 March, 1997 379-382.

31 Reed, A,: 'Controlling Product Quality – I) Particle Segregation' Process Industry Journal, October, 1992. 23-25.

32 Standish, N,. 'Studies of Size Segregation in Filling and Emptying a Hopper', Powder Technology. Vol. 45, 1985. 43-56.

33 Brown, G.J, Creasey, D.S, and Miles, N.J,. 'Coal Handleability – A Good or a Bad Coal ?', Part. Syst. Charact. 13. 1996. 260-263.

34 Creasey, D.S, Brown, G.J, and Miles, N.J,. 'Characterising the Rheology of Coal Blends from their Avalanching Behaviour', 1997 Jubilee Research Event, IChemE, 1997 437-440.

35 Jaeger, H.M, and Nagel, S.R,: 'Physics of the Granular State', Science. Vol. 255, 1992. 1523-1531.

36 Drahun, J.A, and Bridgwater, J,: 'Free Surface Segregation', I.Chem.E. Symposium. Series No. 65, 1981. S4/Q/1-S4/Q/14.

37 Drahun, J.A, and Bridgwater, J,: 'The Mechanisms of Free Surface Segregation', Powder Technology. Vol. 36, 1983. 39-45.

38 Scott, A.M, and Bridgwater, J,: 'Interparticle Percolation: A Fundamental Solids Mixing Mechanism', Industrial and Engineering Chemistry Fundamentals. Vol. 14, 1975. 22-27

39 Bridgwater, J, Cooke, M.H, and Scott, A.M,. 'Inter-particle percolation: Equipment Development and Mean Percolation Velocities', Trans. IChemE. Vol. 56, 1978. 157-167

40 Matthée, H,. 'Segregation Phenomena Relating to Bunkering of Bulk Materials: Theoretical Considerations and Experimental Investigation', Powder Technology, 1, 1967/68. 265-271.

41 Stephens, D.J., and Bridgwater, J,. 'The Mixing and Percolation of Cohesionless Particulate Materials: Part I. Failure zone formation', Powder Technology. Vol. 21. 1978. 17-28.

42 Bridgwater, J, Foo, W,S, and Stephens, D.J,: 'Particle Mixing and Segregation in Failure Zones: theory and Experiment', Powder Technology. Vol. 41. 1985. 147-158.

43 Tanaka,T,. 'Segregation Models of Solid Mixtures Composed of Different Densities and Particle Sizes' Ind. Eng. Chem Process Design and Development., Vol. 10, No. 3, 1971. 332-340.

44 Williams, J.C,. 'The Segregation of Particulate Materials. A Review', Powder Technology. Vol. 15, 1976. 245-251.

45 Holmes, C,. 'The Sampling of Coal-II', Colliery Engineering. February, 1934. 40-46.

46 Brown, R, L,. 'The Fundamental Principles of Segregation', The Institute of Fuel. Journal. Vol. 13. 1939. 15-23.

47 Lawrence, L.R, and Beddow, J.K,: 'Powder Segregation During Die Filling', Powder Technology, 2. 1968/69. 253-259.

48 Harris, J.F.G, and Hildon, A.M,. 'Reducing Segregation in Binary Powder Mixtures with Particular Reference to Oxygenated Washing Powders', Ind. Eng. Chem. Process. Des. Develop., Vol. 9, No. 3, 1970. 363-367.

49 Williams, J.C, and Khan, M.I,: 'The Mixing and Segregation of Particulate Solids of Different Particle Size', The Chemical Engineer. 1973. 19-25.

50 Williams, J.C and Shields, G,. 'The Segregation of Granules in a Vibrated Bed', Powder Technology. Vol. 1. 1967. 134-142.

51 Shinohara, K., Shoji, K., and Tanaka, T.,: 'Mechanism of Size Segregation of Particles in Filling a Hopper', Ind. Eng. Chem. Process Design and Development. Vol. 11, No. 3. 1972. 369-376.

52 Shinohara, K., and Miyata, S.,: 'Mechanism of Density Segregation of Particles in Filling Vessels', Ind. Eng. Chem. Process Design and Development. Vol. 23, No. 3. 1984. 423-428.

