THE EFFECT OF PELLETS PHYSICAL PROPERTIES ON HANDLING PELLETED BIOMASS MATERIAL IN PRACTICAL USE

By

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Thesis submitted in partial fulfilment of the requirements for the award of the

Degree of Doctor of Philosophy

This research was carried out at The Wolfson Centre for Bulk Solid Handling Technology

Faculty of Engineering and Science

University of Greenwich

October 2016

Declaration

I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy being studied at the University of Greenwich. I also declare that this work is the result of my own investigations except where otherwise identified by references and that I have not plagiarised the work of others.

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Acknowledgements

I would like to acknowledge and expressed my profound gratitude to Allah.

I will also like express my sincere gratitude to my major supervisor, Prof. Michael S.A Bradley for his unrelenting and tremendous contribution and guidance that lead to the successful completion of this work.

I would like to thank Dr. Stefan Zigan and other member of staff and colleagues at The Wolfson Centre for Bulk Solid Handling Technology for their support, inspiration and contribution toward the success of this research. Many thanks to you all.

I also wish to acknowledge and express my warm appreciation to the research collaborating team at Forever Fuel Ltd, and particularly Mr. Bruno Prior for their active participation and contribution in all forms toward the success of this study. They have done fantastically well beyond my expectation.

Kudos to Dr. Sylvia Larsson and all member of staff at Biomass Technology Centre, Swedish University of Agricultural Sciences, Umea, for giving me the opportunity to take part in the pellet production research and use their equipment.

My profound gratitude goes to The Nigerian Petroleum Technology Development Fund (PTDF) and (TET Fund) organisations for sponsoring and supporting this my PhD study.

I would like to extend my special thanks to my mother (Hajiya Habiba Abdulmumini), my late father (Alhaji Abdulmumini, may his soul rest in peace) and my wife (Oumoulhayrath Ramanou) for their endless good wishes and emotional support throughout this study. Similar my keen appreciation goes to Alhaji Salisu Kalamu Aliero, Mallam Ahmed Aminu Galadima, Mallam Salihu Dankeni, Mallam Ibrahim Abubakar Dogon Daji and all other friends and relatives who has been honest and supportive throughout my life. May you all live long to reap what you sow.

Abstract

This research investigated two important aspects of wood pellet production and use; (a) the effect of varying pelleting process parameters (i.e. steam moisture content, conditioning temperature) and feedstocks species (Pine and Alder wood powder) on the mechanical strength and durability of the pellets, during pelleting and (b) how variable pellet durability is, how different testers for measuring pellet durability (i.e. resistance to damage in handling) compare against each other, and how the measurements relate to the breakdown of pellets observed in real handling systems.

In the first part, wood pellets with different production histories were produced using a large-scale conventional pellets mill. The strength and durability (quality) of the pellets with different production histories and other batches of industrial standard wood pellets from Forever Fuels Ltd were evaluated using the existing standard bench-scale Ligno, tumbling box testers and a newly introduced rotary impact tester, developed at The Wolfson Centre. In the second part of the study, a medium scale storage facility was constructed and used long with an existing pressurised tanker truck to assess pellets degradation due to change in blowing pressures, convening air and particles velocity in a full-scale pneumatic blow delivery system, in accordance with the standard delivery practice. A novel simplified breakage matrix model was designed to examine the link between the bench and full-scales blow pellets degradation tests. The model used the data obtained from a systematic experimental approach testing of same batch wood pellets samples in both bench and full-scale pneumatic degradation tests. The results of the bench scale pellets durability tests were compared and also scale-up to test both methods, for predicting real pellet degradation in full-scale pneumatic blow deliveries.

The findings indicate the existence of substantial difference in the pattern of pellets degradation between the three bench-scale durability testers used. The variation was attributed to possible difference in the breakage mechanism of each bench tester. The bench to full-scale comparative pellets degradation study, shown that the newly introduced rotary impact and Ligno testers are of high potential to predict pellets degradation in full-scale pneumatic delivery system. The breakage pattern of pellets in tumbling tester was found to have negative correlation and has little relevant to the measurement of pellets mechanical resistance to breakage in real handling or pneumatic deliveries. However, it can possibly be use to achieve an indication of pellets dustiness tendency in real handling system. The argument between the preferable pellets blow delivery pressures appears to depend on the delivery distance and tanker operator as well. The predicted and real simplified breakage matrix modelling results have shown a better agreement in the Ligno and rotary impact durability tests and possibility to predict pellets degradation in full-scale pneumatic deliveries, from bench tests. It also avoids the needs to undertake multiple breakage tests on different size fractions, by means of assuming values in columns, other than the first one.

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Nomenclature

Symbol	**Symbol names**	**Unites**
MC_{db}	Dry base moisture content	%
MC_{wb}	Wet base moisture content	%g
W_o	Initial mass of pellets in a wet base	Kg
W_d	Dried mass of pellets in a dried base	Kg
BD	Bulk density	Kg/m^3
M	Total mass of pellets	Kg
V	Volume of cylinder	m^3
ε_o	Porosity	m^2
ρ_b	Bulk density	Kg/m^3
P_ρ	Particle density	Kg/m^3
PDI	Pellet durability index	%
M	Mass of surviving or coarse pellets after testing,	Kg
M_o	Initial mass of pellets before testing,	Kg
V_p,	Particles impact velocity	m/s
N	Number of revolution per minute	Rpm
R	Radius of the accelerator disc	M
θ	Impact angle	°
T	Time	Second
T	Temperature	°C
M	Breakage matrices	
I	Input vector	
O	Output vector	

Chapter 1 Introduction

1 Introduction

The use of pelleted biomass material for renewable heat and power generation is widely increasing across the world. For instance, United Kingdom is expected to attain more than 15 % clean renewable energy by the year 2020 and import about 24 million tons of wood pellets increasingly per annum, with about 11 million tons of the pellets being imported from Canada, Germany and Sweden (Verhoest & Ryckmans, 2012). Pelleted biomass materials are recognised as the current major source of renewable energy that has the potential to replace fossil fuels use in several applications to minimises greenhouse gases (SO_2, NO_2, (CH_4, & N_2O) and carbon (CO_2) emission in the environment (Ehsanollah, 2011).

Wood pellets are often manufactured through compaction of ground wood powder (feedstock) at high temperature and pressure, via a process known as densification or pelleting (Phani K Adapa, Tabil, & Schoenau, 2013). The unprocessed biomass materials are grounded into powders (i.e. sawdust) and compacted to increase the bulk density from about 200 kg / m^3 to 600 - 800 kg / m^3 after pelleting (P.K. Adapa, Schoenau, Tabil, & Singh, 2007; Behnke, 1994; Holley, 1983; Nalladurai Kaliyan & Vance Morey, 2009a; Larsson, Thyrel, Geladi, & Lestander, 2008; S. Mani, Tabil, & Sokhansanj, 2003; McMullen, Fasina, Wood, & Feng, 2005). The increase in bulk density comes with the benefit of enabling the material or cheaper to handle and maximised storage volume to saves the transport costs. However, all the advantages of pelleting unprocessed biomass material could be forfeited in the absent of adequate understanding of pelleting process parameters (i.e. die length and diameter ratio, gap between die and rollers, die speed, feedstock particles sizes, steam-conditioning temperature, feedstock moisture content) relationship with the feedstock properties during pelleting (Song et al., 2010).

Similarly, pellets have regular shape and sizes, usually between 6 mm or 8 mm diameter and ≤ 40 mm length (E. V. Alakangas, 2009). The regularity in shape and sizes of the pellets was one of the major feature that made it viable to be use in standard bio-based conversion equipment during pyrolysis, gasification or in a domestic heating boilers (Annual Report, 2013; Hägglund & Andreas Käck, 2012). However, it has been reported that pellets produced in British Columbia experience not less than ten elevations and drops during transport or handling, from point of production to the final place of uses (Oveisi et al. 2013). This simply means that weaker pellets are very likely to degrade or break down to generates fines and dust due to compression (crushing), impact (cause shattering on both surfaces) and shearing (acting along the surface and edges of the pellet) forces encountered along the transport chain (Holley, 1983; Young, Pfost, & Feyerherm, 1963). Pellets may also gain or loses it moisture content during transport or handling, which could increase the pellets susceptibility to degrade and produces broken fine and dust during handling. The fines and dust generated from the pellets are harmful to human health and could consequently increase the chance of having dust or fire explosion, reduce boiler efficiency and increase smoking tendency, due to poor aeration (airflow) within the burning pellets bed, in the boilers combustion chamber.

Therefore, the quality (strength or durability) of pelleted biomass material must be improve to withstand the wear and impacts experience in transport or handling systems, such as during ship loading and unloading, silo discharging or feeding, tipping or pneumatic blow deliveries. The resistance of the pellets to degradation in a handling is often measured in terms of pellets durability index (PDI) and is determined by 1 - percentage mass of the surviving pellets, after durability testing, over the initial mass of the pellets, before testing. The fractions of the broken pellets below 3.15 mm diameters, generated after sieving is known as pellets fines content (Pellets & Version, 2013).

In order to prevent the occurrence of unwanted broken pellets fines (< 3.15 mm diameters) in small domestic pellets stores, where fines are highly undesirable or in handling systems, pellets with different production histories (in term of steam moisture content, conditioning temperatures and feedstock species) were produced. The pellets were produced to examine ways of improving pellets strength and durability during pelleting. Similarly, the strength and durability of pellets were evaluated using both the existing standard bench-scale pellet durability testers (i.e. tumbling box and Ligno testers) and the newly introduced rotary impact tester. The new bench-scale tester was deployed to clear suspicion about the existing standard pellets durability testers' credibility to predict the actual resistance of pellets to degradation in real handling system, because there are several complain about wood pellets with high pellet durability index (PDI) values, turning out to produce more than expected fines and dust content in real handling systems. Despite all the necessary measures, taken to ensure the pellets fines content remains below 1 % (by weight), after loading as required by the European pellets council EN 14961-2 (Pellets & Version, 2013).

Therefore, this research aimed at investigating (a) how to improve pellets quality (strength and durability) during pelleting by mixing two different feedstocks (Alder and pine wood powder) at distinct moisture contents and steam conditioning temperatures. (b) To determine how variable pellets durability is, how different bench-scale testers for measuring pellet durability (i.e. resistance to pellets damage in real handling) compare against each other, how the measurements relate with the pattern of breakdown pellets observed in real or large-scale handling systems, and explore the most favourable operating conditions for practical pneumatic deliveries of pellets into stores.

This will also involves measuring the influence of each pelleting process parameters on pellets strength and durability using the standard tumbling box, Ligno and the newly introduced rotary impact testers. Rotary impact tester was introduced because is a well-known bench-scale particles degradation tester, at The Wolfson Centre, with successful record of predicting other particulate materials degradation in pneumatic conveying line, but had not been extensively used for pellets hitherto. The broken-down pattern of the pellets in each of the bench tester will be compared to that of full-scale blow delivery equipment (i.e. pneumatic blow delivery system), with a view of using a breakage matrix model to predict pellets degradation in a chain of handling system, from bench tests. The breakage matrix approach would be the key means to link the size distribution of broken pellets fractions (fines and dust particle sizes) derived from the impacts of pellets on the test equipment to the break down in real handling and possibly develop recommendations on how to improve pellets durability and best industrial handling practices.

1.1 The specific research objectives

- To conduct a wide range of literature review across factors affecting pellets strength and durability during and after pelleting, methods of evaluating pellets durability and tests equipment.
- To evaluate and compare the existing methods of measuring wood pellets strength and durability and appraise the standard bench-scale test equipment for their ability to provide pellets breakage measurements that are scalable to full-scale pneumatic conveying line.
- To assess the applicability of using the large-scale rotary impact tester for measuring pellet durability and recommend the procedure for wood pellet durability test.
- Explore where correlations that seem to exist between the breakage pattern of pellets in standard tumbling box, Ligno and rotary impact testers and recommend the most preferable bench-scale pellet durability tester.
- To analyse the characteristics of the surviving and broken pellets fines size distribution derived from the two standard pellet durability testers and that of rotary impact tester.
- To set up a full-scale pellets degradation experiment that can evaluate the breakage resistance of pellets in real industrial handling (i.e. pneumatic conveying line).
- To relate the breakage of pellets observed in the full-scale pneumatic blow delivery or belt-conveying system to the bench-scale testers and test the possibility of using a "breakage matrix" approach, in scaling the bench-scale test data to predict the pellet degradation in full-scale pneumatic delivery systems.

It important to note that in reporting the findings of this research, limitations to some of the methods applied were considered during the data analyses. The diagram in figure 1 presents the summary of the research plan and the entire milestones.

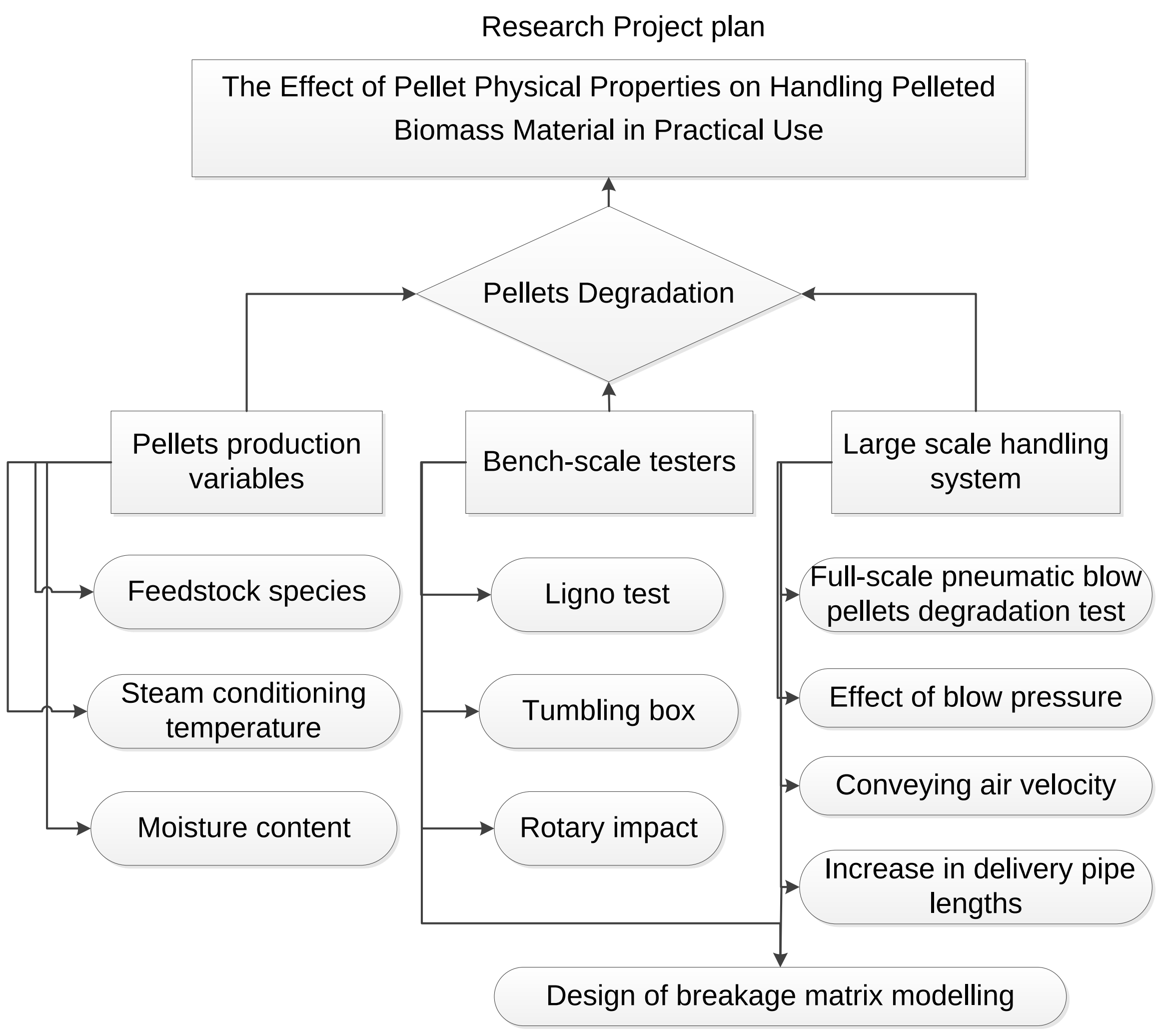


Figure 1.1 The entire project plan

Chapter 2 Literature review

2 Introduction

The first part of the literature review explains the effect of particle bonding and densification mechanisms on powdered materials. The second part emphasis on factors affecting pelleted / densified biomass material quality (strength and durability) during and after pelleting, with more emphasis on how improve pellets mechanical durability using pelleting process parameters (such as steamed moisture content, conditioning temperature, compaction pressures, energy used, die length and diameter ratio) and feedstocks (wood powder) species variability.

In addition, the literature review will also focus on investigating factors affecting pellets strength and durability due to change in pellets physical properties (i.e. pellets moisture content, bulk / particle density etc.) during handling. Most importantly, how variable pellet durability is in different bench scale testers and the methods of testing pellet durability. Finally, the important area of comparisons between the existing bench test techniques and against the breakdown of pellets observed in real handling systems will be address even though the literature in this area is scant.

2.1 Particles Bonding Mechanisms

The bonding mechanism between particles were reviewed in this research to understand the fundamental principles of particles compaction, necessary for tableting, densification or pelleting of powdered materials. Optimising the process involve could yield a stronger production of bonded densified biomass material, if the fundamental principle of particle bonding and interlocking mechanisms are well understood (Rumpf,. 1962). Most often, binders are added to powder during agglomeration to strengthen the bonds between the particles and form a rigid densified structure of solid particles. However, in pelleting or densification of ground biomass material, the inherent chemical binders (i.e. lignin, cellulose, hemicellulose, gelatinised starch and denatured protein) are often secreted at high temperatures and pressures to cement the joints. The increase in temperatures between 30

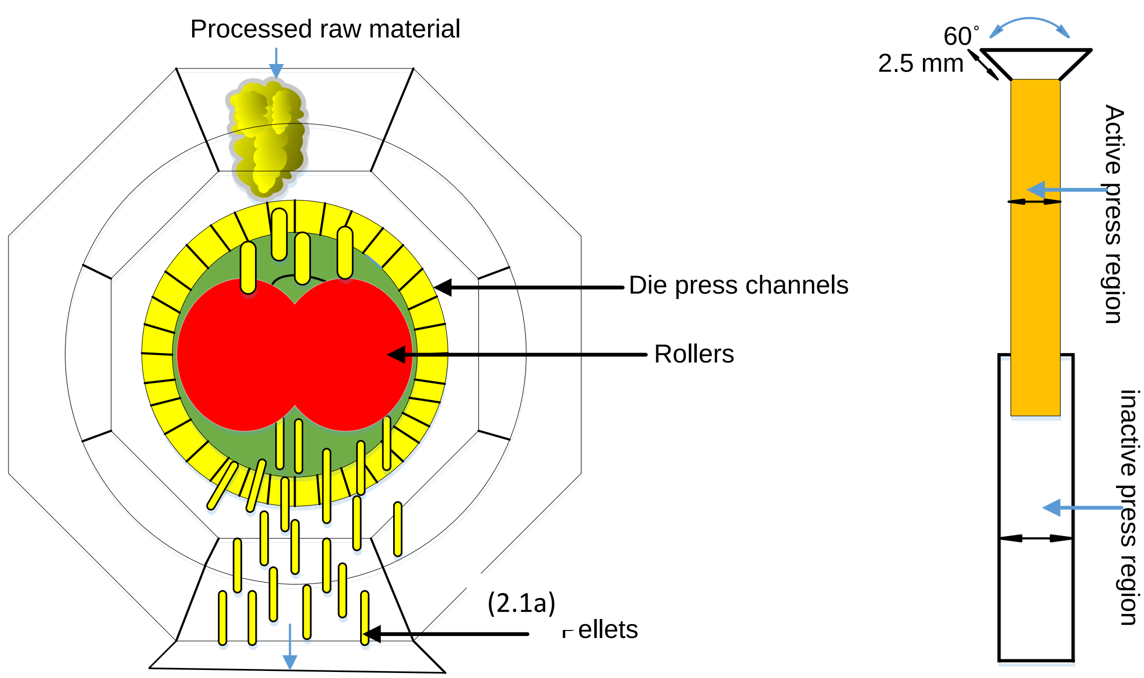
– 110℃ and pressures on the ground biomass powder (feedstock), during densification or pelleting can enhance the binding agent (Tumuluru, 2014). The bonding strength of particles during densification or pelleting depends on the inherent feedstock chemical binders secreted due to induced compaction pressures, temperature and moisture content (Rumpf, 1962; Sastry, 1973; Tumuluru, Wright, Hess, & Kenney, 2011). Meanwhile, this research is not focusing on bonding or binding agents, but understanding the key fundamental principle of particles bonding would make a vital impact on the design of biomass pellets manufacturing processes to produce quality pellets, that are highly resistant to degradation in handling.

2.2 Pellet Pressing

A pellet mill or press is a device used for extruding ground wood residues (sawmill by-products) or other agricultural feedstocks to form a highly dense cylindrical shape material called pellets or briquette. The process of extruding or compacting ground biomass feedstock using conventional pellets mill is known as pelleting. Conventional pelleting is a well-known industrial method of producing animal feeds pellets (Mina-boac, Maghirang, & Casada, 2006). However, in pelleting of biomass material, binders are often not added, the inherent natural binders (lignin, cellulose and hemicellulose) plasticised within the feedstock, at high glass transition temperatures of about 140°C and compaction pressures between 100 - 150 MPa (Heinz, Köser, & Werner, 1982; Thomas, Van Zuilichem, & Van Der Poe, 1997; van Dam, van den Oever, Teunissen, Keijsers, & Peralta, 2004). The glass transition temperatures may vary with the inherent properties of different biomass feedstock species.

2.2.1 Brief Description of Large-Scale Pellet Mill and the Press Channel

The set-up for the large-scale conventional pellet mill press consist of die and mounted rolling bearings as shown in figure 2.1. The lengths of large-scale pellet mill die could vary from 150 – 250 mm with inner diameter ranging from 800 mm to 1 m. Nielsen & Gardner (2009) have investigated the effect of pellets strength and durability due to change in die thickness. The thickness of die was found to influence pellets strength and durability due to prolonged heat retention capability of the heated die during pelleting. A large scale conventional pellet mill die has several number of cone-shaped press-channels matrices with typical openings size edges of about 2.5 mm deep at 60°, radially placed at a proximity to the rollers, that force the milled wood powder continuously into the channels. The force-fed milled powders are compacted in the press channel, due to opposing skin wall friction that build up between the compressed feedstock and the die channel walls, as it travels down to exit the press channel. The resistance to the flow due to friction induces heat to the feedstock to secrete its natural binders, responsible for gluing the particles bonds and form a highly dense cylindrical shape material known as a pellet. An adjustable knife is mounted just above the die press channel, exit to trim down the pellets to a required size length. The density of pellets produced through conventional pelleting could increases up to 1200 - 1300 kg / m^3 (Nielsen et al., 2009). The diagram of the large-scale conventional pellet mill die / rollers and the pressing channel unit are shown in figure (2.1 a) and (2.1 b).



(2.1 a) Pellets mill die compartments

(2.1 b) Press channel

Figure 2.1 The diagram of; (a) pellet mill and (b) press channel (Nielsen et al. 2009)

2.2.2 Pellet Mill Variables

Pellet mills have many different variables and each of these variables have vital role in making good pellets. Previous authors have investigated the effect of pellets mill die length and die diameters ratio, die speed, die thickness, and the gap between rollers and die on quality (strength and durability) of pellets produced and consequently on pelleting energy consumption.

For instance, Hill & Pulkinen (1988) found an increase in alfalfa pellets durability from 50 % to 80 % with corresponding increase in die length to diameter ratio (l / d) of 5 to 9. They also observed an increase of about 10 % in durability of pellets produced with die length to diameter ratio (l / d) of 10 (at d = 6.4 mm), in comparisons to pellets produced with l / d ratio of 8 (at the same d = 6.4 mm). Heffner & Pfost (1988) reported to have observed high increase in energy consumption in a thicker die dimension pelleting, and that thicker dies takes longer time to heat up and discharge heat to the feedstock (i.e. due to slow conduction). However, the long duration of time taken to discharge the absorbed heat was found to have benefit on improving the pellets quality, due to increase in plasticization of the inherent binder (e.g. lignin, cellulose) to enhance starch gelatinization at high temperatures and pressures. They also found that a smaller die produces poultry layer feed pellets with high quality.

Recent research by Kaliyan & Morey, (2009a) reported that the shear force between compressed feedstocks powder, varies with the ratio between the die lengths to diameter (L/D) during pelleting. That pellet durability increases with increase in die length to diameter (L/D) ratio. However, there was no data presented in this regard to evidence their views.

Hogqvist (2012) investigated the effect of die channel length (mm) and storage time (days) on bulk density (kg/m^3), mechanical durability (%), fines (%), moisture content and energy consumption (A) during pelleting of assorted stem wood and whole pine tree log poles. The assorted stem wood showed a positive correlation between increase in bulk density and die channel length from 45 mm - 55 mm length and moisture content 9 – 13 % respectively.

Several authors had investigated the influence of conventional pellets mill die speed (revolutions per minute) on pellets strength and durability in the past and some of their findings are:

Stevens (1987) reported to have not observed any significant change in pellets durability due to variation in pellets mill die speed between 150 – 268 rpm, during biomass feedstock pelleting, though, die speed effect may vary with biomass species. However, Kaliyan & Vance Morey, (2009a) reported that increase in die speed during cold pelleting (i.e. without steam conditioning) of highly fibrous biomass materials could lead to die channel blockages.

Tumuluru (2014) investigated the effect of increasing 8 mm thick die rotating speeds (from 40 - 60 Hz) on pellets durability by using 4.8 mm diameter corn Stover feedstock particles size to produce pellets at high feedstock moisture content between 28 - 38 % (w.b) and pre-conditioning temperatures between 30 - 110 ˚C. The study shows that pellets produced at 70 ˚C pre-conditioning temperature and above 50 Hz pellet mill, die speeds and feedstock moisture content between 33 % - 34 % (w.b) are highly durable to some extent. Therefore, concluded that feedstock moisture content, preheating and die rotational speed are interactive process parameters that can influence pellets bulk or tapped density, moisture content and durability. However, the optimum requires die speed for production highly durable pellets was not stated in this study.

The gap between die and rollers of a pellets mill press was found to have effect on feedstock sharing and compaction tendency in a die press channel, during pelleting. Robohm & Apelt, (1989a) and Robohm (1992) observed decrease in pellets durability due to increase in gap between die and rollers from 4 mm - 5 mm. The decrease in pellets durability was attributed to poor shearing of the feedstock (wood powder), as the gap between the die and rollers increases, which might have limit the close contact friction to enhance natural binder's plasticised during compression or pelleting.

Double pelleting is another method of increasing pellet strength and durability, especially during hard wood pelleting. Double pelleting occurs when a biomass feedstock is compressed using two different sizes of pellets mill die with the same press channel diameters, but different lengths, in a conventional pellet mill, during pelleting. The feedstocks are pre-compressed using the first thin die (typically 5 mm diameter) before pushing it into the thicker die (25 mm diameter and 40 mm height), where the final phase of the pelleting is completed. Robohm & Apelt (1989b) reported that double pelleting consumes more energy during pelleting compare to single pelleting system; however, the data for the comparative estimate of energy consumption between the single and double pelleting was not presented.

Retention or relaxation time is the time taken by the processed feedstock to exit the die channels during pelleting. Shaw & Tabil (2007) observed differences in relaxation time of biomass feedstocks during pelleting and have concluded that feedstock relaxation time varies with the moisture contents but appears to have less effect on the strength and durability of the pellets produced. They also reported that the effect of holding time was responsive to pressure, because the lower the pressure applied to feedstock during pelleting the longer the relaxation time required, short relaxation time often occur at higher pressure compaction to achieve high pellets durability. The variation was attributed to the reluctance in the material expansion due to increase in pressure applied.

Pellets' cooling is an essential practice found to have influence on pellets strength and durability, after pelleting. Thomas & Poel (1996) reported that pellets leave the press at a different range of temperatures usually between 60 °C – 95 °C and moisture content in the range of 12 % - 18 % wet base (w.b). The excessive heat and high moisture content of hot pellets could be liberated through ambient air cooling at about 23°C or by using commercial air cooling system at 5 °C about 4 to 15 minutes to reduce the pellets moisture content to below 13 % (w.b) before storage.

Robinson, (1984) reported that pellets could easily crack or break down to generate fines and dust due to mould that could results to self-heating or fire explosion in a large silo which can cause monetary losses due to improper cooling and drying. The durability of biomass pellets can deteriorate to generate excessive fines during storage due to poor storage facilities. Tabil (1996a) observed a decrease in alfalfa pellet quality with increase in relative humidity conditions up to about 90 % in the store.

Fasina & Sokhansanj (1996b) also observed decrease in alfalfa pellets durability from 81 % to 75 % with corresponding increase in pellet moisture content from 7.5 % to 19 % wet base, due to increase in relative humidity condition of the store from 70 % to 90 %. They found that the pellets durability was stable at stored average moisture range between 6.3 % to 10 % (w.b) moisture content. The durability of the pellets also decreases with increase in pellets moisture content from 12 % - 14 % (w.b) due to poor storage condition. Recently Graham, (2015) conducted research on white wood pellets and reported that rainfall and humidity exposure of pile of pellets could influence the level of degradation observed in the stores.

The review on bonding and binding strength, pellet mill and pelleting process variables, cooling, and storage was conducted for understanding of how each of the parameters affects the quality (strength and durability) of pellets during and after pelleting. In conclusion, it seems overall that die speed and other variables influence pellet durability but were not the key focus of this research. Therefore, the effect of pelleting process parameters such as steam conditioning temperatures, moisture content and feedstocks specie variability on physical quality of pelleted biomass material in an engineering point of views were reviewed. In additional, the principles and techniques for evaluating pellets physical qualities (strength and durability) using the existing bench-scale pellets durability testers and the changes in pellets physical characteristics, due to degradation in large-scale handling systems (i.e. degradation in pneumatic delivery systems) was also reviewed.

2.3 Densification Process Variables and system parameters

Process variables are often altered during industrial pelleting to improve pellets quality. The review in this section will cover the influences of pelleting process and other important parameters such as steam conditioning temperatures, moisture contents, feedstock species, particles size distribution, blending or mixing of wood powders and compaction pressures on pellets strength and durability.

2.3.1 Effect of Pressure

It is often difficult to measure the exact pressure applied on processed feedstock, by the rollers in large-scale pellet mills die compartment during pelleting. However, the effect of pelleting pressure on a densified / pelleted biomass products quality (strength and durability) are often measured using a single die or piston arrangements. The rate of pressure applied on the feedstock, in the die, varies with the feedstock inherent properties, moisture content and densification / pelleting temperatures.

Koser, Schmalstieg, & Siemers, (1982) reported that increase in pressure during wood powder compaction, to form pellets, increases the inter-particle bonding to enhance solid bridges between two or more particles that join to form a densified durable product. Graham and Blanski (1984) observed increase in grass pellet density from 1137 to 1459 kg/m^3 and alfalfa pellet density from 1267 to 1402 kg/m^3 with corresponding increase in pressure from 15 to 45 MPa. While Christopher et al. (2005) found a strong correlation between density of Norway spruce sawdust pellets and high compression strength but the correlation decayed with further increase in compressive forces between 46 - 114 MPa and recommended that pressure in the die may require not exceeding 50 MPa. Kaliyan (2008) reported to have observed increase in density, strength or durability of densified biomass products with increase in densification pressures. However, the increase was at the expense of specific energy used during the densification or pelleting. This indicates that applying pressure beyond certain thresh-hold limit will only be at the expense of energy cost during pelleting instead of increasing the strength and durability of the pellets. The downside of this method is that what is mostly applicable for single pelleting, but is not achievable with large-scale pellet mill use for commercial pellets production due to the difficulty of getting access the rollers in the large pellets mill die compartment during pelleting, to instrument them and extract force signals.

2.3.2 **Effect of Steam Conditioning Temperature**

Despite the heat, induce to wood powder (feedstock) due to friction that build up between the compressing feedstock and die press channel wall, during pelleting. Thomas et al. (1997) emphasises that heat in form of hot steam are often added to the feedstocks prior densification / pelleting to soften and modify biomass natural or physicochemical binders such as lignin, cellulose, hemicellulose, denatured protein and gelatinization starch to improve bonding of particles and durability of the product.

Reece (1966) reported that highly stable compacted products of hay were found to be produced when it was pre-heated heated at conditioning temperatures between 60 - 70˚C compared to other similar unheated hays densified product. Hill & Pulkinen (1988) observed an increase in Alfalfa pellets durability from about 30 % - 35 %, with increase in steam conditioning temperatures ranges between 60˚C to 104˚C. At the same time, Aqa & Bhattacharya, (1992) observed a decrease in specific energy consumption of about 41.2 % when saw-dust was pre-heated to 130 ˚C at die heating temperature of 300 ˚C.

Gilpin et al. (2002) reported to have found an increase in pellets quality with corresponding increase in feedstock steam conditioning temperatures of about 70˚C - 80˚C. Similarly, Thomas et al. (1997) observed an increase in pellets hardiness and durability due to steam conditioning of mesh feedstock and recommended that conditioning system must be justified in terms of cost and quality rather than product design, however, the mass of steam added was not expressed in detail. Kaliyan & Morey (2006) also reaffirm the increase in pellet durability was observed due to corresponding increases in pelleting temperature between 75˚C to 100˚C but in this case, the increase in durability diminishes with further increases in temperatures beyond the glass transition temperature of 150˚C.

Kaliyan & Morey, (2009b) affirmed that steam conditioning at high temperatures activates the feedstock inherent binders to strengthen the particles bonding during Pelletisation and improve pellets quality. Peter et al. (2009) have the same view that beech pellets durability increase with increase in steam conditioning temperature and low extractives. Reverse is the case in the durability observed on similar Beech pellets produced at lower steam conditioning temperatures. However, excessive steam conditioning could limit the friction between the feedstock and die channel walls, which in return result to production of poor compaction pellets with low quality. Stelte et al. (2010) investigated how to improve beech pellets durability and found that pellets produced at about 100˚C were more resistant to degradation compared to other beech pellet produced without steam conditioning at 20˚C. Evidence from the effect of steam conditioning temperature on pellets strength and durability has shown that optimum steam conditioning temperature for a particular feedstock species may not be suitable for another type of biomass feedstock due to differences in their resilient inherent characteristics. However, the increase in the pellets durability observed appears to have varied with the feedstock inherent binder's response to high steam conditioning temperatures, which activate the binders to secret the elastic and thermoplastic moisture responsible for consolidating particles bonding, and improves the pellets quality upon cooling.

2.3.3 **Effect of Feed Moisture Content**

Moisture content (percentage water content) in this case, is the condition of wetness or dryness of biomass feedstocks before pelleting. The moisture content of wood chips before milling is usually between 20 % - 60 %. The review in this section focused more on the effect of feedstock moisture content on pellets quality (strength and durability). The moisture content of biomass feedstock particles promotes binders' plasticised to enhance the inter particles binding strength during densification or pelleting and could also influence pellets calorific energy (≥ 16.5 MJ/kg) and increase smoking tendency as well. The level of moisture content in feedstock could also alter pelleting pressure (due to change friction between the compressed feedstock and die channel wall), which can affect the strength and durability of the pelletized / densified biomass product

Pickard et al (1961) reported that hay compacted at 10 % (w.b) moisture content are of high quality compared to hay compacted at 20 % feedstock moisture content. Srivastava et al. (1980) reported that optimal durability of hay wafer containing 15 - 20 % alfalfa was achieved at 11 % moisture content. O'Dogherty & Wheeler, (1984) investigated the effect of feedstock moisture content on wheat straw wafers and found that high durable wafers are produce between 10 % - 20 % ranges of moisture contents. Stevens (1987) stipulated that quality corn-based feedstock pellets could only be produce between 11 % - 12 % (w.b) moisture content.

York and Pilpel (1972) and Pietsch, (1984) explain that moisture increases the surface contact area between particles at subsequent equilibrium melting points, to improve the bonding strength. Grover & Mishra (1996) agreed that moisture content have influences on the level of surface contact between feedstocks particles, and it improve the initial Van der Waals' bonding forces during pelleting. Similarly, Thomas & Poel, (1996) reaffirm that moisture in a biomass feedstock is indistinguishable from lignin content in terms of binding to produce highly durable pellets. Obernberger & Thek (2004) quantify the optimum moisture for pelleting and reported that pellets with optimum resistance to breakage are produce between 8 % to 12 % wet base (w.b) ranges of feedstock (wood powder) moisture content.

Kaliyan & Morey, (2009) also conducted an extensive large-scale corn Stover pellets / briquettes production research and found that high durable Stover pellets / briquettes are produced between 15 % - 20 % (w.b) ranges of feedstock moisture content, at room temperature (25 $^{\circ}$C). However, when the feedstocks were pre-heated to dry at 75°C temperature, the range of moisture required during pelleting reduced to about 10 % - 15 % (w.b).

Similarly, recent investigation by Zeus, (2015) stipulated that increase in moisture content from 10 % to 15 % have resulted to increase in wood pellets durability from 62 % to 84 %. He further reaffirmed that several studies have been conducted on how to improve wood pellets durability by altering the moisture content until it reaches an optimum stage and found that wood pellets of high quality could only be produced between 6 % to 12 % initial feedstock moisture content. The finding correlate with other similar researchers' views that high-quality pellets could only be achieve between 8 % to 12 % feedstock moisture content. However, the researcher seems to ignore the fact that feedstock moisture content could vary with steam conditioning due to moisture ingress, and feedstock variability.

2.3.4 Effect of Feedstock Particle Sizes Distribution

Numerous study has reported that aggregates of milled feedstock particles size distribution could affect the quality of the densified products. MacBain, (1966) reported that the use of uniformly single size large feedstock particles during pelleting could lead to production of poor quality pellet, because larger particles arrangement creates wide voids during pelleting which could consequently results to cracks or weak points on the pellet surfaces. MacBain, (1966) and Payne (1978) have gone further to investigate the effect of finer feedstock particle size distribution on a densified / pelleted product and found that lower voids increase the contact surface area to strength solid bridges between the particles during densification / pelleting, which make pellets to be highly durable. The principle was deployed during pelleting of alfalfa feedstock to produce highly durable alfalfa pellet.

Grover & Mishra, (1996) and Payne (1978) re-emphasised that pellets with optimum quality could only be achieved with a mixture of different particle size distributions because smaller particles tends to fill in the void gaps created by the bigger particles during pelleting to produce strong inter-particle bonding. In view of this, Vest (1993) conducted a survey on 34 feed milling screen sizes and found that most of the double hammer milling screens have 3.2 mm and 4 mm diameters split ring. The arrangement of the rings is in the order of 4 mm above the 3.2 mm diameters screens. However, 3.2 mm diameter screen size is often recommended for single hammer milling. They concluded that 3.2 mm single screen size hammer mill tend to produce more quality feed pellets compared to single 4 mm screen size, that smaller screen sizes consume more milling energy. However, the research is not particularly focusing on the effect of woods milling particle size distribution on pellets durability.

Bergström et al (2008) investigated the effect of raw material particle size distribution on the pelletizing process, physical and thermomechanical characteristic of Scots Pine sawdust fuel pellets, and found that the particle size distribution had some effect on current consumption and compression strength. However, no evidence of the effect was found on single pellet abrasion resistance, bulk density, moisture content and absorption during storage. Stelte et al. (2011) reported that using feedstock with finer particle size distribution often increases friction within the die press channel during pelleting leading to higher pressure at the expense of pellet mill energy to produce strong beech pellets.

2.3.5 **Bulk and Particle Density**

The bulk and particle density are part of the major physical properties that determine the quality of pelleted biomass material. Unprocessed biomass material is often densified to increase it bulk density, which returns save transport cost, enhance free flow and make it easier to handle. However, the benefits may be lost due to an increasing number of agitation and impacts encountered by the pellets during transport or handling system. The bulk density of pelleted biomass material tends to decrease with increase in pellets degradation to generate fines and dust within the unbroken pellet in the vessel. The variation in length and diameter of the broken pellets could also vary the bulk density of the pellets in the vessel.

Zou et al. (1997) reported that change in the particle shape or dimension could lead to a change in bulk density and packing system in the storage vessel. Alakangas, Valtanen & Levlin, (2006) measured the density of a pellet and found that it varies from 960 to 1120 kg/m^3. The bulk density of pelleted woody material could also range from 550 - 700 kg/m^3. Yazdanpanah (2009) examined the resistance of airflow in a bulk bed of wood pellets containing different percentage fine content required for design and control of ventilation and drying of bulk pellets in storage. The level of aeration in the bulk wood pellets was measured in the presence of fines (≤ 4 mm diameter) and found that pressure drop in mixed pellets with two different fines contents (1 % and 20 % by mass) was about 2 to 191.2 Pa m^{-1} and 7.9 to 1779.0 Pa m^{-1} ranges respectively. However, the change in bulk density due to a difference in the percentage of fine content was not known. Sui lam, (2011) defines solid density as the density of pellets measured immediately it pass out of the press channel and is some time known as relaxed density.

2.4 Biomass Composition and Its Effect on Pellet Strength and Durability

2.4.1 Effect of Feed Constituents

The change in pellets strength and durability due to chemical composition of biomass material varies with type or feedstock species. Wood (1987) and Thomas et al. (1998) stated that the plastic deformation that takes place in biomass pelleting was due to combined effects of moisture and heat supply to the feedstock at high temperature to activate binders (i.e. Lignin, gelatinizes starch and desaturase protein) responsible for gluing the particles to form pellets. Similarly, Briggs, Maier, Watkins, & Behnke (1999) reported that starch and protein plasticise at high temperature during pelleting to increase the binding strength of the pellets produced.

Van Dam et al. (2004) acknowledge that Lignin are ejected from softened feedstock at higher pressure and low glass transition temperature of about 140°C to increase the binding strength of the compacted produced (Van Dam et al. 2004). The natural binders (such as starch, protein and lignin) derived from milled wheat, barley and alfalfa biomass material was found to increase the strength and durability of densified products without adding artificial binders (Tabil 1996; Adapa et al. 2002b; Adapa et al. 2009; Mani et al. 2004). For instance, Sokhansanj et al. (2005) reported that many agricultural biomass materials, especially those from straw and Stover, have poor compaction properties which make it costlier and difficult to be used for manufacturing pellets that could not easily degrade to generate fine dust during handling. The difficulties arise due to poor understanding of the inherent binder's characteristics during pelleting or densification.

Kaliyan and Morey (2006) have also found that the physicochemical constituents (hemicelluloses, lignin, cellulose, crude fibre, protein, fat, starch and ash content) of biomass material are part of the relevant factors that play a major role in binding the particles during densification to improve pellet quality. The science behind the change in biomass feedstock characteristic due to the inherent physical and chemical properties tends to influence the quality of densified biomass products produced but varies with different tree species.

2.4.2 Biomass Feedstocks Variability

In all attempt to exploit other available biomass resources for greener energy improvement different species of biomass feedstock tendency to produce high-quality densified products were examined. The chemistry of wood species could also have an effect on the durability of pellets produced because of differences in their natural binders (lignin, cellulose and hemicellulose content) and densities (Ehsanollah, 2011).

Reece (1966) conducted research on the effect of feedstock variability with different sections of banana plants (i.e. stems and leaves). The two parts were mixed at different ratios to produce pellets, the durability of the heterogeneous pellet containing 58 % stems, 19 % finer screen size leaves particles and 23 % (2.4 mm) screen size particles of the leave, mostly broken leaves, which resulted in 49.5% durability index. However, the particles sizes distribution of the heterogeneous feedstock was changed to 41 % leaves, 44 % stems and 15 % (2.4 mm) screen size particles of the leave was also pelleted, the durability index to 90 %. Winowiski (1988) observed an increase in initial pellet durability from 45 % - 74 % by adding 15 % - 60 % wheat to turkey breeder ration during pelleting. Similarly, an increase in pellet durability index (PDI) from 93 % - 99 % was observed when 15 – 35 % barks of the same hardwoods (i.e. white oak, tupelo, sweet gum and yellow poplar) were added during pelleting. Adapa et al. (2003) conducted research on how to improve pellets strength and durability using different combined parts of fractionated alfalfa hay (i.e. stem or leaves) at different states. The breakage resistance of the heterogeneous alfalfa hay pellets was found to increase from 25 % to 73 % when 10 % ground leaves were added to the stem. However, the pellet durability decreased from 73 % to 43 %) when 100 % pure alfalfa stem feedstock was used in the pellets production.

Serrano et al. (2011) used an annular die pellet mill to produce pellets of barley straw at an optimum range of moisture content from 19 % - 23 % which resulted to 95.5 % PDI value. However, when the barley straw was added to Pine to produce heterogeneous pellets, the pellet PDI value was found to increase from 97 % - 98 % with added 2 %, 7 %, and 12 % (by weight) pine to straw increasingly during pelleting. Obidzinski (2014) also investigated the effect of adding 15 to 20 % Potato pulp to Oat bran feedstock at the same moisture content during pelleting and found decrease in energy usage by the pellet mill. Similarly, the kinetic durability of the heterogeneous pellets tested with Holmen tester, was found to decreases with increase Potato pulp to Oat bran content from 15 - 25 % under similar production condition. Thus, hitherto no one had tried adding pine to other available soft wood (e.g. Alder wood) to examine the effect on pellets durability, which could possibly contribute to renewable energy production.

2.5 Pellet Characteristics and Durability Measurement Techniques

Pellets are compacted cylindrical shape biomass material produced at high temperature and pressure. The standard physical and chemical properties of pellets include: dimensions (length ≤ 40 mm and diameter 6 – 8 mm), bulk and true density (650 kg m^{-3}), moisture content (≤ 10 %), hardness or durability (≥ 97.5 %), net or gross calorific energy values, ash content, corrosiveness and other unspecified characteristics. The most significant chemical elements that are often measured in pellets are Chlorine, Hydrogen, Nitrogen, Carbon, Potassium, Oxygen, heavy metals such as Mercury, Cadmium, Copper, Lead, and Zinc (E. V. Alakangas, 2009; Obernberger & Thek, 2004).

The quality of wood pellets was categorised based on either United State standard CEN/TS 14961 and currently European standard EN 14961-2 standards. The standard classify pellets base on their PDI values into four groups such as super-premium, premium, standard and utility. The minimum standard for premium EN plus pellets mechanical durability index is ≥ 97.5 % and the moisture content is within ≤ 10 %.

Kaliyan, Morey, Tiffany, & Extension, 2009; Pfost, 1962) reported that the mechanical resistance of pelleted biomass material to degradation are measured inform of strength and durability where pellets strength was categorised as the compressive, impact and water resistance, and durability as abrasion resistance. The review of each form of measurement techniques and the limitations were discussed in the following sub-headings. Salman, Ghadiri, & Hounslow (2007) narrated that the extent of material resistance to applied compressive force is known as hardness or critical limits of deformation.

2.5.1 **Compressive Resistance**

The ability of a pellet / briquette to withstand pressure or applied load in a handling system is known as compressive resistance. It is determined by applying load to a pellet until it start to develop cracks along the surface or break down into two or more piece or fines. Kaliyan & Morey (2009a) stated that compressive or tensile strengths of pellets are measured to simulate the breaking or crushing resistance of the pellets / briquette due to stress applied by the pellets on top of the other pellets underneath in store, during loading and unloading, discharging into storage vessels or at conveyor belt transfer points in the handling systems. However, uniaxial compression test (using texture analyser) may not possibly predict the actual bulk pellets dust tendency or wear resistance in handling systems.

However, Pietsch (2002) and Tabil (1996) have studied the compressive resistance of agglomerated powdered material and reported that agglomerated materials strength depends on the intermolecular forces between the particle and solid bridges between the compresses two or more particles contact points. They also examined the compressive resistance of sawdust logs and found that the elastic behaviour of the log decreases the length to about 1 / 3 of its original length before it finally cracked and broke down into pieces. The compressed breakage pattern of pellets may differ from that of logs due to difference in moisture content.

Graham (2015) investigated the compressive resistance of five white wood pellets samples (one at a time) using an instron mechanical tester with 5 kN load cell. The samples of the pellets were taken from different layers (i.e. top surface and middle layers) of pile pellets in the stored at different time interval. The resistance compression and shear resistance of each pellet was measured at distinct moisture contents and storage period. The strength of the pellets was determined based on minimum force or load require creating crack or break down the pellet into two pieces. The diametric compression strength of the white wood pellets varies insignificantly with the other types of pellets and the surface and middle layer pellets demonstrated a linear trend in terms of change in pellet moisture content and measured strength. The white pellets on the surface and middle layers of the pile appeared to have similar trend of young's modulus but different in uniaxial compressive resistance strength. The middle layer pellets also demonstrated a stable shear modulus with wide range of variation in pressures applied (25 – 50 MPa).

Uniaxial compression tests may possibly give an indication of actual single pellet strength but cannot use to understand bulk pellets wear resistance and dustiness tendency and it was also found to have poor repeatability.

2.5.2 **Impact Resistance**

Most of the existing methods of estimating briquette / pellets resistance to impacts degradation during handling are either by using a drop height test or by resulting to tumbling box tests. The impact resistance of the pelleted particles is often measured to simulate the resistance of the material to breakage due to series of impacts or wear in the handling systems such as ships loading and unloading, tipping or dropping from a chute height into silos.

However, Pietsch (2002) investigated the effect of high impact velocities on particle degradation to estimate the change in impact energy sustained by the particles during handling and found that particles degradation increases with increase in impact velocities.