53 Shinohara, K.,: 'Mechanism of Segregation of Differently Shaped Particles in Filling Containers', Ind. Eng. Chem. Process Design and Development. Vol. 18, No. 2. 1979. 223-227.

54 Bagster, D.F: 'The effect of coarse particle concentration and of water content on the segregation of particles in bins', Proc. EFCE Pub. Reliable Flow of Particulate solids. 45. 1985. 289-302.

55 Bagster, D.F· 'The influence of cohesion on the segregation pattern in bins', Int. Con. on Bulk Materials Storage, Handling and Transportation. Newcastle, Australia. 1993. 203-206.

56 Bagster, D.F· 'Studies on the effect of moisture content and coarse and fine particle concentration on segregation in bins', Kona. No. 14, 1996. 138-143.

57 Allen, T: 'Particle Size Measurement' Powder Technology Series, 2nd Edition. Published by Chapman and Hall Ltd. 1975.

58 Popplewell, L.M, Campanella, O.H, Sapru, and Peleg,. 'Theoretical Comparison of Two Segregation Indices for Binary Powder Mixtures', Powder Technology. Vol. 58, 1989. 55-61.

59 Alonso, M, Satoh, M, and Miyanami, K,. 'Optimum Combination of Size Ratio, Density Ratio and Concentration to Minimise Free Surface Segregation', Powder Technology. Vol. 68, 1991. 145-152.

60 Arteaga, P, and Tüzün, U,. 'Flow of Binary Mixtures of Equal Density Gradients in Hoppers – Size Segregation, Flowing Density and Discharge Rates', Chemical Engineering Science, Vol. 45, No. 1, 1990. 205-223.

61 Reisner, W and V. Eisenhart-Rothe, M,: 'Bins and Bunkers for Handling Bulk Materials-Practical Design and Techniques. 2nd Edition. Published by Tans Tech Publications, Ohio, USA. 1971. 308-220.

62 Williams, J.C,. 'The Mechanisms of Segregation' Internal Document, University of Greenwich. September 1978. 1-15.

63 Shinohara, K., and Enstad, G.G.,. 'Segregation Mechanism of Binary Solids in Filling Axi-Symmetric Hoppers', Proceedings of 2nd World Congress, Particle Technology. September 19-22, 1990. Kyoto, Japan. 45-52.

64 Mosby, J,: 'Investigations of the Segregation of Particulate Solids with Emphasis on the Use of Segregation Testers', Ph.D. Thesis, Telemark College, Porsgrunn, Norway. 1996

65 Savage, S.B, and Lun, K.K,: 'Particle Size Segregation in Inclined Chute Flow of Dry Cohesionless Granular Solids', J. Fluid Mech. Vol. 189, 1988. 311-335.

66 Dolgunin, V.N, and Ukolov, A.A,: 'Segregation Modelling of Particle Rapid Gravity Flow', Powder Technology. Vol. 83, 1995. 95-103.

67 Meakin, P, and Jullien, R,: 'Simple Models for Two and Three Dimensional Particle Size Segregation', Physica A 180, 1992. 1-18.

68 Wilkinson, H.N, Duffell, C.N, Reed, A.R, and Bunting, G.J: Bulk Solids Physical Test Guide, British Materials Handling Board. 1983 (ISBN 0946637 01 6).

69 Air Comparison Pycnometer. Model 930. Reference Manual. Scientific Instruments Division, Beckman Ltd. Irvine, California, USA.

70 Barnes, R.N, :'Resonant Vibratory Feeders', 4th Int'l Conf. On Bulk Materials Handling and Transportation; Symposium on Freight Pipelines, Wollongong, Australia. July 6-8, 1992, 321-326.

71 Salter, G.F, Pittman, A.N, and Barnes, R.N, :'Mixing of Particulate Solids Using Static Mixers', 5th Int'l Conf. On Bulk Materials Handling and Transportation, Wollongong, Australia. July 10-12, 1995, 395-402.

72 Caulcutt, R: 'An Introduction to Taguchi Techniques' Statistics in Research and Development, 2nd Edition. Chapman and Hall. 1991.

73 Forberg, H: 'Modern Mixing – Theory and Praxis' Powder Handling and Processing. Vol. 4, No 3, September 1992. 318-321

74 Excel, Users Manual, Microsoft, INC.