Al-Widyan & Al-Jalil, (2001); Khankari, Shrivastava, & Morey, (1989) used the drop height method to estimate the impact resistance of bulk feed pellets by releasing the pellets from 1.85 m drop height onto a metal plate four consecutive times. The mass of damaged pellets (fines passing through 4 mm diameter sieve) due to impact appears to decreases with increase in mass of the dropped samples.

Lindley & Vossoughi, (1989) also dropped a briquettes size (50 mm diameter × 18 mm thick) from 1 m drop height onto a concrete floor surface repeatedly for 10 consecutive times and found an increase in damage briquette with corresponding increase in drop height using same mass of fresh briquette samples. This method of examining shatter resistance is also a well-known method of measuring coal durability in the coal industries. The level of damage caused by the impact was determined by the percentage mass of broken pellets by weight (i.e. fines generated) over the initial weight of the coal sample before testing.

Li & Liu (2000) have also used the ASTM. D440-86 standard method developed for measuring coal shatter resistance to evaluate the impact resistance of biomass logs (48.5-mm diameter and 50-mm length) by dropping it twice on a concrete floor from an approximate height of 1.83 m.

Sahoo & Roach, (2005) and Salman, Ghadiri and Hounslow (2007) investigated the impact resistance of particles using both single, double and rotary impact tests to measure the shatter or drop impact resistance of particles during handling. Recently, Oveisi et al., (2013) conducted an experiment to examine the impact resistance of pellets from different drop heights, where it was reported to have observed increase in pellets breakage with a corresponding increase in dropping height for pellets sample mass within 1000 g. However, the linear increase in breakage due to increase in drop height of the pellets diminishes for sample of wood pellets above 1000 g, which was believed to have occurred due to shielding or cushioning effect (i.e. poor contact to the impact surface due to other pellets shedding as the mass increases). The drop height test may not be considered as a better option for bulk pellets impact resistance test because of air resistance, which can also contribute errors in the measurements, could affect it. Richards (1990) reported that particles impact resistance index (IRI) could be calculated using equation 2.1.

$$\mathrm{IRI} = \frac{(100 \times \mathrm{N})}{\mathrm{F}} \qquad \text{Equation 2.1}$$

Where

N is the number of drops and F is the total number of pieces after N drops and IRI is the impact resistance index.

Most of the impact tests employed by previous authors were within a limited or short drop height if compared to the real pellet drops in modern large-scale handling systems to the stockpiles and silos. This raises a question of whether the durability measured at low impact velocity correlates with that measured at higher, more realistic velocities. It also involves very small numbers of pellets, which is not enough to be a representative sample for bulk pellet handling in industry.

2.5.3 Water Resistance

Water resistance is the tendency of a densified biomass material to resist absorption when immerse in water or exposed to the humid environment. Pellets / briquettes often degrade when it was exposed to high humid condition or rain during transportation or storage. The rate at which the water or moisture degrades the densified biomass material is determined by the level of humidity or rainfall exposure (Nalladurai Kaliyan & Vance Morey, 2009b).

Lindley & Vossoughi (1989) immersed a briquette (50 mm diameter × 18 mm thick) into water for 30 seconds at 27^{0}C to determine the water resistance. Tabil (1996) and Fasina & Sokhansanj (1996) investigated the effect of high atmospheric relative humidity on pellet strength and durability by conditioning the pellets between 70 % - 90 % relative humidity in a conditioning chamber, at a different temperature range between 10 - 40°C respectively. They found that pellets compressive strength decrease with increase in moisture content absorbed by the pellets as the test duration increases.

2.6 Testing of Pellets Quality and the Devices Used

2.6.1 Durability

Pellet durability is the ability of the pellets to overcome any form of kinetic abrasion or impact forces encountered during processing and handling. Pfost, et al. (1962) and Thomas & Poe, (1996) categorised forces that often lead to pellets degradation into impact, shear and compressive forces which can be summarised into abrasive or fragmenting forces. Fahrenholz, (2012) defined pellets durability in animal feed industry as the ratio of whole pellets to fines consumed by the animals during feeding. Pellets degradation could occur before cooling as the pellets travels down to the cooling point or after cooling, due to a series of impact and wear in bulk transport or handling in a conveyor belt, pneumatic air transport or ship loading and unloading processes.

The actual resistance of pellets to degradation during series of handling practices was first determined by Pfost, et al. (1962) where a tumbling box durability tester was designed using stainless steel box with inner dimension (305 mm x 305 mm x 140 mm). The box was also equipped with long baffle (230 mm length) placed symmetrically diagonal in each box with 50 mm extension on both ends. The baffle enforces the tumbling and wearing attrition to cause pellets degradation. The tumbling machine uses 500 ± 10 g of clean pellet sample for every test at 50 ± 2 revolutions per minute (rpm) in 10 minutes fixed speed. According to the author, the square box dimension was used to ease the manufacturing specifications and provide closed particles attrition. The collective effort led to the establishment of United States Standard ASAE S269.4, which later extend to form part of the European standards EN 14961-2 for measuring densified biomass material such as pellets, cubes and crumbles durability and other physical properties such as moisture content, bulk and particle density (ASE, 1997). The standard also allows determination of pellet durability index (PDI) which is the percentage of tumbled surviving whole pellets (> 3.15 mm diameter) over the initial mass of the pellets sample before testing. The pellets were sieved to separate the broken fines from the surviving pellets in accordance with the ISO 3310-2 standard.

Winowiski, (1988) investigated the effect of tumbling times and rotational speed on pelleted biomass degradation behaviour and in (1998) the same author recommended that steel nuts and bolts or small ball bearings should be added to hard diary pellets during tumbling box durability tests evaluating the actual resistance of the pellets.

Temmerman (2006) investigated the comparisons between the existing methods of measuring densified biomass material mechanical durability, using about 26 different types of pellets and 5 briquettes. The tumbling tests were in accordance with the ASAE S269.4 standards while the Ligno durability test were carried out in accordance with the ONORM M7135 standard. The finding showed that that pellets durability index values could be influenced by the method of testing and biomass fuel types. That no correlation seems to exist between tumbling or Ligno pellets durability test results with the particle density and it should not be compared. Thus, there was no further investigation on repeated patterns of whole pellets broken down or broken fines generated from the two-standard bench-scale durability testers in comparison to any of the real handling breakage.

2.6.2 Holmen Tester

Instead of tumbling test method, another device that is widely used in Europe for assessing pellets durability in animal feed mill industries known as Holmen tester. Holmen tester uses air stream as a prime mover to convey 100 g of pellets through a conduit pipe or tube, for about 30 - 120 second test duration period. The pellets impinge on the hard surface bend repeatedly as they travel through the right angle corners of the tube, which results in pellets breakdown to generate fines and dust. Thomas & Poel, (1996) and Franke & Rey (2006a) reported that Holmen tester was more harsher (i.e. creates more breakage) than tumbling box testers and requires smaller sample (100 g) than the tumbling box tester (500 g).

Thomas & Van der Poe, (1996) compares the Holmen and tumbling box pellet durability tests results of animal feed pellets and reported to have observed wide range of variation in the 6 mm diameter pellets Holmen durability index values from 60 – 95 % within 5 minutes' test cycles. When the same batch sample of animal feed pellet was tested using tumbling box tester for about 20 minutes testing duration, the range of the PDI values (91 – 98 %) variation was lesser than that of Holmen tester. However, Holmen tester was more responsive to pellets make or types compare to tumbling box tester. Another downside of Holmen tester is that, the air requirement to operate was very strict in supply and may not be feasible in a large blow system. The flow pattern of pellets within the Holmen tester are shown in figure 2.2.

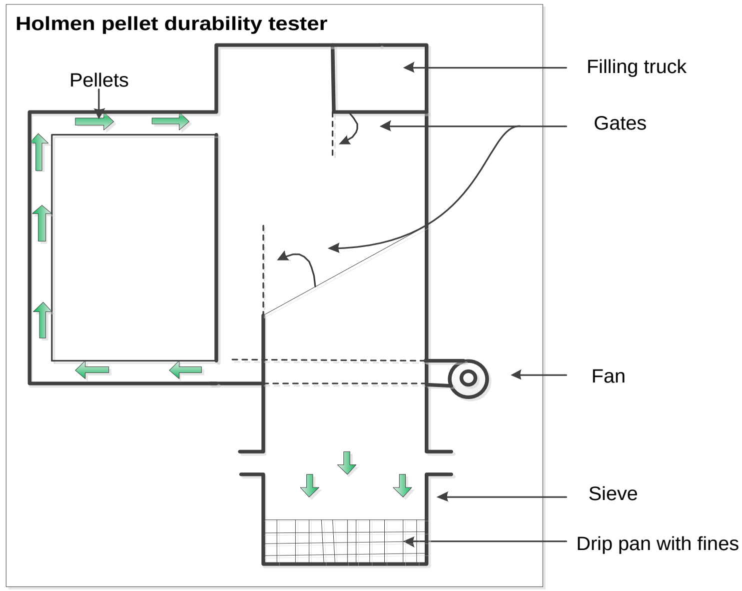


Figure 2.2 Holmen pellet durability tester (Borregaard Lignotech, Hull, UK)

2.6.3 Ligno Tester

A modernised form of Holmen pellets durability tester (Ligno tester) was developed by Borregaard Ligno Tech USA (Winowiski, 1998). Ligno tester operates in a similar way the Holmen tester operates but the only slightly different is in terms of size and blow air pressure. Ligno tester requires about 60 – 80 mbar air pressure to instigate collation between 6 mm or 8 mm diameter pellets contain within an inverted perforated (3.15 mm diameter round holes) square pyramid chamber for 30 – 60 s, instead of blowing through the pipeline, as it is in the Holmen tester. The surviving pellets (> 3.15 mm) were retrieved at the end Ligno durability test cycles and the broken down fines screened automatically through the pyramid sieve during the test. Winowiski, (1998) indicates that pellets above 4.8 mm diameter tend to require more pressure during Ligno pellets durability test. This makes it doubtful whether comparison of results between pellets of different sizes has any validity. The comparison between the Ligno and tumbling tester shows that Ligno tester was faster to use and requires a smaller sample than the tumbling box tester. Which is probably why Ligno tester was recognised as one of the Austrian standard methods of measuring wood pellets / briquette durability (ÖNORM, 2000). However, the sample size (100 g) is questionable because such a small sample size may not be sufficient to represent or give an indication of bulk pellets degradation behaviours. Temmerman, (2006) and Oveisi et al. (2013) have observed lack of correlation between the resulting PDI values of 6 mm and 8 mm diameter pellets tested in the Ligno and tumbling box testers and commented that Ligno tester results were less repeatable compared to that of tumbling box tester. The schematic diagram of the Ligno tester pyramid chamber is shown in figure 2.3

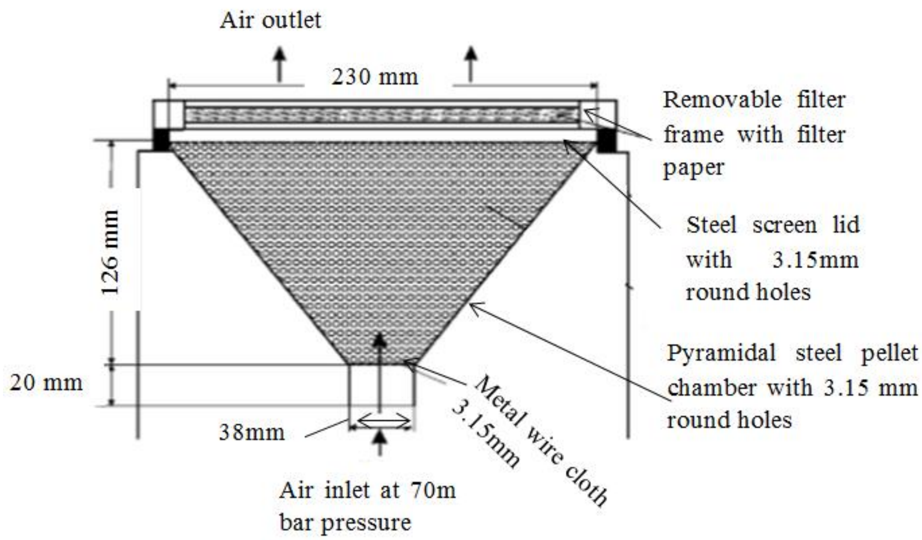


Figure 2.3 The description of Ligno tester (Temmerman et al. 2006)

2.6.4 **Drop Test**

Drop height test is one the simplest ways of assessing the impact resistance of coal, biomass or animal feed pellets in the industries. However, with the growth in pelleted biomass industries, the method was less efficient for prediction of bulk pellets degradation in handling systems.

Recent research by Ehsanollah (2011) have shown that pellets degradation decreases with corresponding increase in sample mass above 1000 g, that the breakage versus an increase in drop height was only proportional for a limited sample within ≤ 1000 g of pellets mass. This method of evaluating pellets durability may not give the actual level of pellets degradation in large-scale handlings system such as lean phase pneumatic blow delivery systems, a conveyor belt transfer points or even tipping, which are the common industrial delivery practices.

2.6.5 **Dural Tester**

A new modified prototype of Dural tester was designed at University of Saskatchewan, Agricultural Process Engineering Laboratory, Canada, by Larsen, et al., (1996) and was modified by Ehsanollah (2011). The modified new Dural tester is shown in figure 2.4, which is a modified version of the previous Dural tester designed to measuring animal feed pellets strength and durability.

The Dural tester units consist of rotating impeller contained in the canister, which has four blades. The dimensions of the blades are tip-to-tip blade diameter 16.5 cm, canister inside diameter is 15.3 cm, outer height 20.7 cm, and depth 14.5 cm. The impeller was attach to a motor under the removable canister compartment, which controls the speed of the impeller. The tester essentially consists of a grinder that applies uniform impact and shearing force on the pellets. The new Dural tester uses 100 g of pellets sample for every single pellet durability test and it takes 30 seconds to complete a test cycle at a control motor speed of about 1615 rpm. The initial pellets preparation procedure was similar to that of tumbling test and the Dural pellets durability test are conducted in accordance with method describe in the EN 15210 - 1 standard.

Mani et al. (2006) reported to have observed linear relationship between 6 mm diameter pellets durability index values derived from Dural durability test and a corresponding increase in the number of revolutions per minutes (speed) of the tester. While, Ehsanollah (2011) uses similar operational setting of the previous Dural tester to examine the durability of both brown and white pellets by increasing mass of the pellets sample from 50 g to 200 g during the test. The average PDI results show an increase in PDI values brown and white pellets from 58.3 - 66.1 % and 62.8 - 69 % with corresponding increase in the masses. From the resulting PDI values, one can say that Dural tester is doing nothing but grinding the pellets instead of measuring the elastic mechanical and inelastic wear and impact resistance of the pellets to breakage and to worsen the situation the tester appears to lack repeatability or reproducibility in measurements.

(a) (b)

Figure 2.4 (a) Photograph of assembled Dural tester and (b) the rotating blades housing (Ehsanollah 2011)

The Ligno and Holmen testers were reported to have high level of exposing the pellets to impacts and wear compare to tumbling box tester. However, when two hexagonal bolts and nuts were added in tumbling test, the pellets attrition, in tumbling test, was found to have increases to a level that is similar to that of Ligno and Holmen testers (Thomas & Van Der Poe, 1996; Winowiski, 1998).

The Ligno tester was also reported to have been more responsive to pellets produced with added binders or fat specific feedstock (i.e. broiler pellets containing 2 % fat and turkey grower pellets) in comparison to enhanced tumbling box and Holmen testers (J. W. Payne et al., 1994; Winowiski, 1998). By contrast, the tumbling box was less responsive to pellets containing feed ingredients but produces very highly repeatable pellets durability tests results.

The level of both brown and white wood pellets distortion observed in the newly Dural durability tester was higher than the level of breakage observed in Ligno and tumbling box testers. Similarly, when Ehsanollah, (2011) tested the durability of Pine, Douglas fir, and Spruce pellets using Dural and tumbling box testers, the average pellet durability index (PDI) of the pellets tested in the Dural tester was relatively low (68.8 %) and is far below the required minimum of 97.5 % stated in the EN 14961-2 standard. All this calls into serious question to the choice of which devices might be the best to choose for effective measurement of pellet durability.

2.6.6 **The Rotary Impact Tester**

In all effort to have a credible bench-scale pellets durability tester that can possibly predict pellets degradation in large-scale handling system, a large-scale rotary impact tester known for prediction of particle degradation in pneumatic blow delivery, but has not been extensively use for pellets, was modified and introduced. The modified large-scale rotary impact tester was designed by Bradley at The Wolfson centre, University of Greenwich to simulate breakage of large particles in real handling systems. The tester is a prototype of the small laboratory bench-scale rotary attrition impact tester designed from earlier work of Abou-Chakra et al. (2004), for assessing smaller particles (< 1 mm diameter) degradation in a chain of transport or pneumatic delivery systems. Thus, the large-scale rotary impact tester is of high capacity and be used to assess large particles (>1 mm diameter) degradation under close control impact angles and velocities, to simulate particles degradation in pneumatic or other industrial conveying systems. The interior part of the large-scale rotary impact tester is shown in figure 2.5. The present of other particles sizes in the mixture, particles to be tested have little or no influence on the particles breakage stream during the rotary impact durability test.

The large-scale rotary impact tester has a rotating disc (45 cm diameter) and the disc has eight segmental channels, where the fed particles splits and roll to exit and impinge on the targets. The targets were position on a round ring, called the target holder (76 cm diameter) to suit the impact trajectory points of the particles at 45° impact angle. The jet particles impact angle can be measured using the "slot-and-displaced-wear-scar" method of (Burnett, 1996; Macchini, Bradley, & Deng, 2013) to ensure correct target position on the holder. This also allows the nett velocity to be determined because the tangential component of velocity must always be equal to the tangential velocity of the edge of the disc. The speed of the rotating disc is control by the rotating motor speed and is measured using a digital tachometer in revolution per minute.

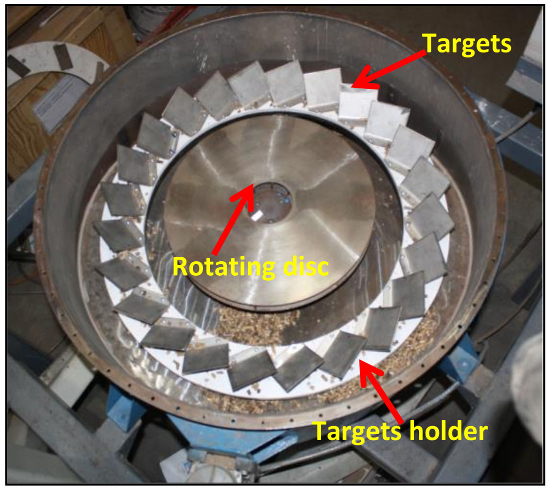


Figure 2.5 The modified large-scale rotary impact tester

Deng, Farnish, & Bradley, (2008) have examined particles degradation using a rotary attrition impact tester and found that inter-particles collisions near the target surfaces could alter the behaviour of particles degradation in the smaller rotary impact tester. Therefore, recommended that the feed rate should be regulated to reduce possible shielding effect at high particles feed rate. However, particle shielding may possibly not occur during the large-scale rotary impact test because samples of the wood pellets are large free-flowing particles and the feeds rate is under control. The use of the rotary impact tester for assessing particle degradation could also facilitate determination of particles "breakage matrices" using population balance method, which is one the popular methods of understanding bulk particles degradation and breakage characteristic under controlled ranges of impact velocities and sizes distribution (Bilgili & Capece, 2012; Pierre et al., 2004).

The impact velocity (V_p) of the particles in a rotary impact tester was calculated using equation 2.2.

$$V_p = \frac{2\pi R}{\cos(\theta)}\, n \qquad \text{Equation 2.2}$$

Where,

n is the rotating disc speed (rpm), R is the radius of the accelerator disc and ϴ is the exit impact angle.

Alternatively, the particles impact velocity can be calculated using equation 2.3, provided the friction of particles in the rotary disc during acceleration are neglected (Vogel & Peukert 2003)

$$V_p = D\, n\, \sqrt{2\pi} \qquad \text{Equation 2.3}$$

Where,

n is the number of disc revolution per minutes, D is the rotary disc outer diameter and Vp is the particle velocity.

Chapelle Patel & Abu-nahar, (2004) have investigated how the experimental results of sugar degradation in a small rotary impact attrition tester can be used to compute a model that is capable of predicting particles degradation, due to collisions, of the particles in a blow pipeline bends wall or in a dilute-phase pneumatic conveying system.

Baxter, Abu-Nahar, & Tüzün, (2004) investigated the influence of a particular class of particles size in a mixture of other class of particles sizes during the attrition impact degradation test. The results were analysed using breakage matrix modelling, which indicates that breakage matrix approach could be promising method of quantifying intra-mixture interactions of particles during degradation processes.

Fistes et al. (2013) studied how the breakage matrix approach could be used for establishing relationship between the input and output size distribution of particles in milling operations. The breakage matrix approach has proven to be a possible means of describing change that could occur in input and output sizes distribution of material in a milling process.

2.6.7 Pneumatic Conveying Systems

Bridle, S., Burnett., & Barnes., (1995) acknowledge that particles breakage is a function of particles velocity and concentration in a pipeline during transport or pneumatic conveying. They also reported to have observed decrease in particle velocity due to increasing pressure along the blowing pipeline and high particles concentration, which reduces the level of particles degradation. It is important to note that high particles concentration could also lead to shielding effect in a pneumatic conveying pipeline, which reduces particles degradation, as discussed by Bradley (1990); Gorman, Bradley, Deng, & Armour-Chélu (2012); and Macchini, Bradley, & Deng (2013).

Sørensen et al. (2008) investigated the degradation of three different commercial diets pellets with different initial PDI values (label A = 30.6, B = 23.7 and C = 16.5) using computer-controlled pneumatic transfer, at different feed rates (9, 19 and 36 kg/m^3) and conveying air speeds (25, 39 and 35 m/s). The strength and durability of similar batch of pellets samples tested in the controlled pneumatic transfer were also measured using Ligno tester and texture analyser. The results of the pneumatic blow tests showed that the three class of pellets have different tendency to degrade or break down to generate fines and dust during pneumatic deliveries and the breakage patterns of each pellets class varies with the PDI values. They concluded that pellets degradation in pneumatic conveying increases with increase in blowing air speed and high feed rate appeared to have induced shielding effect, which prevented some of the pellets from degradation. There was no clear correlation between degradation in pneumatic conveying and other pellets physical properties (i.e. durability index, hardness, bulk density or PDI values). However, high-quality wood pellets are often produce without added binders, depends solely on the inherent chemical binders, which could cause some difference in their breakage pattern in comparison to that of feed pellets, where binders are often added during production.

Macchini et al., (2013) investigated the effect particle concentration along pipe bends erosion in a pneumatic conveying line at different material blowing density. The result affirmed that the magnitudes of shielding effect occurring due high particle concentration are more responsive to particles density than the particle sizes. That pipe bends erosion appears to decreases with increase in particles concentration and density (i.e. low shielding effects).

2.6.8 The Physics of Particle Breakage

Particles tend to break down when exposed to high-stress conditions during processing and handling operations. Specifically, Wood pellet are fragile materials; Mina-boac et. al., (2006) reported that pellets are handled typically not less than 8 times before arriving into the hands of their final consumers. During these processes, the pellets are affected and breakdown to generate fines and dust each time they are dropped into a silo, on a conveyor belt transfer point or pneumatic delivery system. The broken pellet fines and dust generated could consequently hinder the free flow of the material under gravity and increase the danger of related fugitive dust explosion problems. Oberholzer & Walt (2009) reported that, the breakage tendency or mechanisms of granular materials could only be predicted via understanding of how to classifying breakage phenomena into volume or surface breakage. Teo, Waters, & Nicol, (1990) define surface breakage as a condition of breakage mechanism where the particles experience low impact but high abrasive energy, that often knocks off the edges or corners to product to produce finer dust. Whereas volume breakage is said to occur in a system where the abrasive energy is lower than the impact energy exacted on the products to produce cracks or shattered broken down piece of smaller particles with large sizes of fines and less dust. Kaliyan & Morey, (2009b) reported that the cracks on the surface of wood pellets are often developed during the pelleting processes but that does not indicate weakness along the pellets.

2.7 Literature Review Summary

Wood pellets are mostly used in the industrial contexts for power production or locally as a fuel for domestic heating boilers. Pellets are susceptible to breakage due to impact or wear in the transport and handling chain, which often results to fines and dust creation before getting their final place of uses. The dust generated from pellets have a high tendency to ignite and cause fire explosion, endanger staff's health or limit boiler burning efficiency, due to poor permeability (the ability of air to get the bulk burning pellets).

Pellets are often delivered to domestic and small or medium industrial premises by pressure-discharge road tankers, which blow the pellets through pipelines, air into the pellet store, during which some breakdown occurs.

It must be borne in mind that the pellet strength and durability are often measured prior to or after the delivery using different methods and equipment such as the tumbling box and Holmen or Ligno testers. Generally, Ligno and tumbling box tester appear to be the most widely accepted industrial standard pellets durability testers for measuring pellet durability, largely due to compactness and low price of the equipment, speed and ease of use. Ligno test has been identified to be the less repeatable tester and more responsive to pellets produced with added binders or fats during pelleting. Whereas, tumbling box tests are highly repeatable but less responsive to the pellet types, with longer duration of test period (10 minutes) to run a single test (Ehsanollah, 2011; J. W. Payne et al., 1994; Winowiski, 1998). Others researchers have also reported to have observed no or poor correlation between the two standard testers and recommend that the two testing results should not be correlated (Temmerman et al., 2006).

The merits and limitations of the standard pellet durability testers were summarised below.

(1) Sieving: Ligno tester does not require any form of sieving the material after testing because the broken fines exit the pyramid chamber automatically during testing. However, in tumbling test the pellets need to be re-sieved after testing, which is an added labour in tumbling test compare to Ligno pellets durability test.

(2) Time: tumbling box durability test takes about 10 minutes' duration for every single test at 50 rpm whereas, Ligno test takes just one minute to complete a single test cycle.

(3) Test samples: tumbling box durability tester requires 500 g of clean pellets sample for single test, whereas, Ligno durability test requires just 100 g. Ehsanollah (2011) commented that 100 g pellets sample might not be enough to save as a representative sample or give an indication bulk pellets degradation in a single durability test.

(4) Resolution: The pellets durability index values of standard tumbling box tester was found to be highly repeatable than that of Ligno tester (Temmerman et al., 2006).

However, the direction of this research work is to examine factors affecting different stakeholders in the industry, which need to be considered: -

- Fines and dust have significant negative effects on the handling, safety and combustion properties of the pellets;
- Given that there are large number of manufacturing variables that have a very significant effect on breakdown tendencies, pellets from different sources and made of different feedstocks are likely to very differently in the level of breakdown and related problems they present.
- Because of this, there is a pressing need for pellet producers, sellers and buyers to gain a useful indication of the likely levels of pellets breakdown in the handling and delivery processes so that they can make sensible judgements on what pellets to buy from different sources that are available at different prices.
- There are substantial limitations with the existing tests; firstly, they do not expose the pellets to the impact conditions in a real handling chain, and secondly there is a lack of comparability (or even correlation) between the results of the different tests.

Given this position, it is important to identify or develop a test that can be used to evaluate pellets from different sources and made with different process variables, that can give a meaningful indication of the likely level of degradation in a real delivery process, or produces results that are likely to correlate with the real handling system degradation when comparing different sources and batches of pellets.

2.7.1 **Improvement of Pellet Strength and Durability during Production**

Many researchers have found that process variables such as conditioning temperature, moisture content, die length and diameter, die speed, gap between the die and rollers, and feedstock of different plant component (i.e. leaf, stem, root and back) could influence pellet durability during pelleting (Hill & Pulkinen, 1988; Nalladurai Kaliyan & Vance Morey, 2009a; Obernberger & Thek, 2004; Wilson, (2010), Lestander, 2010)

Similarly, in an effort to expand bio-renewable energy production, an abundant tree species (alder wood) in North Sweden forest might have a possibility to produce mixed quality pellets for greener energy production in Europe. This needed to be examined by adding the alder to pine wood powder to produce pellets of different production histories and determine the effect on the quality. Serrano et al., (2011) reported that adding 2 %, 7 % and 12 % of Pine sawdust to straw have resulted to an increase in pellet durability from 97 % – 98 %. Most common, pure pine woods are known to have high tendency to produce highly durable pellets with high calorific energy values, but the combination pine to Alder pelleting are yet to be exploit.

2.7.2 Further Thoughts on Selection of Pellet Durability Testers for This Project

There are many different testers known for evaluating the breakage resistance of solid fuels (including pellets) but two are the most commonly used once in the fuel pellet industry, which will be the focus of this research. The literature review has disclosed information that stimulates number of thoughts on how this project should be planned as described below.

Neither of these existing standard pellet durability testers (Ligno and tumbling box) really simulates the impact experiences of particles in a real handling system, during which they are blown through a pneumatic pipeline and get broken down in the impacts with the bends. Therefore, the rotary attrition impact tester that has been specially developed to simulate breakage of large particles in pipelines, should also be used (Wu, 2012).

The standard pellet durability testers, as evidenced from the detailed literature review, were surrounded with several limitations particularly that the impact processes inside the testers do not simulate the velocity conditions observed inside a real delivery pipeline. Velocities in the testers are much lower and concentration of particles is much higher, both of which are known to have a strong effect on the degradation process. This can only be investigated by using a comparative test method to evaluate the available standard pellet durability tester (i.e. Tumbling box and Ligno tester) against the rotary attrition impact tester performance. The rotary attrition impact tester employed in this project will be the larger scale version of the original bench scale particle degradation tester (which had capacity of $\leq$ 1mm) used by previous authors (Deng et al., 2008; Pierre et al., 2004) to evaluate bulk multi-particle breakage condition in pneumatic conveying systems. The main advantage of using the large-scale degradation tester is that it allows good control of particle impact velocities at values that simulate the real conditions in a pipeline, and it takes a small quantity of the pellets sample compared to what will be required to run a single degradation test in either lean or dense phase pneumatic conveying system. Correlation of the pellets durability index results from all the bench scale standard pellet durability tester (i.e. tumbling box and lingo tester) and rotary impact degradation tester will be conducted. Equally, a pilot small-scale pneumatic conveying system will be designed to simulate particle breakage in a pneumatic conveying system. Breakage matrices would be used to quantify and link the particle size distribution of the fines from various test results to make a conclusion that will contribute to the knowledge of pellets breakage in the industries.

2.8 Conclusive Summary from the Review

The most important things to learn from the literature in relation to the research question are: -

- It indicates the degradation tendencies of batches of the pellet can vary with the types of testers, and the breakage mechanism may differ. Therefore, it is relevant to pellet producers, sellers and users to ensure satisfactory quality in this respect.
- Many different testers have been used to test the degradation tendencies of bulk solids and two have become popularly accepted standards but they expose the pellets to different types of degradation process, neither of which are like the processes in a real handling system, so the usefulness of the indications from the two testers is unknown.
- Another type of bench scale tester has been identified in the past for simulation of particles degradation in pneumatic transport, but not proved for pellets.
- Much work has been done on exploring the effect of different pelleting process conditions, feedstock variability, moisture content and steam conditioning temperature on pellets degradation indicated by the standard testers, but virtually no work has been done on predicting the degradation in real delivery systems or any relevance tests, so this needs to be explored.

Chapter 3. Experiment Design, Material and Methods

3 Introduction

The experimental section was divided into four different segments: The first part describes the process of acquiring feedstocks and experimental design for pelleting, where pellets were produced to examine the effect of feedstocks and process parameters on pellets quality (strength and durability) during production. The second part described the stages involved in pelleting such as pre-pelleting operation, which includes size reduction of particles, mixing or blending feedstock samples (i.e. pine and Alder wood powders), initial feedstock moisture content analysis and steam conditioning. The third section described methods of evaluating pellets durability using bench scale tester's standard (i.e. standard tumbling box and Ligno tester) and a newly introduced modified rotary impact tester and their responsiveness to different pelleting process parameters. The fourth stage described the large-scale pneumatic blow pellets degradation experiments, in chapter six, while the procedures for the breakage matrix model was elaborated in chapter eight. However, the key objective of these experimental chapter is to compare the resulting breakage resistance of pellets with different production history, tested across different bench scale testing machines to that of real world industrial handling systems.

3.1 Experimental Plan

To examine the independent influence of each processing parameter in a multivariate process involved in pellets production (pelleting), a systematic experimental approach becomes necessary. Therefore, Taguchi factorial design of experiment was considered viable because is widely known as a robust method of optimising multivariate processing parameters for product quality improvement. The method was adopted for the pellets produced at Swedish University of Agricultural Sciences, Bioenergy Technology research centre, Umea. The systematic experimental design approach was adopted to examine the influence of adding alder to pine feedstocks pellets strength and durability, manufactured at different steamed moisture content and conditioning temperatures.

The three significant parameters considered in this pellets production plan are initial feedstock moisture content, steamed moisture content, steam-conditioning temperature and two different feedstock species (pine and alder wood powder). The selected parameters (i.e. factors) were arranged in different orders to suit the pellets manufacturing process plan shown in table 3.1.

Table 3.1 The experimental plan for pellets production obtained from Taguchi's factorial design of experiment.

Experimental order	Initial feedstock moisture content (%)	Feedstock species pine content (%)	Steam-conditioning temperatures (°C)
1	11.5	90	50
2	10	100	20
3	13	100	20
4	10	80	20
5	13	80	20
6	11.5	90	20
7	10	90	50
8	13	90	50
9	11.5	100	50
10	11.5	80	50
11	11.5	90	50
12	10	100	70
13	13	100	70
14	10	80	70
15	13	80	70
16	11.5	90	70
17	11.5	100	50

The effect of each factor was examined on the quality of both homogenous (i.e. 100% pine or alder) or heterogeneous (i.e. predetermined mixture of pine to alder feedstocks) pellets produced at distinct moisture content and conditioning temperatures. The specific choice of combination depends on the pre-determined characteristics of the desired pellets to be produce. The order of combining the process and feedstock parameters, during the pellets manufacturing are shown in the experimental plan table 3.1.

For instance, the first row in table 3.1 indicates that 10 % alder was added to 90 % pine wood powder to produced pellets at 11.5 % initial feedstock moisture content and 50°C steam conditioning temperature.

3.2 Pelletisation Process

The pelleting processes were divided into the three major parts, as shown in the bullet points:

- The pre-pelleting process is the earlier stage of pelleting which involves the collection of raw material, chipping, milling, particle size analysis, feedstock moisture analysis, blending and steam conditioning.
- The second stage, which is the actual pelleting involved compressing the steam conditioned or unconditioned feedstocks at different conditioning temperatures (20°C, 50°C and 70°C) and pressures. The feedstock at this stage also experiences different forms of internal and wall friction during compaction, which produces heat due to opposing wall friction between the die channel wall and the compressed feedstock. The heat elevated the compressed feedstock temperature to enhance the discharging natural binder's (Lignin, cellulose and hemicellulose) as the rollers force the wood powder into the die channels continuously, in the conventional pellet mill compartment, during pelleting, to produce pellets.
- Post-pelleting process is the last stage of pellets production process, which involved the collection of pellets, cooling, pellets temperature measurement and sieving to remove the fines in accordance with the ISO 3310-2 standard.

A sequential order of stages involve in pellet production chain are shown in figure 3.1. The detailed description and analyses of the stages are given in the next sections.

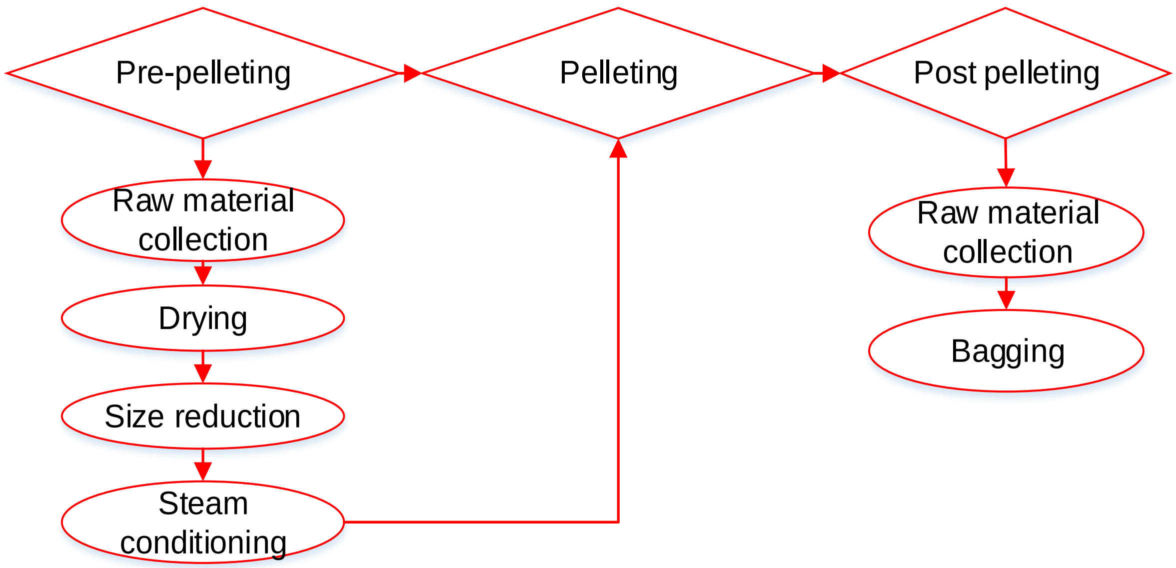


Figure 3.1 Schematic diagram of the pellets production chain

3.2.1 Raw Material Preparation

Two different types of feedstock (pine and alder wood powder) were used to produce either homogenous (pure) or heterogeneous (fixed wood) pellets. The pine feedstocks came from one of the pellet production plant located in Northern Sweden region. Whereas, alder wood was delivered in a logs form. Alder wood was selected for this research because is one of the abundant wood species in the region that are not suitable for furniture works but can potentially contribute to the "greener" environment if integrated to pine wood during pelleting. pine woods species are well known to have high tendency to produce quality heterogeneous pellets when combining to other biomass feedstocks has demonstrated by (Serrano, Monedero, Lapuerta, & Portero, 2011) but the effect of combining alder to pine for quality wood pellets production is yet to be known.

The pine feedstock was delivered to the pelleting centre with moisture content hovering between 7 % – 8 % dry base. While, alder woods were supply in logs, and the logs were debarked and chipped using a small-scale PX-800Y chipping machine at the Swedish University of Agricultural Sciences, Bioenergy Technology Research Centre, Umea. The chipped alder wood was kept to dry off at ambient temperature (≈ 23℃) for 30 days to discharge its excess moisture content before milling. The temporary storage was an essential method of regulating the feedstock moisture content to minimised cost of drying before milling. The snapshots of the alder wood chip and milled alder and pine wood powders (feedstocks) are shown in figure 3.2. The red arrows on each figure represent ranges of the particle size diameters scales for the wood powders (≤ 3.2 mm) and chipped alder wood, before milling (≤ 30 mm).

(a) (b) (c)

Figure 3.2. The feedstocks types for pellet production: (a) pine wood powder, (b) alder wood powder and (c) alder wood chips

3.2.2 **Milling**

Milling is the process of reducing particles size distribution of wood chips before pelleting. The chipped alder wood sizes were further reduced using an industrial large-scale milling machine to an aggregate standard feedstock particle sizes (≤ 4 mm diameter) required for quality pellets production. The milling machine was equipped with double 'screen' sizes: (3.2 mm and 4 mm diameters) to facilitate aggregate particles sizes distribution and ensure all the milled particles are well within ≤ 4 mm sizes diameters. Double screening technique is widely practised in pelleting industry for achieving consistent particles sizes for quality pellets production (Wolfgang et al 2011).

3.2.3 **Blending and Moisture Regulation**

The milled wood powders (feedstock) from either pine or alder was stirred rigorously to mix the feedstock together using a large-scale mixing machine. The mixing machine has large steel container that can contain up to 1400 kg of wood powder as shown in figure 3.3. The feedstock was blended together to minimise any form of feedstock particles segregation and poor moisture distribution among the particles during pelleting. Rigorous blending is recommended to facilitate equal moisture or heat circulation among the feedstocks, during blending and drying. The feedstock moisture content was altered or adjusted to suit the experimental plan by either adding a calculated mass of water to the feedstock or drying to releases it excess moisture, during blending. Highly wet feedstock was dried using an electrical heat induction device attached to the container during blending.

The blending machine was also equipped with load cells and is use for measuring mass of feedstock inside the mixer. The load cells have also aided the process of combining the two distinct feedstocks (pine and alder powder) together at different ratios to produce heteronomous pellets as required by the experimental plan. The photograph of the blending or mixing machine containing wood powder (feedstock) is shown in figure 3.3.

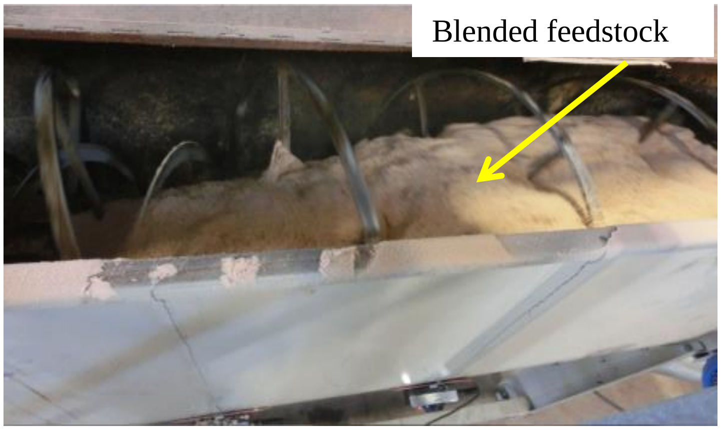


Figure 3.3. The blending machine containing blended feedstock

3.2.4 **Measurement of Initial Feedstock Moisture Content**

The moisture condition (wet or dry states) of the blended heterogeneous or homogenous feedstocks before steam conditioning or pelleting is known as initial feedstock moisture content. The feedstock moisture content was regulated to suit the experimental plan by either adding calculated mass of distilled water to the feedstock (to increase the moisture level) or drying to reduce the feedstock moisture content during the blending process. Whatever the condition of the feedstocks, the feedstocks are often blended continuously for about 30 minutes to allow proper circulation of moisture across the particles before the moisture analysis. The mass of the dry or wet feedstock sample was measured using Adam PMB 53 moisture analyser set at 105 ± 1 °C. The measurements were carried out repeatedly during the moisture content analysis to ensure accuracy. The steamed feedstocks moisture contents were also measured using an oven drying method, stipulated in the EN 14774-2 standard (Alakangas, Iii, & Tc, 2009).

3.2.5 **Effect of Steam Conditioning Temperature**

Review have detailed the influence of temperature and moisture content on feedstock lubrication and binding characteristics of pellets during manufacturing. However, until now there was no detail effect of steam conditioning temperatures on either homogenous (pine or alder) or heterogeneous (combined pine to alder) feedstocks pellets quality. Therefore, the effect of steam conditioning temperature on both the homogenous and heterogeneous pellets strength and durability were determine by producing pellets at two different steam conditioning temperatures (50°C and 70°C) and compared to the un-steamed pellets, produced at 20°C.

During this pellets production exercise, each of feedstock ample was temporarily stored in a separate silo, after blending, before blowing it into the pellet mill-conditioning chamber, where the steam conditioning took place. Hot steam at about 50°C or 70°C were injected to the feedstocks using the steam-conditioning machine, at pressures between 2 - 3 bars. The hot steam was sprinkled on the feedstock (wood powder) to soften and activate the binding agents. The steam conditioning process take about 2 - 10 minutes' period. The steamed feedstock temperature was monitored until it reaches the pre-determined conditioning temperature before using screw feeder to convey it through the optic clear flow region (just before the die compartment), where samples were taken for moisture analysis, as the steamed feedstock flows down into the die compartment. The choice of conditioning temperature depended on the pellets production plan, shown in table 3.1. It is instructive to note that steam conditioning at 50°C or 70°C often results to increase in feedstock moisture content, other than the initial feedstock moisture content measured before the steam conditioning. The steamed conditioned feedstock temperatures were recorded directly using data logging system, during the pelleting and the moisture content was measured using an oven drying method described in the EN 14774-2 standard.

3.2.6 Pelletisation Process

Different batches of homogeneous (pine or alder) and heterogeneous (pine to alder) feedstocks pellets were produced using a pilot scale conventional Buhler DPHD/DPHE pellet mill, located at The Biofuel Technology Centre, Swedish University of Agricultural Science, Umea. The pellets were produced using different condition of the pelleting process parameters (i.e. moisture content, steam conditioning temperature and variable feedstocks (i.e. pine and alder wood powder) as specified in the experimental plan table 3.1. The influence of each parameter on the pellets strength and durability (quality) was examined to understanding how it can be used to improve pellets quality during pelleting.

Therefore, 90 % and 80 % pine was added to 10 % and 20 % alder wood feedstocks to produce the pellets at three different initial feedstock moisture contents (10 %, 11.5 % and 13 %) and pre-conditioning temperatures (20°C, 50°C and 70°C). The processed feedstocks were temporarily stored in a separate silo, after mixing or blending at different conditions. The feedstocks in the temporary silos were blown in batches, into the pellet mill conditioning chamber, where the steam conditioning was conducted, if required, or otherwise, the feedstock is conveyed using screw feeder to pass through the optic flow region (just before the die mill press). Sample of the conditioned feedstock are collected at the optic flow region for moisture analysis before feeding into the pellets milling chamber, containing die and rollers. The feed rates and temperatures of the processed feedstocks were monitored using temperature sensors inserted along the flow region and values were displayed on a computer screen linked with the pellets milling machine. The two rollers act on the processed feedstock continuously to force and compact the feedstock through the die channels which results to pellets production due to exacted pressure and heat generated because of opposing wall friction within the matrix die channels to the compressed wood powder. The pellets exit the mill channels press at high temperatures, typically between

90˚C - 105˚C and an adjustable knife was mounted just above the matrix die to trim down the pellets to a required size length. The trimmed pellets exit the pellet mill and travel on a conveyor belt to the retrieving point, where is collected in a large plastic container. Samples of the pellets between (7 – 12 kg) were collected in the plastic container until a stable production (i.e. when consistent production rate is attained) in one-minute intervals. The samples of the pellets collected in the plastic containers were then air cooled at ambient temperature of about 23˚C, for 24 hours, before the pellets durability test. Similarly, some hot pellets samples between 200 – 300 g were also collected in a sealed plastic bags to examine the level of moisture migrated from the pellets, during the cooling period. The schematic diagram of the pellet production plant is shown in figure 3.4.

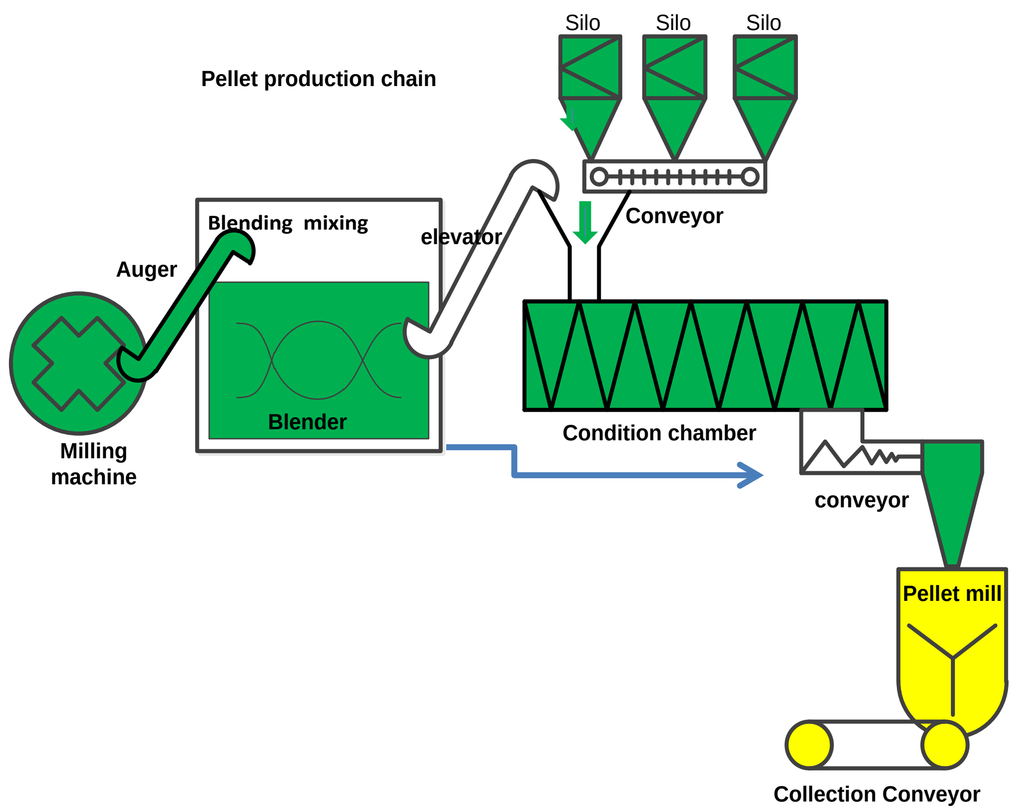


Figure 3.4. Schematic of a generic wood pellet production plant

3.2.7 **Cooling**

Cooling of freshly manufactured pellets is an important method of avoiding degradation due to possible water condensation. Condensation is an undesirable process that often leads to pellets degradation or poor resultant pellet strength and durability. Therefore, the hot pellets samples were collected in a large plastic container and allowed to air-cooled at ambient temperature (≈ 23℃) for 24 hours. The mass of the hot and cooled pellets states was measured using digital weight balance and recorded after the 24 hours for understanding the level of moisture migration during cooling. Each sample pellets collected for air-cooling was carefully labelled for easy identification of individual batches of pellets produced with same or different production histories.

3.2.8 **Sieving**

It is some time difficult to using automated sieving technique for small number of pellets (100 g – 2000 g) without inducing further breakage due to chokes or vibration. Automated sieving may also induce some errors in the PDI values calculated due to escape of some very fine pellet dust during the emptying process, after sieving. Therefore, the cooled pellets were manually sieved in accordance with the ISO 3310-2 standard (ISO 3310-2, 2010). This standard screening method was adopted to minimise extra breakages that could arise during automated sieving of the small pellets samples tested in three bench scale pellets durability testers (e.g. tumbling box, Ligno and rotary impact tester) which is in line with the EN 15149-2 standard.

The samples of the pellets collected were subjected to initial manual sieving to separate the fines from the clean pellets before taking any samples for the bench scale pellets durability test. The degraded pellets were also sieved again after testing to determine the surviving and broken pellets / fines. The first initial manual sieving of the pellets before testing was conducted using 3.15 mm wired mesh diameter sieve and the degrade pellets, after the durability testing, were separated using stack of wired and round-holed sieve in the order of 4.75 mm, 3.15 mm wired and round holed, 2.36 mm and 1 mm diameters. However, in this case, the surviving pellets were categorised as pellets above 4.75 mm diameter sieve while the broken pellets (fines) are the fraction of pellets below 4.75 mm diameter. The fraction of pellets below 4.75 mm diameter were further sieved into different particle size distributions. The corresponding mass of both the surviving and broken pellets fines were also measured and recorded for further analysis. The round-holed sieve was included in the screening process because it is one of the standard sieve sizes recommended for standard pellets durability test. It is unclear why the standard specifies a round-hole sieve for the 3.15 mm size but wire mesh sieves for all other sizes, but it was felt to be best to use the protocol widely used by industry to enable comparison of results against any other studies.

However, during the full-scale pneumatic blown pellets degradation test, a Rotex screening machine was deployed due to bulkiness of the pellets (≈ 1000 kg per blow test) required to separate the bulk pellets into surviving and broken pellet fines fractions, after each blown degradation test. The machine may possible induced about 0.002 % damage to the pellets, due to shocks or vibration during sieving, but this had been taken in to account, to prevent errors in the data analysis.

3.3 Pellets Quality Influencing Factors

The physical properties of pellets such as pellets moisture content and bulk density were also measured along with the states of pellet strength and durability (quality). The physical properties of the pellets were evaluated in accordance with the EN 14961-2 European standards guidelines for evaluating commercial use biomass pellets.

3.3.1 Pellet Moisture Content

The pellets moisture content was determined in accordance with EN 14774-2 standard (E. V. Alakangas, 2009). The standard categorically states that the moisture content of quality pellets should not exceed 10 % dry basis. It is also important to note that pellets moisture content differs from the initial feedstock or steam moisture content, but all can be measured in the same ways. The hot (direct from the press) and cooled states of the pellets moisture content were measured using oven dry method stipulated in the EN 14774 - 2 standard. In both case (hot or cooled), the pellets were air cool for 24 hours at ambient temperature of about 23℃ before the measurement.

The pellets moisture content was measured by measuring the initial weighing of the dry dish, when is empty and recorded before filling the empty dish with about 200 g – 250 g of pellets and then re-weighed again, using a digital weighing balance. The mass of the empty dish and mass of dish containing pellets before testing was recorded before loading the dish, containing pellets, into the oven chamber at 105 ± 2°C temperature. The pellets were kept in the oven drying chamber for 23 hours before retrieving dried pellets repeatedly to determine the mass for three consecutive times, at 15 minutes' interval of the last 24th cooling hour. The process was repeated until dried mass of the pellets become stable and the pellets were finally removed from the oven to be air cooled again for another 5 minutes before taking the final mass, which is recorded as dried base. The wet and dry states of the pellets masses were used for calculating dry basis (MC_{db}) and wet basis (MC_{wb}) moisture content of the pellets using equation 3.1 and 3.2.

$$MC_{wb} = \frac{(W_o - W_d)}{W_o} \times 100\ \% \qquad \text{Equation (3.1)}$$

Or

$$MC_{db} = \frac{(W_o - W_d)}{W_d} \times 100\% \qquad \text{Equation (3.2)}$$

Where

W_o Is the initial mass of the pellets in a wet state and W_d is the final mass of the pellets dried state.

3.3.2 Bulk and Tapped Density

The bulk density (BD) of the pellets was measured in accordance with the EN 15103 European standard. The pellets bulk density measurement was carried out by loading the clean sample of pellets (> 3.15mm diameter) into five litres measuring cylinder, with dimensions (200 mm diameter × 300 mm height). Mass of the empty cylinder was first measured using weigh balance and recorded before filling the pellets into the cylinder. The pellets were loaded into the cylinder until it gets to the top and protrude (overshoot) above the cylinder surface, forming an angle of repose cone. The cylinder (containing pellets) was then lifted to about 150 mm drop-height and dropped onto a hard surface for three consecutive times to compact the pellets. The overshooting pellets were scraped using flat wood batten and the voids created during the scrapping process, were re-filled by adding some of the clean pellets again to achieve a level plane surface, after the compaction process. The mass of the cylinder containing the pellets, after levelling, was measured and recorded again. The mass of the filled pellets inside the cylinder was deducted from the entire mass (M) of the cylinder containing pellets, after refilling, which was divided by the volume of cylinder (v) to calculated the pellets bulk density (BD) using equation 3.3:

$$\text{BD} = \frac{M}{V} \times 100\ \% \qquad \text{Equation (3.3)}$$

Where

M is the mass of the pellets in grams; V is the volume of cylinder

The pellets bulk density was measured because is one of the physical properties that determined the specified quality of pellets in the biomass commercial market or supply industry.

3.3.3 Pellet Density and Bulk Porosity

Pellet density was calculated from the measured mass and volume of each pellet. The volume of each pellet was determined from their respective length and diameter measured, using a venire calliper. The mass of each pellet was measured using a weigh balance with 0.001g precision. The two specific parameters (mass and volume) obtained from each pellet were used for calculating the pellet density. However, pellet porosity ($\mathcal{E}_o$) was determined by subtracting the ratio bulk to individual pellet density from 1. The pellets porosity was calculated using equation 3.4. Understanding bulk pellets porosity may possibly give an insight on pellets resistance moisture absorption. While poor air circulation within pellet beds due to high concentration of broken fines within the pellets, could induce chances of self-heating or elevated temperature in the store or silo. It may also lead to change in the actual pellets moisture content to alter the burning efficiency in the biomass boilers.

$$\varepsilon_o = 1 - \frac{\rho_b}{P_\rho} \qquad \text{Equation (3.4)}$$

Where

ρ_b and P_ρ are the values of pellets bulk and particle density

3.4 Evaluation of Pellets Mechanical Strength and Durability Using Bench Scale Testers

3.4.1 Introduction

This section describes the bench scale pellets durability tests methods and equipment used for evaluating or testing the pellets strength and durability. The bench scale tests pellets durability tests were conducted using popular standard pellets durability testers (Tumbling box and Ligno tester) and newly introduce large-scale rotary impact tester. The three different bench scale tests were conducted to examine the responsiveness of each tester to the pelleting process parameters (i.e. steam conditioning temperature, moisture content and feedstocks variability) effect on the pellets strength and durability. Similarly, the reproducibility and correlations of each bench-scale tester's pellets degradation patterns were compare, to determine where correlation seems exist between the three durability tests methods. Thurs, the results may provide an indication of which testers should be recommended for evaluating pellet durability in biomass industries.

3.4.2 Methods and Equipment for Pellet Durability Tests

The initial samples preparation for the three bench scales pellets strength and durability tests conducted are the same and the steps involved are as follows: in the first stage, the bulk pellets samples were manually screened in accordance with ISO 3310-2, (ISO, 2010) standard, to eliminate the initial unwanted fines. The fines were removed to ensure that all the pellets remaining are within the range of acceptable standard clean pellets sizes. The initial manual sieving was conducted using 5.6 mm diameter wired mesh sieve. Manual screening is encouraged at this stage because is one of the essential method of ensuring all the pellets are within a uniform size range, without causing further breakage of pellets due to chocks or vibration. Manual screening also minimises the chance of having wide segregation of lower size clean pellet occurring before rifling. Initial sieving of pellets is also an essential method of ensuring that all fines were eliminated to have the clean pellets before testing.

The sieved pellets (clean pellets) samples were then rifled using Hoffman R89P riffle divider to minimise chances of errors occurring due to segregation between the batches before or during testing. Samples of the rifled pellets were taken base on the require sample mass for each bench scale tester and the mass was determined using a digital balance before the different bench scale pellet durability tests. The initial pellets preparation procedures for all the bench scale pellet durability tests conducted are similar.

3.4.3 **Standard Tumbling Box Test**

Tumbling box pellets durability tester was design to measure or give an indication of pellets mechanical resistance to impact or wear tendency in a handling system. The tumbling box pellets durability tests were conducted in accordance with the EN 15210-1: 2009 European standard described in (E. V. Alakangas, 2009). The initial sample preparation for the tumbling test was similar to the earlier procedure described in section 3.4.2. However, in this test, four samples of the clean rifled pellets (500 ± 10 g each) were taken from same batch and the mass of each sample was measured using a weigh balance with 0.001 g precision. Each of the pellets samples taken was loaded into the tumbling box compartment and tumbled at fixed speed 50 ± 2 rpm for 10 minutes. The tumbling machine stopped automatically after the 10 minutes. The tumbled pellets (both fines and coarse pellets) inside the box were retrieved and sieved manually, using 3.15 mm diameter round-holed sieve, to separate the broken fines from the surviving pellets. The mass of the surviving (pellets > 3.15mm diameter) and the broken fines (< 3.15 mm diameter) were measured again. The percentage mass of the surviving pellets over the initial mass of pellets before testing is known as the pellet durability index (PDI) and it was calculated using equation 3.5:

$$\mathrm{PDI} = \frac{M}{M_o} \times 100\ \% \qquad \text{Equation (3.5)}$$

Where:

M is the mass of surviving coarse pellets after testing, and M_o is the initial mass of the pre-sieved clean pellets before testing.

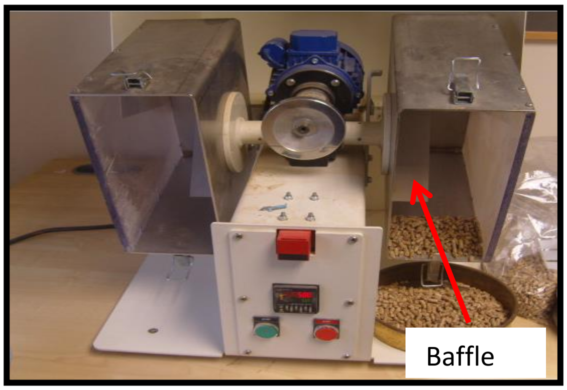
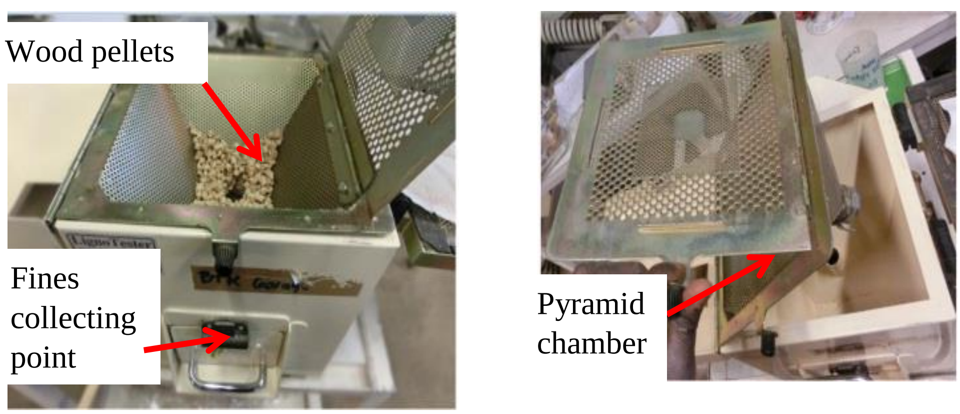


Figure 3.5 Snapshot of tumbling box pellet durability tester

3.4.4 **Pellets Durability Test Using Ligno Tester**

Ligno tester is also one of the commercial standard pellet durability testers mostly used for evaluating pellet strength and durability in the industry. The Ligno pellets durability test was conducted in accordance with the ÖNORM M 7135 Austrian standard. The Ligno pellets durability test was conducted using 100 g ± 0.5 g clean rifled pellets sample, for every fresh durability test. The mass of pellets was measured using weigh balance and loaded into the Ligno tester's pyramid chamber as shown in figure 3.6a. The two lids of the pyramid chamber and the filter paper in between were clipped together to prevent the pellets and dust escaping through the air, during testing. The machine pumped an air stream through a nozzle, at blow pressure between 70 – 80 mbar into the pellets to instigate random collisions between the pellets to pellets and against the chamber walls, for 60 seconds. The random impact and collision forces between the pellets create controlled damages to the pellets.

The surviving pellets above the pyramid chamber sieve (3.15 mm round-hold diameter) were retrieved and the fines were collected via the adjacent side of the tester. The mass of the surviving (> 3.15 mm diameter) and broken fine (< 3.15 mm diameter) pellets retrieved was measured using the same weigh balance and results were recorded for further analysis. The mass of surviving pellets above the sieve, in the case of Ligno durability test, is simply the pellet durability index (PDI). While the percentage mass of the broken fines, generated, over the initial mass of the pellets, before testing, is regarded as the PDI value and was calculated using equation 3.5. The photograph of Ligno tester containing pellets and the pyramid chamber are shown in figure 3.6a and 3.6b.



(a) (b)

Figure 3.6. Standard Ligno test apparatus; (3.6 a) contain pellets & (3.6 b) Pyramid chamber (Borregaard Ligno-tech, Hull,)

3.4.5 **The Rotary Impact Tester**

The large-scale rotary impact tester was designed for assessing large particulate materials (>1 mm diameter) degradation in a processing and handling systems, specifically in a pneumatic conveying system. The tester was a prototype developed from smaller version of the rotary impact attrition tester design for assessing smaller particles (<1 mm diameter) degradation in a pneumatic conveying systems, that arose from the EPSRC funded "Quality in Particulate Manufacturing" project (Pierre et al., 2004).

The initial sample preparation for the rotary impact pellets durability test is similar to that of standard tumbling box durability test prescribed in section 3.4.2. The only difference is in terms of sample size, where the rotary impact durability test requires 2000 g of the clean rifled pellets, for every fresh impact durability test. In comparisons to standard tumbling box and Ligno pellets durability tests where 500 g and 100 g of clean pellets are use, for every durability test. The mass of the pellets was measured using a digital (MSU14202P-000-D0) weigh balance. The revolution per minute's (rpm) speed of the rotary disc was determined using handheld Tachometer PCE-DT 63.

The actual rotary impact pellets durability test commences after the sample preparation by placing the top round lid and fasten the bolt and nuts to protect the pellets and dust escaping through the air, when impinged on the target, during the rotary impact test. A plastic bucket (40 cm height) was also placed beneath the test rig outlet, for collecting both the surviving (coarse pellets) and broken pellets fines, during and after the impact durability tests. The rotary disc switched, was turn on and adjusted to match the predetermined particles impact velocity of about 18.8 m/s, which corresponds to the fixed rotating accelerator disc speed at about 576 rpm (revolutions per minutes). The clean rifled pellets (2000 g) were loaded into the hopper and fed continuously into the rotary disc, using a table feeder, set at about 17 g/s feed rate. The pellets accelerate with trajectory force; from the rotary disc to hit the surrounding targets and disintegrate into different factions of surviving and broken down fines. The rotary impact pellets durability test takes about 120 seconds to complete a single test cycle. The surviving and broken pellets fines around the targets were manually brushed-down and collected in the plastic bucket, via the outlet. The debris retrieving process was aided using a vibrating machine, attached to the test rig and manual brushing. The surviving and broken pellets, collected in the plastic bucket were manually sieved in accordance with the (ISO 3310-2, 2010) standard and the masses were determined. The fraction broken fines were separated using stack of wire-mesh and round-holed sieves in the order of 4.75 mm wire-mesh, 3.15 mm wire-mesh, 3.15 mm round-hole, 2.36 mm wire-mesh and 1 mm wire-mesh diameters. The snapshots of the before and after test, appearance of the pellets was taken for comparisons. The percentage mass of the surviving or broken pellets fine measured was divided by the initial mass of the pellets before testing to achieve the pellet durability index (PDI), using equation 3.5. The process was repeated for calculating the PDI values of different size fractions of broken pellets fines. The flow diagram shown in figure 3.7 illustrate how the pellets flows in the rotary impact durability test rig during testing and other components of the tester.

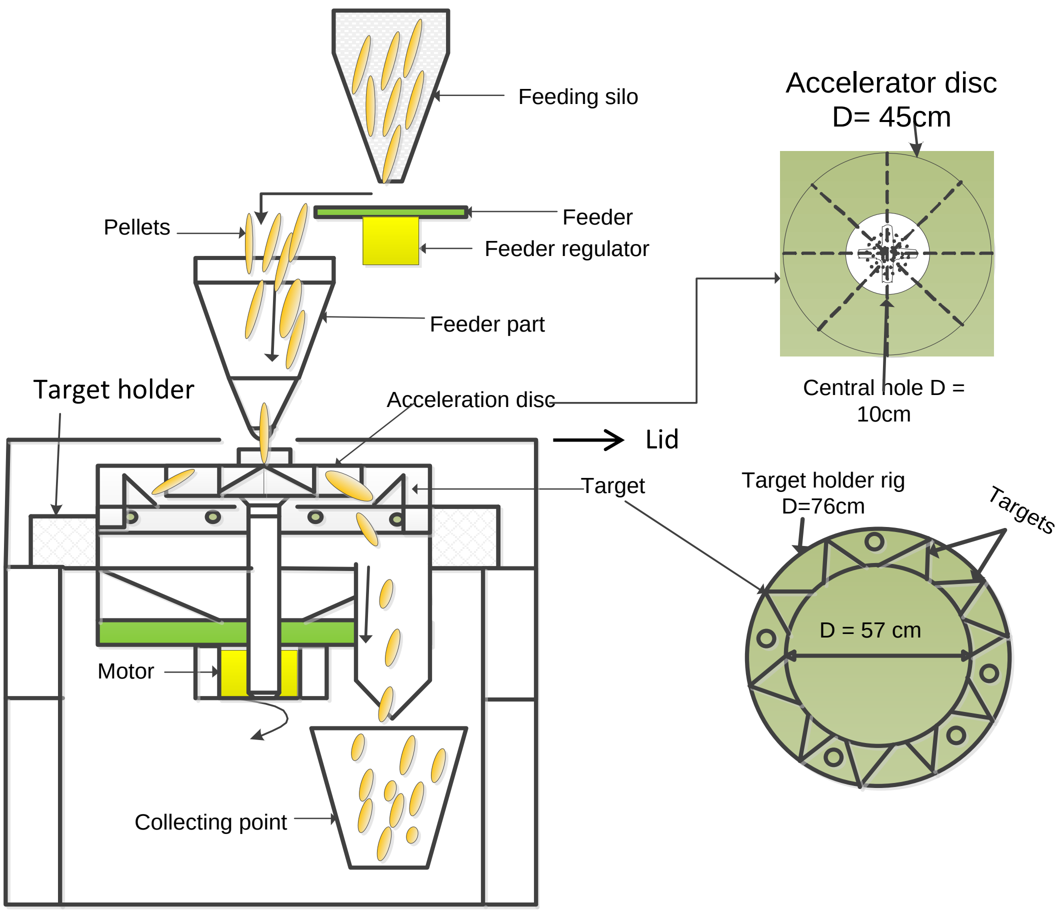


Figure 3.7. The flow diagram of rotary impact durability test

The ability of the rotary impact tester to work effectively under controlled impact velocity (at adjustable disc speed) and impact angle (by chosen a target angle) is a key feature that suggested that rotary impact tester have high tendency to predict pellets degradation in real pneumatic blow conveying system. A similar related study had been conducted in the past to validate the degradation of particles in this tester against real pipelines. However, the effect of particles concentration in a blow pipeline was not taken into account in this test (concentration is an operating variable known to affect degradation level in actual pneumatic systems) (Macchini et al., 2013). The targets impact angle was fixed at 45˚ throughout the impact tests.

The particles impact velocity V_p, was calculated using equation (3.6) (Pierre et al., 2004)

$$V_P = \frac{2\pi R}{\cos(\theta)} n \qquad \text{Equation (3.6)}$$

Where,

n Is the number of revolution per minute (rpm), R is the radius of the rotating accelerator disc and the particles exit angle θ may vary between 40˚- 50˚.

The impact velocity (V_P) was calculated by substituting the corresponding values in equation (3.6):

(a) First step, the circumference (C) of the rotating disc was calculated using

$C = 2\pi R$ such that

= 2 * 3.142 * 22.5cm = 1.413716 m

(b) Conversion of revolution per minutes (rpm) to meter per second (m / s), which was achieve

Using

$C = 2\pi R * revolution\ per\ munite\ (n)$

= 1.413716 * 576 rpm = 814.30 revs per minute or $\frac{814.30\ meters}{60\ seconds}$ = 13.572 ms^{-1}

The n equal 576 rpm was measured using handheld Tachometer PCE-DT 63 and the measured rotary disc speed at that point is equal to 18.8 m /s velocity, which seems to correspond with the average pellets velocity in a lean phase blow system.

(c) Therefore, the maximum pellet impact velocity was calculated using equation (3.6) such that

$V_P = \frac{2\pi R}{(\cos 44 \pm 5^{\circ})} * revolution\ per\ second,$ Implies $\frac{13.572}{0.7193}$ = 18.87 ms^{-1}

3.4.6 **Uniaxial Compression Test**

Pellets uniaxial compressive resistance and three points bend tests were conducted on sixty selected piece of pellets from different types (i.e. wood, peanuts and sunflower pellets) and Brookfield CT 3 texture analyser. The three points bend test was conducted to examine the elastic strength of every single pellet under compressive load stress during transport or handling system. The 3-points bend test deployed are similar to that of the surgical sutures needle bend strength test described in the ASTM F1874 - 98 (2011) standard. This method of testing was chosen because it allows equal applied stress distributed across the pellet. However, it may not give an indication of possible bulk pellets degradation or dust tendency in a large-scale handling system, due to heterogeneous properties of pelleted biomass materials.

3.4.7 **Sample Preparation for Three Points Bends Tests and Method**

The sixteen piece of pellets selected mass, length and diameter was determined before subjected to three points bend test. The lengths of the pellets selected were categorised into three different classes, ranging from 10 - 20 mm, 20 - 30 mm and 30 - 40 mm lengths respectively. The volume of each pellet was also determined from their respective length and diameter measured, using a digital venial calliper. Mass of each pellet was measured using weight balance with 0.001g precision.

The 3-points bend test was conducted by placing a single pellet horizontally across the centre position of the adjustable 3-point-bend fixture as shown in figure 3.8. The pellet was firmly held at fixed points during compression using Bostick "blu-tack" holder. The load cell (limited to 1000 N) require to fracture the pellet was mounted to the texture analyser prop. During the test, the prop pushes down toward the pellet and apply stress across the sectional area of the pellets, which result in creating crack or failure on pellets surface at a fixed speed of 0.5 m /s. The prop intrusion was stopped immediately after the first failure (indicated by the reducing load) before the pellet finally disintegrated into two pieces. The maximum loads required causing failure (fracture) on the pellet and distance covered by the fixture prop was recorded. The results were used for calculating the Young's modulus and compared with other bench scale pellets durability index (PDI) values. The photograph of CT3 texture analyser and the specimen (pellet) positions on the 3-points bend texture, during the test, are shown in figure 3.8.

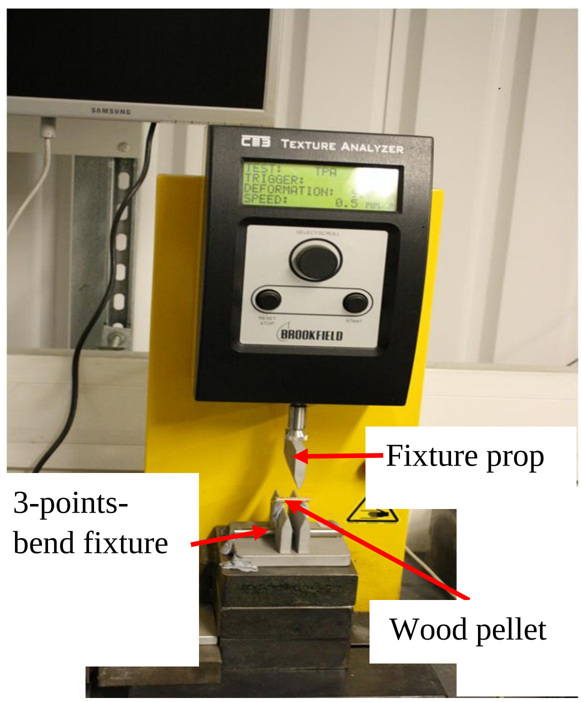


Figure 3.8 the 3-points bend test for pellet mechanical strength measurement

Chapter 4 the Influence of Feedstock Variation and Pelleting Process Parameters on Wood Pellets Strength and Durability

4 Introduction

The influence of pelleting process parameters (i.e. moisture content and steam conditioning temperatures) and feedstock variation (pine and alder wood powder) on pellets strength and durability (quality) during manufacturing was investigated. The investigation was carried out by producing pellets from homogeneous (100 % pine wood powder) or heterogeneous (combined pine and alder wood powders) feedstocks using conventional pellets mill at different moisture content and conditioning temperatures. The heterogeneous pellets were produced by adding 10 % or 20 % alder to 90 % or 80 % pine feedstocks at three distinct condition of temperatures (23℃, 50℃ or 70℃) and initial feedstock moisture contents (10 %, 11.5 % or 13 %). The pellets were produced to aid understanding of how to improve pellets quality (strength and durability) using different pelleting process parameters and feedstocks.

The influence (response) of each pelleting process parameter and feedstocks variability to pellets strength and durability was measured using both the existing standard bench scale testers (tumbling box and Ligno testers) and the newly introduced rotary impact testers. The pellets durability index (PDIs) was calculated using equation 3.5, after testing and the results were compared. The PDI values of the pellets produced may differ; therefore, this will be relevant to the pellet producers, sellers and users to ensure satisfactory quality improvement in this respect.

4.1 Results and Discussion

The summary of all the measurement and the calculated values obtained during and after the pellets production processes were presented in table 4.1. The measured variables and calculated data such as the pellets durability index (PDI), initial feedstock and pellets moisture contents, the pellet mill motors power consumption, feedstocks conditioning temperatures, and etc. were all presented in the table.

Table 4.1 The summarised of the data collected during and after pellets production.

Exp Name/order	Durability (%)	Fines (kg)	MC Conditioning sawdust (%)	Effect kW	Eff./prod. kWh/ton	Pellet MC warm %	Pellet MC coo/ %	Matrix temp (ºC)	Pellet temp (ºC)	Prod kg/h	Motor current A	Motor current /prod
1	92.72	6.47	13.80	28.2	77.4	9.3	8.0	75.5	82.4	364	66.6	182.6
2	91.55	10.61	10.19	30.5	84.4	7.1	6.4	73.6	90.0	361	69.1	191.6
3	93.98	3.69	12.98	30.7	83.4	9.7	8.2	72.5	83.2	368	69.2	187.8
4	88.81	11.94	10.04	27.1	74.4	7.5	6.6	71.5	83.8	365	65.4	179.3
5	94.28	3.78	13.02	30.6	85.1	9.9	8.3	67.0	82.2	359	69.2	192.7
6	92.09	21.23	11.60	27.3	73.9	8.9	7.9	68.5	79.4	370	65.7	177.6
7	91.97	9.04	11.55	28.3	76.2	8.4	7.3	74.5	85.2	372	67.1	180.5
8	93.57	5.87	16.85	28.5	77.6	10.4	8.8	76.7	80.7	367	67.0	182.6
9	93.97	4.82	13.58	29.4	82.2	9.5	8.4	74.9	83.8	357	67.6	189.2
10	92.63	12.30	13.24	27.1	76.8	9.0	8.2	77.5	82.0	353	65.5	185.5
11	92.67	8.81	13.28	27.4	75.0	9.1	8.2	78.3	83.3	365	65.5	179.3
12	94.80	7.64	13.54	30.6	84.4	8.7	7.3	87.1	86.7	362	69.1	190.6
13	94.53	7.07	15.49	28.2	78.1	10.6	8.8	72.2	82.6	361	66.3	183.6
14	90.77	35.14	13.01	25.3	67.8	8.3	7.4	84.5	82.6	373	63.7	170.6
15	91.88	7.31	13.73	29.2	78.6	10.6	9.5	51.3	77.6	372	67.1	180.3
16	94.03	3.37	14.97	29.4	77.6	9.8	8.6	59.9	82.5	379	67.0	176.9
17	94.48	3.02	13.73	31.1	78.3	9.9	8.7	54.3	82.0	397	68.9	173.7

It is important to note that some of the data presented in table 4.1 were not analysed in this thesis because is not part of the key research interest of this project but were included for completeness to enable further investigation in the related areas.

The graphs of the calculated PDI values were plotted against the response each parameter (steamed moisture content, conditioning temperature and feedstock variability) to determine their effects on the pellets resistance to degradation. The mean and corresponding standard deviations (SD) of the PDI values achieved was divided and multiplied by 2 to determine the error margin and 95 % confidence interval (CI).

4.1.1 Effect of Feedstock Steam Moisture Content on Pellets Strength and Durability

The effect of feedstock steamed moisture content on pellets strength and durability was examined from set of homogenous and heterogeneous pellets (containing 90 % pine and 10 % alder wood powder). The pellets were produced at three distinct levels of steamed feedstock moisture content (i.e. 11.6 %, 13.3 % and 16.8 %) at 50°C steam conditioning temperatures. Hot steam was added to the feedstock samples at different initial feedstock moisture contents but same steam conditioning temperature. The increase in steam moisture was expected have influence on the lignin and other binder’s production to improve the pellets quality. It is, however, important to note that feedstock steam moisture content was found to increases with increase in the initial feedstock moisture content (i.e. prior to steam conditioning), which was believed to have occurred due to moisture accumulation within the particles.

The strength and durability of the heterogeneous pellets produced at the three different steamed moisture contents were measured using the standard tumbling box, Ligno and the modified rotary impact testers. The response of each bench tester to the increase in steamed moisture effects was analysed based on changes in pellets durability indices (PDIs) values calculated for each bench scale tester. The values of the PDIs obtained from the three different bench durability tests, were plotted against the corresponding increase in steamed moisture contents as are shown in figure 4.1. The mean and standard deviation (SD) of PDI values were calculated to determine the coefficient of variation. The average of all the mean SD values was divided and multiplied by 2 to determine the possible 95 % confidence interval.

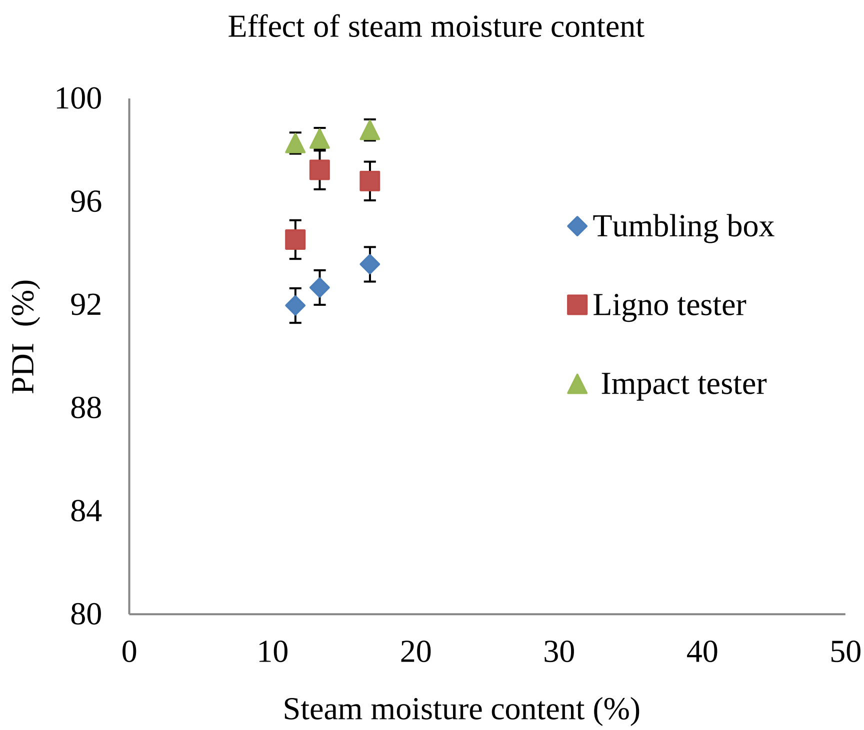


Figure 4.1 Compares the effect of increasing steam moisture content to change in pellets strength and durability

As observed in figure 4.1 the increase in pellets durability due to corresponding increase in steamed moisture content trend, as indicated by the PDI values, was highly pronounced in the tumbling and Ligno testers, though, one batch of the Ligno PDI result did not fit the trend order. The anomaly was not simply due to experimental error in the durability measurement (all the test was repeated three times). It is likely an evidence of problems associated with the Ligno tester's results, which is possibly due to small sample size (100 g) required for Ligno test. However, the increase in the PDI was not clearly picked by the rotary impact durability tester, as seen in the standard tumbling box and Ligno testers. Thus, the result of the rotary impact tester on steam moisture content effect was highly repeatable and showed lower percentage error margin. It is also of interest to note that a change in PDI values from 98.2 % to 98.8 % must be considered quite significant, because the matter of real interest in terms of pellet performance in a boiler is the fines content, which is effectively 1-PDI, i.e. in this case changing from 1.8 to 1.2 percent, a reduction of one-third.

4.1.2 Effect of Initial Feedstock Moisture Content

Initial feedstock moisture content is the pre-determine feedstock moisture before steam conditioning or pelleting. In this case, similar set of heterogeneous pellets containing 10 % alder to pine content were produced without injecting hot steam to the feedstock before pelleting. The heterogeneous pellets were produced at two different levels of initial feedstock moisture content (10 % and 13 % w.b) without steam conditioning (i.e. ≈ 23°C ambient temperature).

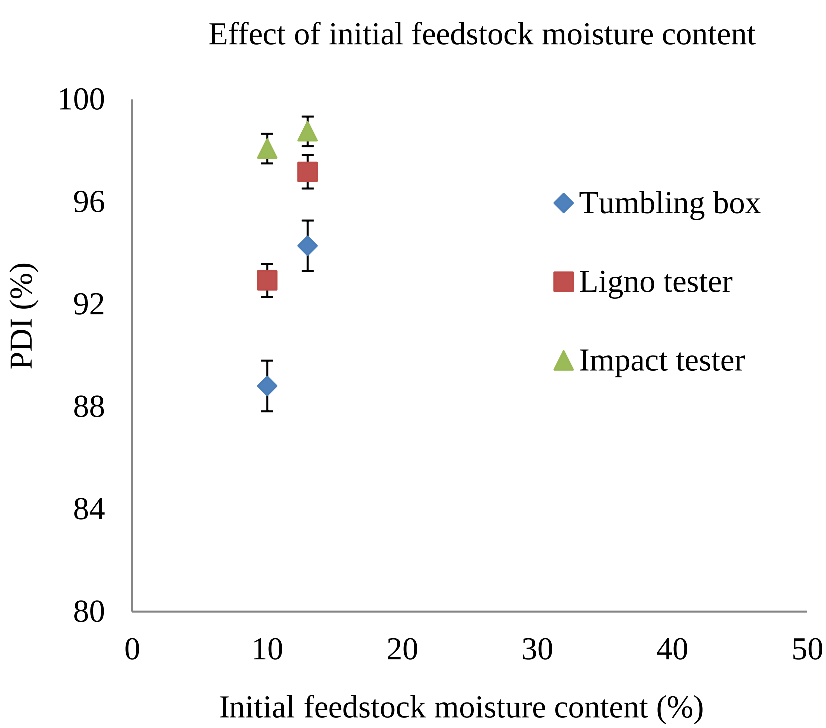


Figure 4.2 The effect of change in initial feedstock moisture content on pellets durability

The change in pellets strength and durability due to increase in initial feedstock moisture content (10 % to 13 %) without steam conditioning, shown in figure 4.2 were demined based on the PDI values of each bench scale measurements. The increase was more pronounced in the results of standard tumbling box and Ligno testers compare to rotary impact tester. The rotary impact durability tester has shown slow response to the increment in pellets durability due to corresponding increase in un-steam feedstocks moisture content, as observed in the two standard durability testers. However, increase in pellets impact resistance from 98.08 % to 98.75 % can still be considered as an improvement in domestic use pellets quality, because an increment of about 0.67 % in terms of 1- PDI value, where fines are highly undesirable can make a difference in the pellets market value. Additional results on effect of both steamed and un-steamed feedstock moisture content on pellet strength and durability are shown in appendix B.

4.1.3 **Effect of Adding Alder to Pine Wood Powder**

Two set of heterogeneous pellets containing 10 % and 20 % alder to pine content were manufactured at 13.4 % steamed moisture content and 50°C pre-conditioning temperature. The strength and durability of the heterogeneous pellets were measured using the three bench scale testers and the PDI values of pure pine (100 % pine) wood pellets were compared to those of the heterogeneous pellets produced at same pelleting conditions.

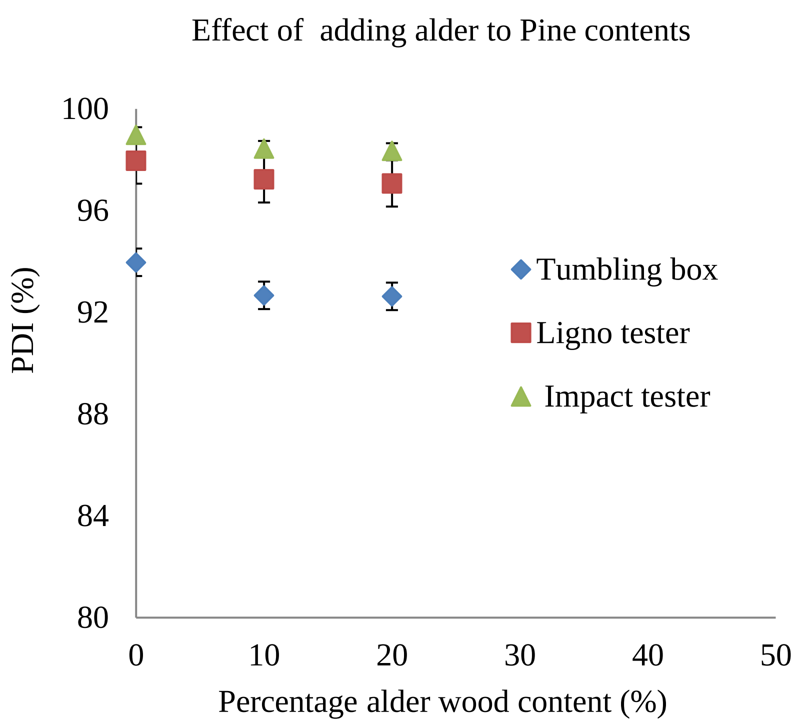


Figure 4.3 The effect of alder to pine wood content on pellets strength and durability

The PDI values of the homogeneous pine wood pellets was slightly higher than that of heterogeneous pellets containing 10 % or 20 % alder to pine content, as shown in figure 4.3. The measured strength and durability of the two set of heterogeneous pellets brands (i.e. containing (10 % or 20 % alder to pine contents) showed a similar range of resistance to breakage across the three bench scales testers. The PDI values depicted identical trends, except for pellets of pure pine wood powder (i.e. no or 0 % alder). It can be concluded that pure pine wood pellets are slightly more resistant to degradation compared to the heterogeneous pellets brands. This is because the proportionate change in the impact factor 1-PDI was marginally greater for the impact tester than for the other two testers. It can be seen from the error bars that a higher degree of repeatability was observed in the PDI values of the rotary impact tester measurement compared to that of the two standard durability testers.

4.1.4 **Effect of Steam Conditioning Temperature**

The effect of feedstock steam conditioning temperatures on pellets strength and durability was determined from the heterogeneous pellets (containing 20 % alder to pine content) manufactured at same initial feedstock moisture content (10 %) and distinct temperatures (without steam conditioning at 20°C) and steamed conditioned at 70°C. The corresponding pellet durability index (PDI) values of each bench-scale tester against the feedstock steam conditioning temperatures during pelleting are shown in figure 4.4.

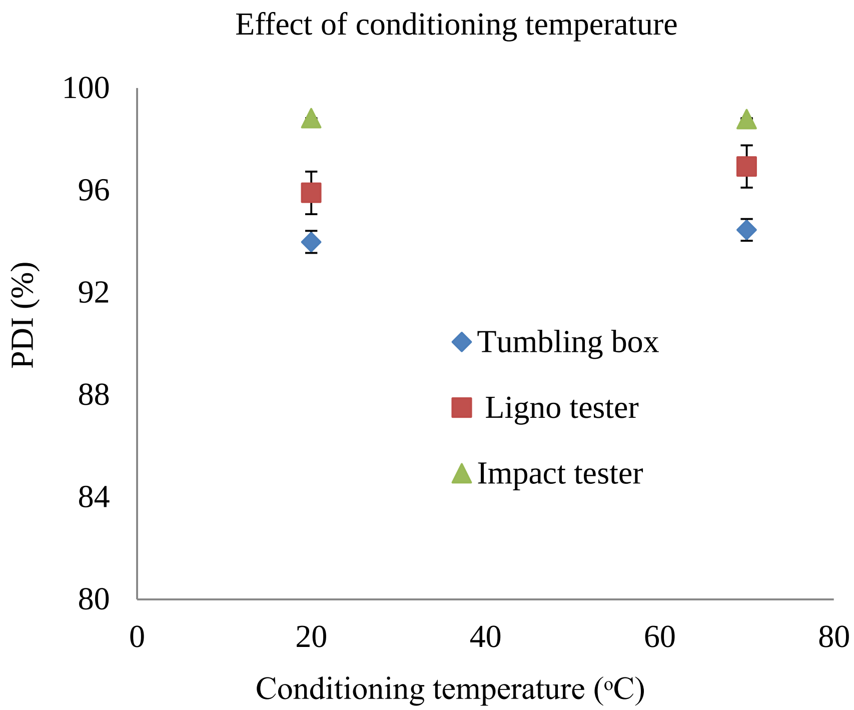


Figure 4.4 The effect of steam conditioning temperatures on pellet strength and durability

No significant increase in pellets durability due to change in conditioning temperature was observed across the PDI values of the standard tumbling box, Ligno and rotary impact testers. Thus, the results of two standard testers appear to be slightly more responsive to increase in conditioning temperature compared to rotary impact tester. However, it is also instructive to note that pellets experience many impacts and wears in the standard pellets durability tester, per every test cycle, while, the pellets experience single impact, per test cycle, in every rotary impact durability test. Again, the results cannot be put down as a rogue because the results of impact tester are much more repeatable compared to that of standard durability testers. Other results of the conditioning temperature effect on pellets durability are presented in Appendix B.

4.2 Correlation of Pellet Durability Index (PDI) Values Derived from Different Bench Scale Pellet Durability Testers

The difference in pellets durability index (PDI) values calculated after testing the durability of pellets with different production histories, across the three bench-scale pellet durability testers (i.e. Ligno, tumbling box and rotary impact tester) were compared as shown in figure 4.5, 4.6 and 4.7. The goal was to examine the degree of random variation and correlation between the three-bench scale pellet durability testing machines.

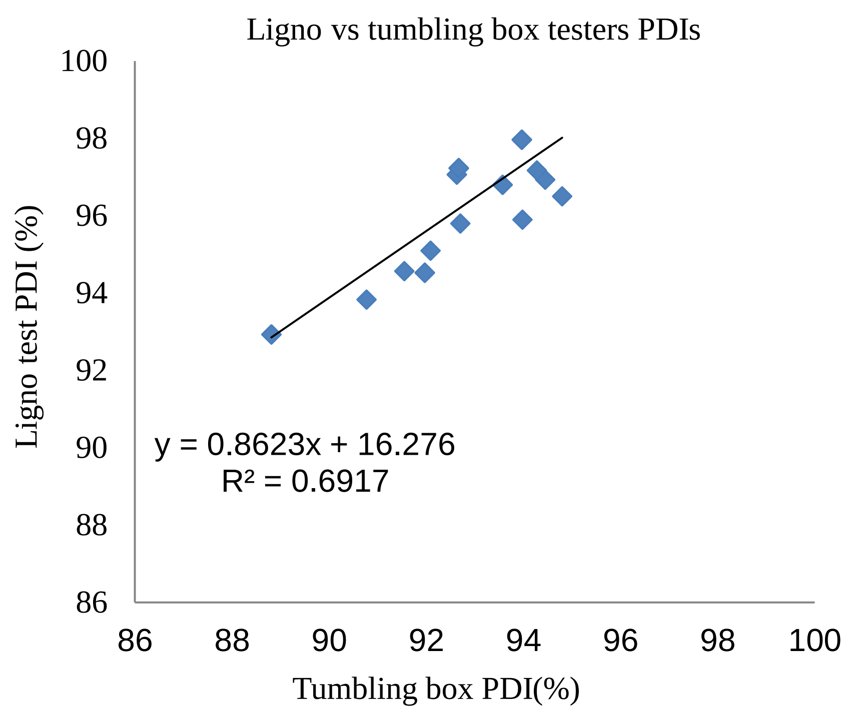


Figure 4.5 The PDI values of Ligno vs tumbling box durability tests

The degree of correlation between the PDI values of the standard Ligno and tumbling box pellets durability testers, shown in figure 4.5 indicates an existence of some degree of correlation between the two testers, especially at the low region below 96 % with a very significant difference (typically 4 % at the bottom of the trend line and 3 % at the top). However, the region of good correlation is below the minimum 97.5 % acceptability stated in the EN 14961- 2 standard. In the region where pellets are within the acceptable durability, i.e. above 97.5 %, the Ligno test PDI values vary with very significant scatter of up to 2 % in the correlation. Given that the critically important factor is the fines content, i.e. 1- PDI, an uncertainty in a correlation of up to 2 % in (1-PDI), and a difference of around 3 %, is extremely large when the maximum acceptable value of (1-PDI) is 2.5 %. Overall, the poor comparison between the Ligno / tumbling box tests in figure 4.5 must be considered a very serious problem if both tests are to be used interchangeably.

Similarly, some samples of the same batch of pellets durability tested in the standard Ligno / tumbling box testers, earlier, were also used in the rotary impact tester. The calculated PDI values were compared to that of the Ligno tester as shown in figure 4.6.

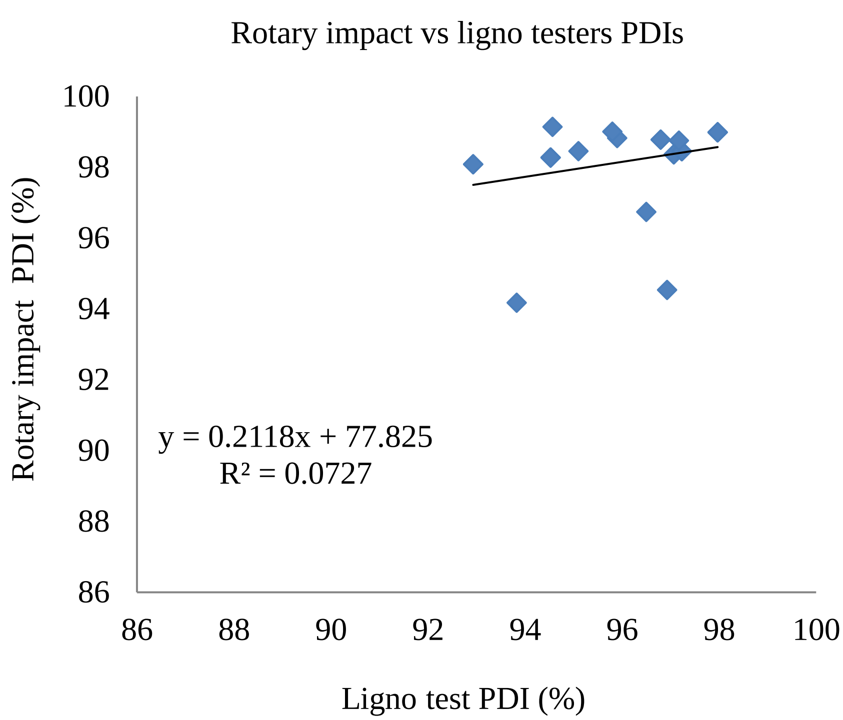


Figure 4.6 The PDI values of rotary impact vs Ligno durability tests

There is almost complete lack of correlation between the PDI values of rotary impact / Ligno durability tests. The lack of correlation in the PDI values below the region of < 97 % with offset points was significant. The offset points may have possibly occurred due to poor correlation in breakage mechanism between the rotary impact and Ligno testers, which was exaggerated by wide variation in the pellets production histories. The apparent outliers appeared to have occurred due to difference in the pellets quality (i.e. resistance to pellets breakage) cause by the difference in their production properties. The R^2 value 0.07 was also very low.

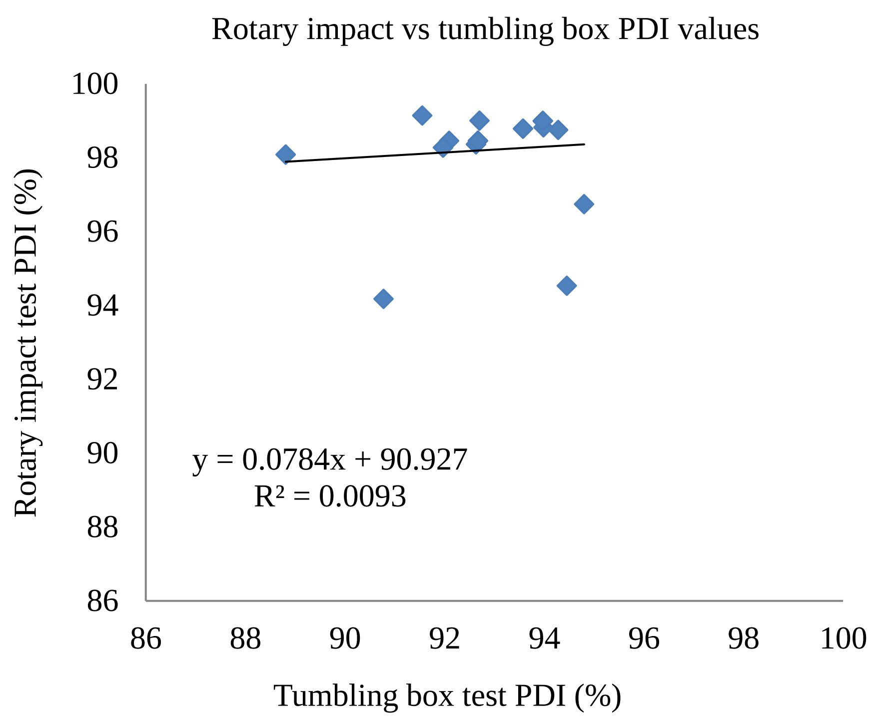


Figure 4.7 The PDI values of rotary impact vs tumbling box durability tests

Same data of rotary impact durability tests PDI values were compared to that of tumbling box tests and the results were presented in figure 4.7. The lack of correlation between the PDI values of rotary impact / tumbling box tests was even higher than that of rotary impact / Ligno tests. The R^2 value 0.009 was very low. The offset points in case may have also occurred to buttress the absolute lack of correlation between the breakage patterns of pellets in the rotary impact / tumbling box durability testers. The apparent outliers also appeared to have occurred in figure 4.7 due to wide variation in the pellets strength and durability (PDI values) caused by the difference in production histories. This could also expand the lack of appreciable correlation between the two bench testers' mode of pellets degradation and resistance to impact and wearing energy in the testers.

In summary, the conclusive remark on PDIs values is that none of the two standard pellet durability testers (i.e. Tumbling box and Ligno tester) appears to have a direct correlation with the rotary impact tester pattern of pellets degradation. However, the two standard testers appear to have shown some degree of correlation in them, albeit in the region of less interest. The Ligno tester's result was less repeatable with more scatter points, at the maximum specified acceptable values of standard pellet durability index.

4.3 Comparisons of broken pellet fines (< 2.36 mm diameter) derived during the three-different bench scale pellet durability tests

To examine the difference in the breakage pattern of pellets in the three bench scale pellets durability testers (i.e. tumbling box, Ligno and rotary impact testers). The PDI values of broken pellets fines (< 2.36 mm diameters) generated from testing the durability of the wood pellets with different production histories, across three bench scale testers were compared. The fines content is simply 1-PDI, but the objective of looking at the data in this way is a clearer understanding of the fines content effect, which is the factor that affects the performance of a pellet boiler. The 1-PDI values of broken pellets fines from the three bench-scale testers were compared and the results are presented in figure 4.8, 4.9 and 4.10 respectively.

The comparisons between the 1-PDI values of broken pellets fines below 2.36 mm derived after the Ligno and tumbling box durability tests are depicted in figure 4.8. The result indicates existence of some degree of correlation between fractions of broken pellets fines (< 2.36 mm diameters) derived from the two testers in the more limited size range. Again, in the lower region of fines (under 7.2 % in the tumbling tester); there was a scatter of about 2 %. This also shows that tumbling box tester produces finer particles, during tumbling durability test compared to Ligno tester.

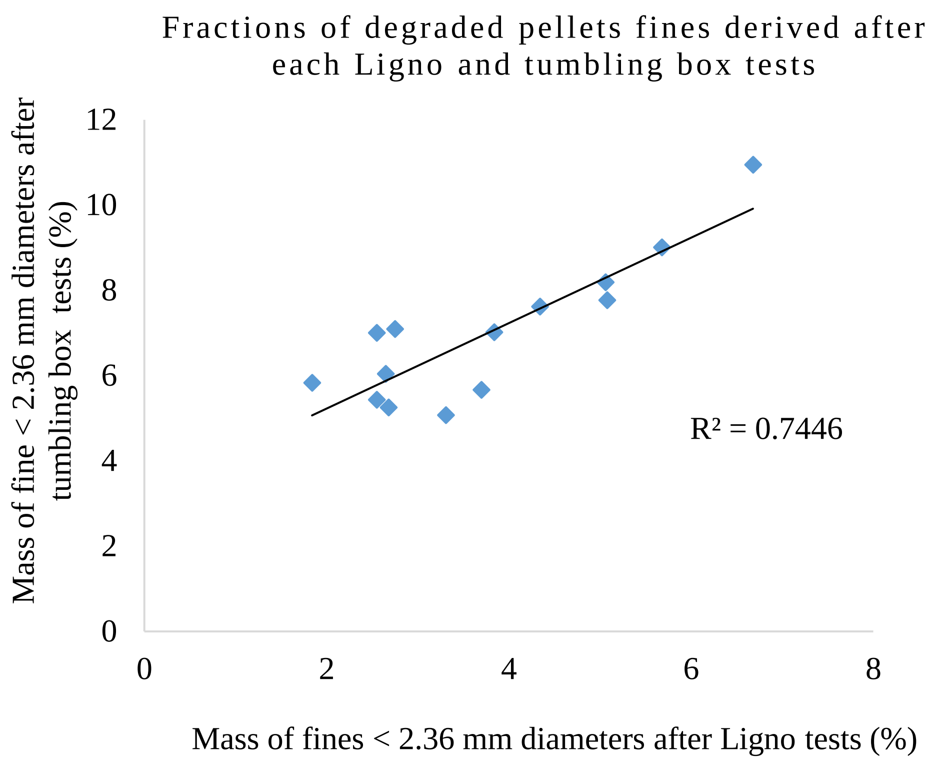


Figure 4.8 Comparisons the 1-PDI values of broken pellets fines (< 2.36mm diameters) derived from Ligno vs tumbling box durability tests

4.3.1 **Comparisons of Broken Pellets Fines Derived during Tumbling Box and Rotary Impact Durability Tests**

Similarly, the correlation between the 1-PDIs values of fines (< 2.36 mm diameters) generated from each tumbling box / rotary impact pellets durability test and results obtained were compared as depicted in figure 4.9.

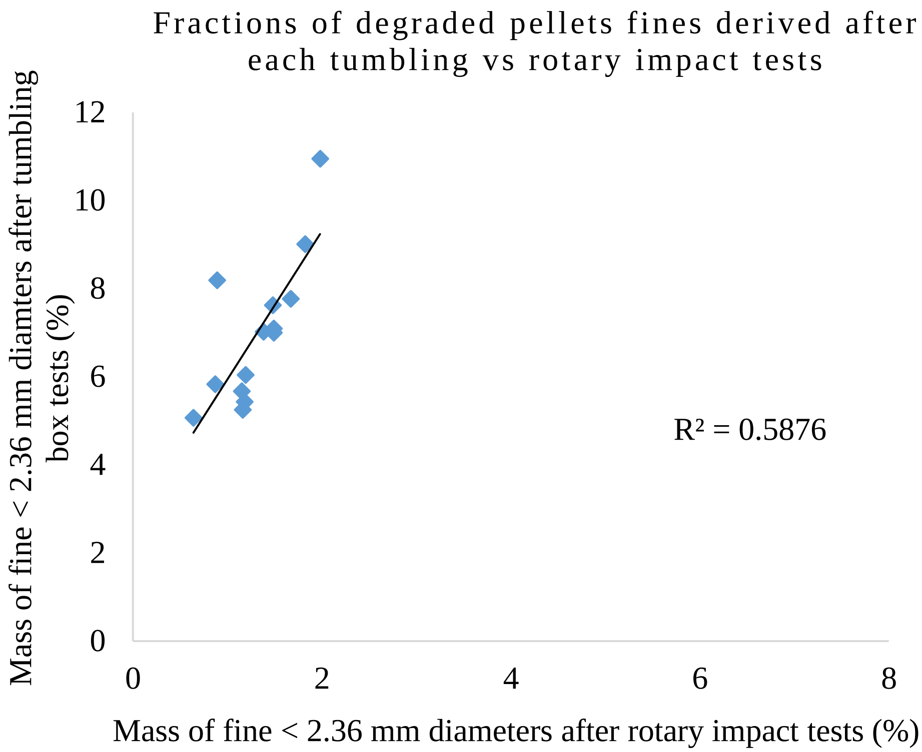


Figure 4.9 Compares the 1-PDI values of fines (< 2.36mm) derived from tumbling box and rotary impact durability tests

The 1-PDI values of fines (< 2.36 mm diameters) derived from the tumbling box versus rotary impact durability tests, in figure 4.9 shows poorly correlated with scattered points. The quantity of degraded fines below 2.36 mm generated from tumbling test is almost twice the quantity of the same size of fines produced from rotary impact durability test. This also shows that tumbling box produces finer particles than the rotary impact tester, though; pellets experience single impact per every rotary impact test whereas multiple wear and impact occur in tumbling durability tests.

4.3.2 **Comparisons of Fines Derived during Ligno and Rotary Impact Tests**

The percentage mass of broken pellets fines (< 2.36mm) derived from the standard Ligno and rotary impact durability tests were calculated and the 1-PDIs values of each bench durability tests were compared as shown in figure 4.10.

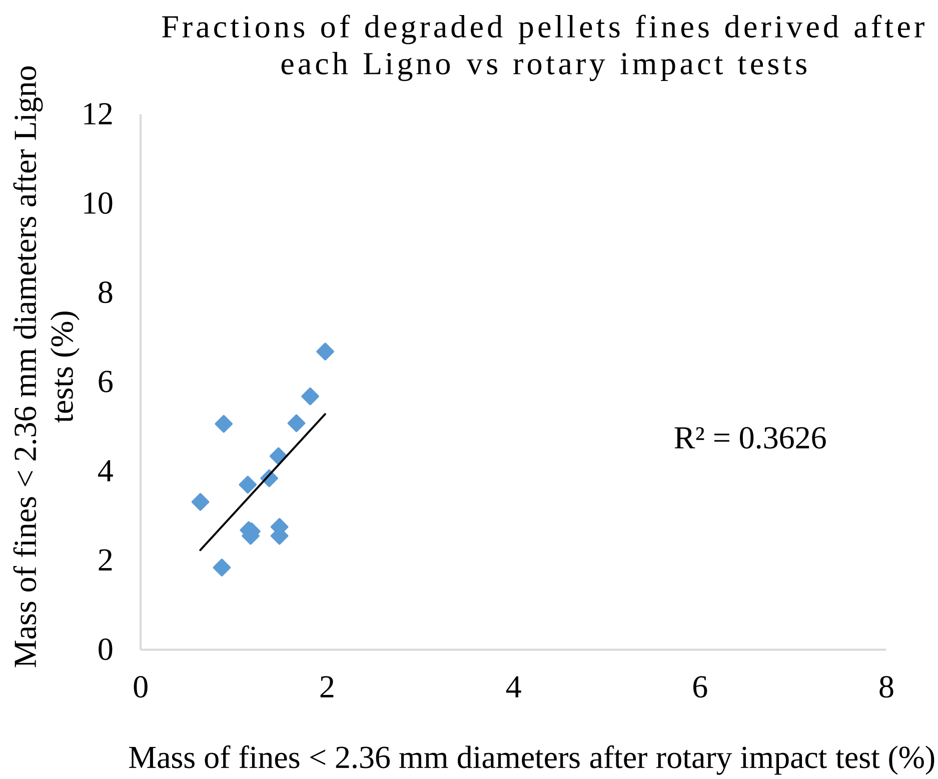


Figure 4.10 Compares the 1-PDI values of fines derived from Ligno and rotary impact durability tests

The 1-PDI values of the broken pellets fines below 2.36 mm diameters derived after Lingo and rotary impact durability tests appear to have poor degree of correlation, especially in the lower region below 4 % Ligno 1-PDI values. The slight lack of correlation the two-bench scale tester's mode of pellets degradation is an indication of slight difference in their pellets breakage mechanism. The R^2 = (0.4) was also lower than that of tumbling / rotary impact durability test shown in figure 4.9. However, the pattern of pellets breakage in Ligno / rotary impact test, may possibly give some similarity with that of real pneumatic conveying system compare to tumbling test, where the pellets experience a very low impact velocity.

4.4 **Summary**

As evidenced from pellets manufacturing results: -

The increase in feedstock steam conditioning temperatures from 20˚C - 70˚C have resulted to increase in pellets strength and durability to some extent; however, this was at the expense of greater energy used in pellets production.

The heterogeneous pellets containing 20 % alder to pine wood contents have shown a degree of acceptable durability threshold values around ≥ 97.5 %, when tested in both Ligno and rotary impact tester, but the durability of the pellets was slightly lower in tumbling box test. Thus, the use of up to 20 % alder to pine feedstock for pelleting could be encouraged to maximise renewable energy production, because there was no difference in the strength and durability of pellets containing 10 % to 20 % alder content.

Increase in feedstock moisture content to some limit have also resulted to corresponding increase in pellet strength and durability measured, from the three bench scale testers, as indicated by the PDI values of both steam-conditioned and non-steam-conditioned pellets produced.

Comparative evaluation of pellet durability index values and fines contents of the three bench-scale pellets durability-testing techniques: -

As evidence from the results of pellets with different production histories PDIs values correlation, PDIs of Ligno tester results were less repeatable compared to tumbling box test, but the irregularities in the PDIs repeatability was believed to have occurred due to random impact velocity of the pellets in the standard Ligno tester. Rotary impact tester produced the most highly repeatable PDI values with less percentage error tendency compared to tumbling box and Ligno testers.

The relatively poor correlation between the PDI values of the three bench-scale test results (even between the two most widely used “standard” testers), is a major cause for concern. Had there been a close correlation but just with an offset, the test results could be subjected to a “correction” for the difference, or an adjustment of duration, to obtain equivalence. In the other way, poor correlation may possibly be considered as positive result because it shows the relevant of the two tests methods in evaluating pellets strength and durability, since the two breakage mechanisms have possible chance of occurring in pellets handling system.

However, the high scatter and the great lack of correlation in the most important range (97 % to 100 %) of acceptable commercial PDI values, even for the two testers accepted as “standard” and widely used for industrial quality control measurements, and the much poorer correlation against the rotary impact test, that was designed to simulate the conditions of particles degradation in real conveying system, is a clear evidence that industries should expect very little correlation between the PDI reading for a batch, and the actual pellet break-down observed in real deliveries.

Chapter 5 Results of Repeated Impact and Wear Resistance Testing of Pelleted Biomass Material against the Intensive Repeated Handling System

5 Introduction

The idea of the repeated pellets durability testing was conceived from the results of different single sets of pellets durability test conducted using the three bench scale testers, described in chapter four. Where the magnitude of pellets breakage observed in a single rotary impact test was substantially smaller in comparison to a single run of standard (Ligno and tumbling box) tests, which raise a concern on whether exploration of test duration could be a possible means for obtaining equivalence. It was also obvious that the pellets experience single impact in every rotary impact durability test, despite its most representative of particles velocity to real pneumatic delivery system. Thus, it does not simulate the multiple impacts the particles experience along the bends or couplings (maybe 4 to 10) in an actual delivery. It is logical that as pellet attrition takes place, the pellets themselves change (especially "corners" and excrescences are knocked off), so there is likely to be a progressive change in the breakdown rate from one impact to the next. Therefore, it was considered necessary to run multiple durability tests using a single fresh sample of pellets repeatedly for ten times in a bench tester and repeat the same process across the three bench scale testers, to examine how the pellets attrition differs between the testers. For example, would the initial impacts knock off the corners so leaving the pellets less susceptible to further breakdown, or would it weaken the structure so leaving them more susceptible?

Bearing in mind that in real delivery systems, the pipe length, numbers of bends, couplings and so on, varies. So, when trying to obtain some indication of the likely pellets degradation level in a delivery (even if only for comparative purposes between pellet batches), based on attrition tests, it would be useful to understand whether the different in batches or tests procedures could make a difference in this respect. The knowledge would be beneficial to the pellets users and industries that produce and use pellets for quality improvement or a preventive measure to an unexpected outbreak of fines in the industries.

Therefore, a repeated pellets durability test was conducted using both standard (Ligno and tumbling box testers) and the newly introduced rotary impact bench scale tester. A single sample of wood pellets was subjected to multiple repeated durability tests as another way of assessing the impact and wear resistance of pellets during transport or repeated industrial handling systems.

5.1 Material and Method

A multiple numbers of pellets durability tests were conducted repeatedly using the three-bench scale pellet durability testers (Ligno, tumbling box and rotary impact tester). The tests were conducted in accordance with the EN15210-1 standard for ten consecutive times using one sample. Similarly, a series of repeated pellets durability tests were also conducted using other types of biomass pellets (e.g. wood, peanut, sunflower, straw and black pellets). However, only the results of wood pellets are shown in this chapter. A single pellets sample was tested repeated for ten consecutive times to understand the breakage patterns because wood pellets are handled for not less than eight times before getting to their final place of use or destination. The breakage mechanisms of each bench scale testers were assessed based on broken particles size fractions emanated from the pellets during each durability test.

The repeated tumbling box durability test was conducted by loading 500g of pellets into the tumbling box and the pellets were tumbled at 50 rpm for 10 minutes. The process was repeated consecutively for ten times, using same pellets from the beginning. In each run test, the pellets were retrieved and subjected to manual sieving to separate the fines (< 4.75 mm) from the surviving (> 4.75 mm diameter) in accordance with EEN 15149-1 standard. The surviving pellets were loaded back into the tester for the second run test, the tumbling durability tests were repeated for ten consecutive times. The reduction in mass and density of the pellets were neglected during this repeated tumbling test because the broken fines were removed and coarse pellets were loaded back into the tester without the fines to avoid partial surface contact due to “cushioning effect” or reduce friction of the surviving coarse pellets against the baffle inside the tumbling box. The repeated pellets durability test method was similar for the Ligno and rotary impact testers. The only difference was in terms of impacts forces and required initial mass of pellets sample, where Ligno test uses 100g and 2000g for the rotary impact repeated durability test.

The mass of the surviving (> 4.75 mm diameter) and broken fines pellets generated from the pellets during each durability test was measured using weight balance. The fractions of the sieved particles size distributions were in the order of (> 4.75 mm, 4.75 - 3.15 mm, 3.15 - 2.36 mm, 2.36 -1 mm and < 1 mm) diameters. The pellets durability index (PDI) of both the surviving and broken fines were calculated using the mass of the respective fractions.

The correlation that could exist between the PDI values of the fines fractions and breakage patterns of each bench-scale durability tester were compared. The comparisons were of interest to determine the variation in the breakage patterns of the pellets observed in rotary impact tester compared to the standard pellets durability testers results, which was attributed to differences in impact energy and particles velocities in the testers.

5.2 Results and Discussion

In this section, the results of two different batches (A and B) of wood pellets repeated durability tests conducted using tumbling box, Ligno and rotary impact testers are presented and discussed. The batch (A) pellets are heterogeneous wood pellets with different production histories whereas batch (B) pellets are homogenous industrial high-quality wood pellets produced for domestic boiler use. Breakage resistance of the batches of wood pellets in long run handling system was measured and the results were depicted in figures below. Other types of biomass pellets such as (black, peanut, straw and sunflower pellets) were also tested and the results are presented in appendix D of this thesis.

5.2.1 Characteristics of Repeated Tumbling Box Durability Test

The repeated tumbling box pellets durability test of (batch A and B) woods pellets were tested for ten consecutive times and the difference in their mode degradation was presented.

The breakages pattern of the broken fines generated from the pellets batches were plotted against the number of tumbling test cycles and results are shown in figure 5.1 and 5.2.

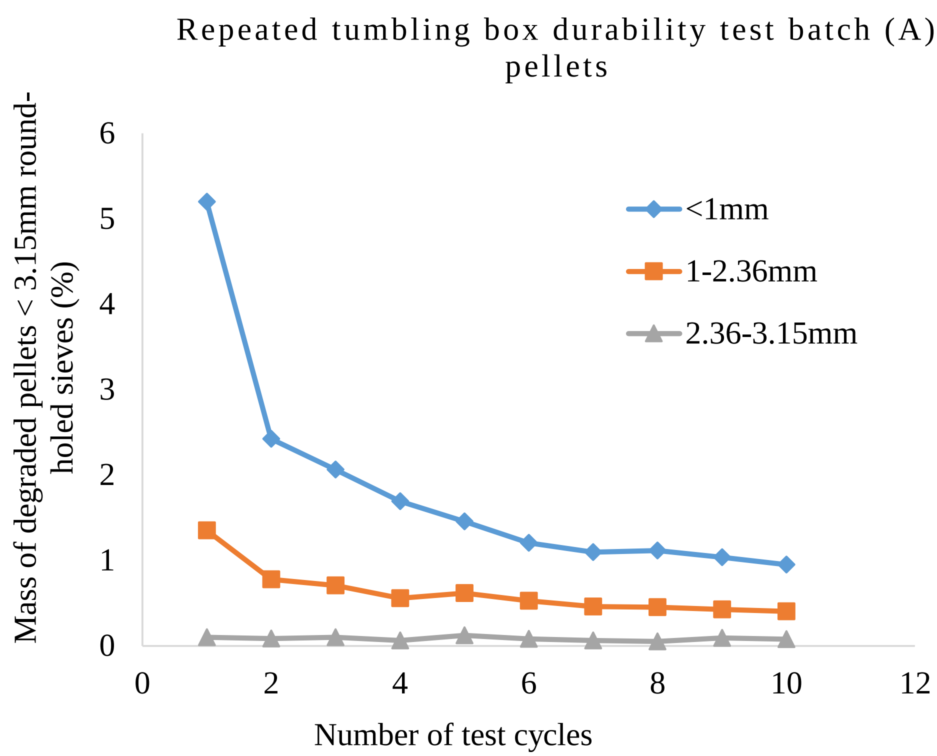


Figure 5.1 Percentage mass of batch (A) broken pellets per tumbling test cycles

The percentage of the original batch (A) sizes of broken pellets fines produced in each tumbling durability test cycles, (cycle = standard 500 revolutions)

The finding in figure 5.1 indicates that pellets durability can disguise to have increase just by tumbling the same pellets sample for three consecutive times and screening it, such that the first pellets durability index (PDI) values, achieved when the pellets are in a virgin state is neglected. The second PDI value replaced the virgin state of the material and is compared with the third pellets durability tests PDI values. Industries may possibly use this method to fake the actual durability of the pellets when it was in virgin state. Therefore, this method may not be preferable for domestic use pellets, where fines are highly undesirable in the boilers because it may lead to serious argument between the pellets producers, distributors and final users, if uncovered by testing similar batch of pellets in it actual virgin test, using tumbling box.

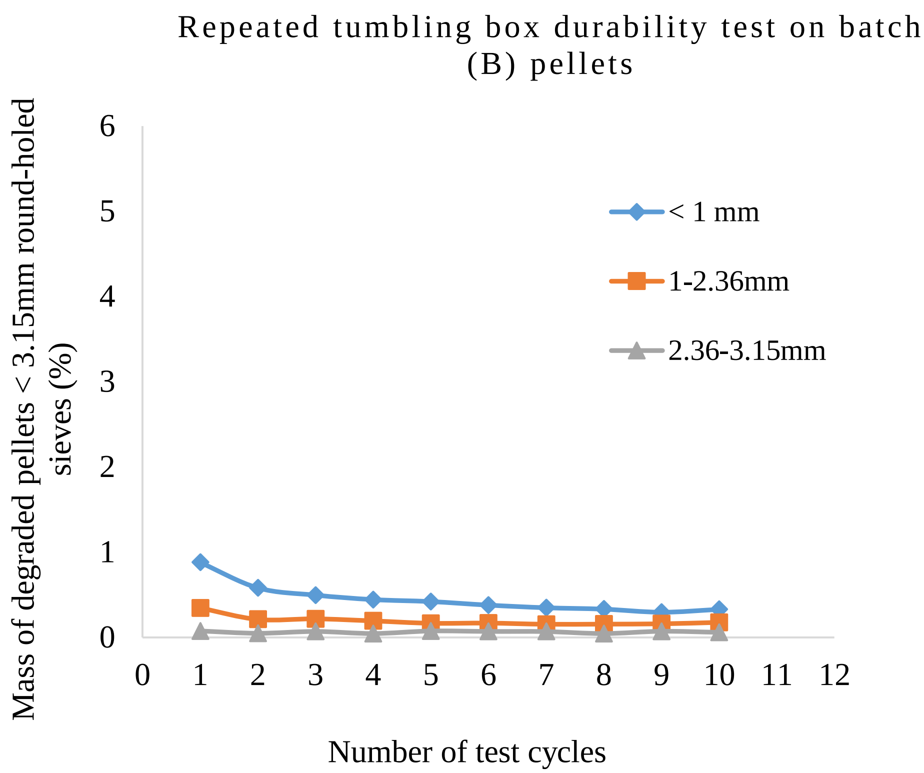


Figure 5.2 Percentage mass of batch (B) broken pellets per tumbling test cycles

The percentage of original batch (B) sizes of broken pellets fines produced from each tumbling durability test cycles, (cycle = standard 500 revolutions)

The two-repeated tumbling box durability test results in figure 5.1 and 5.2 clearly suggest that pellets are more susceptible to abrasive wear in the tumbling test rather than crushing. The first tumbling durability test (i.e. when the material was virgin) in the two results give the maximum number of fines fraction in all three size ranges. The quantity of fines fractions produced in the subsequent tumbling tests decreased with an increasing number of test cycles before eventually steadying out after the 6th test cycles of the same test sample. The tendency to produce mostly very fine attrition products with (about half to two-thirds being below 1 mm diameter) suggests the occurrence of gentle wearing effects on the pellets surface was dominant in the tumbling test. The dominant wearing effect was due to most of the energy being expended in gentle rubbing between particles in the highly-concentrated bed and low impact collision of pellets during repeated tumbling tests. The discrepancies in the amount of fine generated from the two different batches (A and B) of pellets repeated durability test results is a clear indication of different quality effect between the batches.

The conditions of the pellets before and after the ten-consecutive repeated tumbling durability test are shown in a figure 5.3a and 5.3b. The lengths of the pellets have slightly reduced and pellets end edges indicated with red ink patches became very smoother as shown in figure 5.3 b. The red marks on the pellets edges is to indicate the position where most of the rubbing action seems to be highly occurring on the pellets during testing, which was believed to have occurred due to low impact force required to break-down the pellets into smaller lengths with increasing test cycles. This have also proven that the impact fracture energy is lower in tumbling box test than the wearing effect. Thus, this evidence was based on visual or empirical observation along the abraded pellets surface, after the tenths tumbling box durability tests.

(a) (b)

Figure 5.3 Photographs of the pellets, (a) before tumbling & (b) after tumbling tests

5.2.2 Characteristics of Repeated Ligno Durability Tests

Fresh samples of wood pellets from the same batches (A and B) durability were tested repeatedly using Ligno tester. The Ligno pellets durability tests were repeated for ten consecutive times and the fractions of broken pellets fines emanated from each durability test cycle (using same pellets sample from the beginning) was analysed and PDI values of each size ranges were calculated. The results obtained were shown in figure 5.4 and 5.5. The repeated Ligno pellets durability tests were conducted on two different grades of pellets to examine the difference in their mode of degradation and how it differs with the repeated tumbling durability tests results.

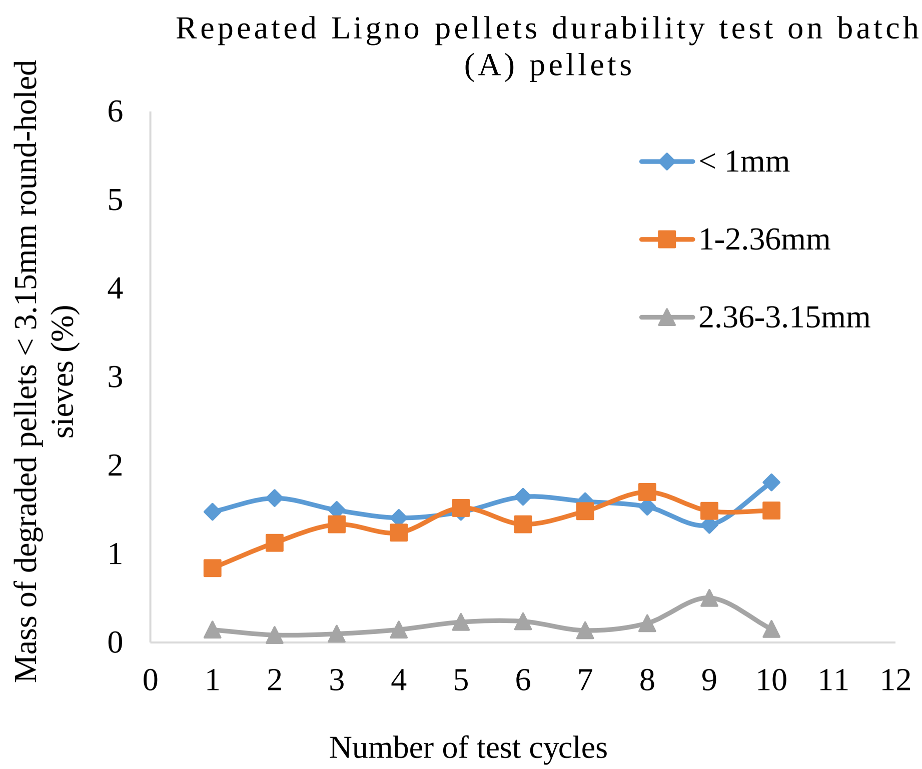


Figure 5.4 Percentage mass of batch (A) broken pellets fractions produced per every Ligno pellets durability test cycles

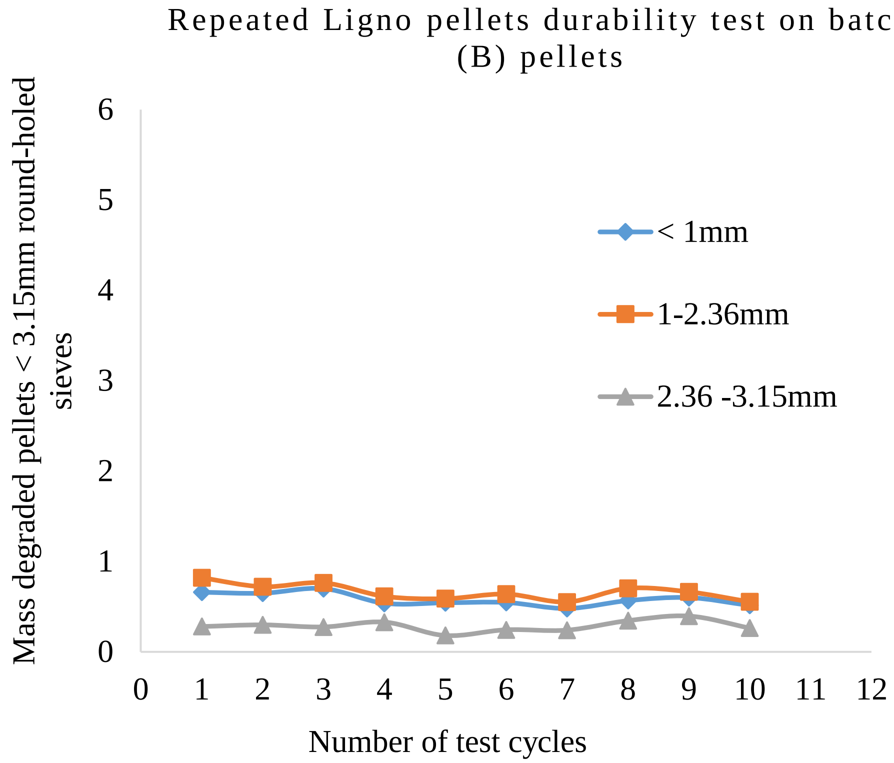


Figure 5.5 Percentage mass of batch (B) broken pellets fractions produced per every Ligno pellets durability test cycles

The results in figure 5.4 and 5.5 present the long run patterns of the two different batches of woods pellets repeated degradation in a Ligno tester. The pattern of both batches of wood pellets breakage in the repeated Ligno durability test was different from that of repeated tumbling box durability tests presented in figure 5.1 and 5.2. The breakage pattern of pellets in the Ligno tester appears to have no sign of decaying in the rate of fines generated from the pellets with increasing number of repeated Ligno durability test cycles, consecutively for ten cycles. Unlike tumbling tests which show a sign of decay in fines production with an increase in tests cycles. The quantity of finer (< 1 mm) and middle (1 - 2.36 mm diameter) ranges fractions of fines produced with increasing number of Ligno durability test cycles are virtually the same. However, the slight reduction in the initial pellets density due to chipping of the pellets was slightly significant in the Ligno tester. Another striking feature is that the Ligno test produced fewer fines in the - 1 mm range, a dominance of fines in the 1-2.36 mm range and a greater proportion of 2.36 - 3.15 mm fines compared to the tumbling box. A third interesting feature is that whilst both tests showed more fines production from batch A, the relative proportion was generally somewhat smaller in the Ligno test i.e. it did not show such a large difference between the two batches.

This showed that the two popular standard pellets durability tests cannot be considered comparable, due to differences in their pellets breakage patterns; the Ligno tester appears to produce a mixture of volume breakage and surface abrasion. The slight irregularity of points in figure 5.4 indicates some lack of absolute repeatability from the results of the Ligno tester, which was a limitation identified by Temmerman et al. (2006b). A stability of the fines produced from one test cycle to the other suggests that the process going on remains the same throughout the repeated tests. This contrasts with the tumbling box, where the absence of mid-sized fines suggests more surface abrasion of pellets and less volume breakage, which is not surprising due to the higher particle impact energy the pellets experience in the Ligno tester. The state of the pellets before and after ten repeated Ligno durability test conditions of the pellets are shown in figure (5.6a and b).

(a) (b)

Figure 5.6 Images of the pellets; (a) before & (b) after ten repeated Ligno tests cycles

5.2.3 **Characteristic of Different Sizes Fractions of Fines Generated from Repeated Number of Rotary Impact Durability Tests**

Repeated rotary impact pellets durability tests were also conducted and the result obtained were compared to the breakage pattern of pellets observed in the two-popular bench scale standard pellets durability testers (tumbling box and Ligno tester). The sample of pellets tested came from the same fresh samples of batches A and B wood pellets tested repeatedly with the tumbling box and Ligno testers. The rotary impact durability tests were also repeated for ten times, using one sample (2000 g) of wood pellets from the first run (test cycle). The repeated rotary impact durability tests were conducted to examine the difference in rotary impact repeated pattern of pellets breakage behaviours and compare the pattern to that of the two popular standard pellets durability testers.

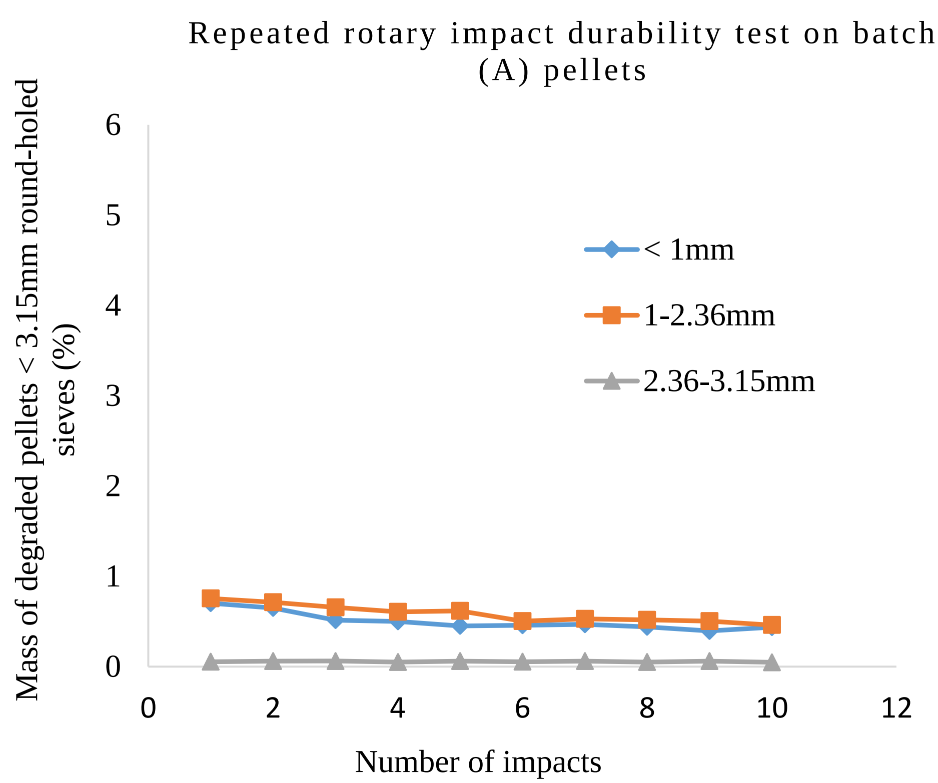


Figure 5.7 Percentage mass of batch (A) broken pellets fractions produced per every rotary impact pellets durability tests for ten consecutive times

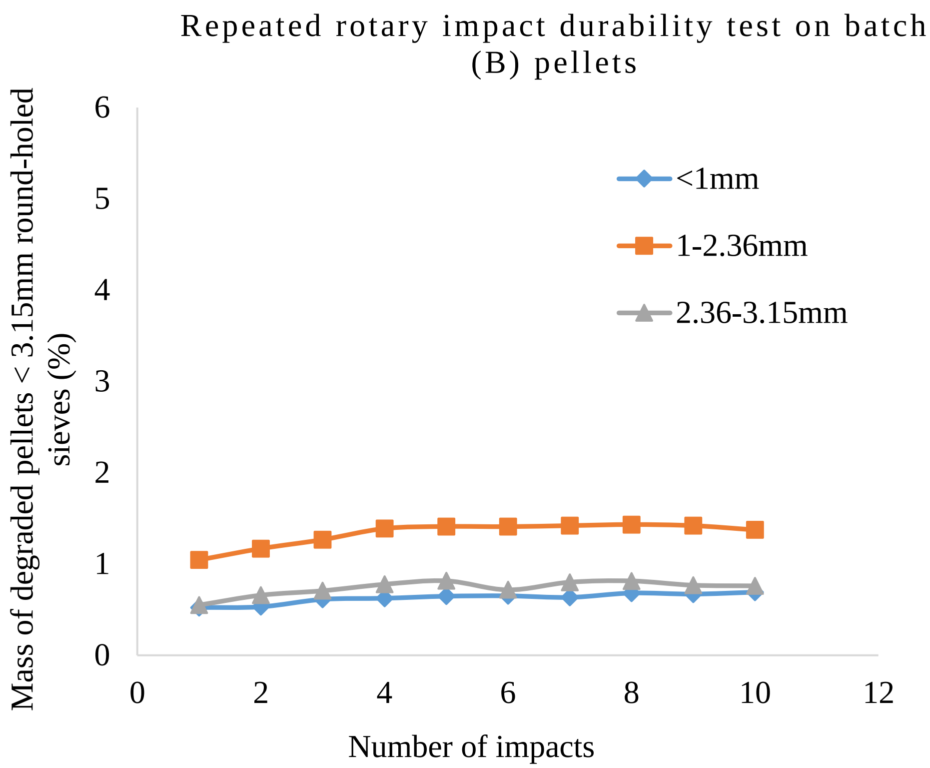


Figure 5.8 Percentage mass of batch (B) broken pellets fractions produced per every rotary impact pellets durability tests for ten consecutive times

In this case of rotary impact durability test, the sample size required for each impact durability test is slightly higher than the once in tumbling and Ligno durability tests. The percentage mass (PDI values) of broken pellets fines (< 3.15 mm diameters) generated from the pellets, as the number of rotary impact durability tests increases was virtually constant in both figure 5.7 and 5.8.

It is interesting to notes that the two figures 5.7 and 5.8 depicts not only the difference in breakage pattern of pellets in comparisons to that of tumbling box and Ligno repeated tests, it also shows a very significant difference in breakage tendencies between the two batches. The breakage pattern of rotary impact has also depicted some similar pattern of pellets breakage in the Ligno tester, especially in the middle-class ranges of fines between 1 - 2.36 mm diameter size fractions, on both batches of pellets. There were some drop-off and a stable breakage level over about the first 4 or 5 impacts in figure 5.7, which is likely due to breakage of the loosely packed particles before the strong once. By comparison, in figure 5.8 the breakage tended to increase a little. Most of the fines produced in batch (A) pellets are within the middle (1 - 2.36 mm) and lower (< 1 mm) class sizes distribution with almost nothing in the large range (2.36-3.15 mm) as depicted in figure 5.7a. This has to do with the pellets quality and contents. However, the breakage into the upper class of fines (2.36 - 3.15 mm diameter) in batch B (figure 5.8) was very much higher than that of batch (A). This was possibly due to the low standard of the pellets batch (A) which makes it break more to powder instead of chipping the larger particles as seen in figure 5.8. In both cases, the middle-class fraction of broken pellets fines (1- 2.36 mm) appears to be floating within a similar region, whereas the lower class (< 1 mm) size range differs. The most obvious difference overall, though, is that in the impact test batch B showed more breakage in total, whereas in the other tests batch A showed more breakage.

The difference is likely due to the difference in quality (strength, durability, and resistance to different mechanical effects) of the original batches of pellets samples used in the experiment. Nevertheless, the combined features of the two graphs (figures 5.7a and 5.8) shows that rotary impact tester can possibly be used in place of the two standard pellets durability testers, in terms of evaluating pellets durability. The surviving pellets above 3.15mm sieve appeared to suffer a huge reduction in length after ten consecutive impacts from the rotary impact tester. This observation corresponds to the anecdotal observation of pellets degradation behaviours in real handling systems for domestic and small industrial pellet deliveries (i.e. pneumatic conveying systems). The before and after appearance of the pellets tested in the repeated rotary impacts tester indicates clearly the existence of a dominant volume breakage pattern in the rotary impact tester as shown in figure 5.8b, a much more severe sort of volume breakage in comparison to what was seen even in the Ligno tester; pellets being broken in two yet producing little of the shattered pellet pieces that were the predominant breakage fraction in the Ligno test.

(a) (b)

Figure 5.9 The of images of wood pellet; before (a) & after (b) ten consecutive repeated number of rotary impact durability tests

5.3 Comparisons of Pellet Durability Index Values from Three Different Bench Scale Pellet Durability Testers

Having seen the breakage characteristics and the broken fine (< 3.15 mm diameter) fractions from pellets tested repeatedly in three bench scale durability testers deployed in this research, it was of interest to understand how the PDI values of pellets (> 3.15 mm diameter) that survived the impact and wear choking during the three-bench scale pellet durability tests correlates or differed. The findings in this section, would contribute to knowledge, especially, to pellets producers and users whose wishes to understand the bench scale tester that provide the most accurate correlation or predict the actual strength and durability of the pellets with different production histories, usable for both domestic and industries, when conveyed in real pneumatic delivery systems.

Therefore, single pass pellets durability tests were conducted using pellets with the same and different production histories across the three bench scale testers (tumbling box, Ligno tester and the rotary impact tester). The pellet durability index (PDI) of the surviving pellets fraction (> 3.15 mm diameter) was calculated using equation (3.5) and the results obtained from each bench scale pellets durability test were compared as shown in figure 5.10, 5.11 and 5.12.

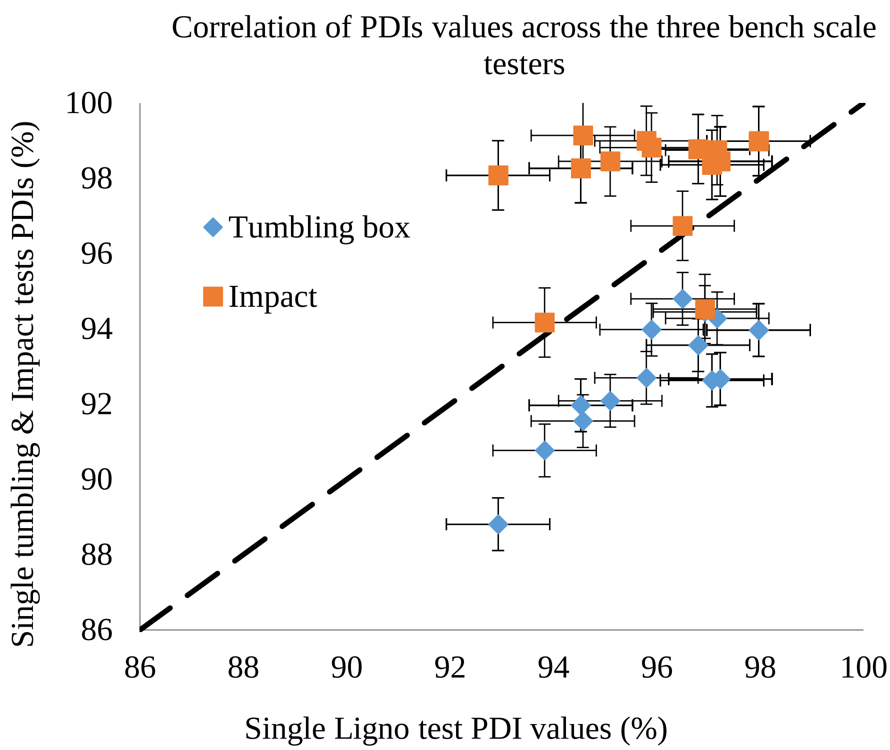


Figure 5.10 Compares the correlation of single run tumbling box and rotary impact against Ligno tests PDI values

The PDI values calculated after each bench scale tumbling and rotary impact pellet durability tests were compared to the corresponding single run Ligno durability test PDI values shown in figure 5.10. The PDI of the two standard testers (tumbling box and Ligno) appears to have some degree of correlation with lower PDI values (below 96 % by Ligno), but with a significant difference in values of about 3 % on the best fit straight line, however, the correlation vanished at the higher PDI values, of industrial interest (above 97.5 % is required for compliance with industry standards). Also, there was some loose correlation with the rotary attrition impact test results (albeit with several severe outliers), but the latter only produces about one-fifth to one-quarter of the sub-3.15 breakage products compared to the other testers. The R^2 values which denote the level of correlation between standard tumbling box and Ligno testers is 0.73, which must be considered poor.

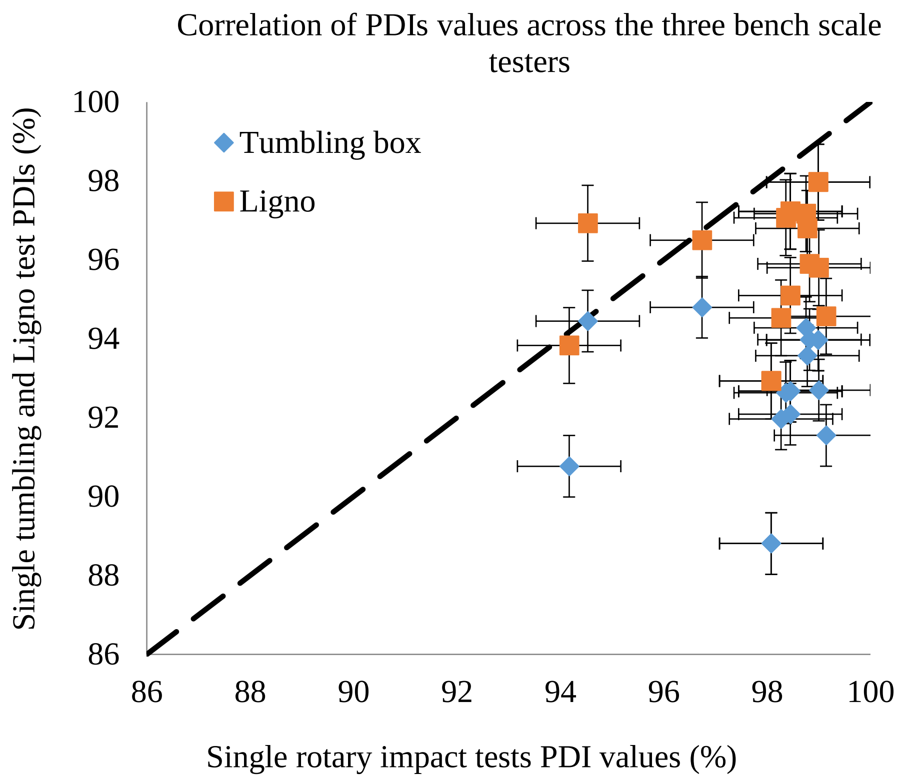


Figure 5.11 Compares the correlation of single run tumbling box and Ligno against rotary impact pellets durability tests PDI values

The same data was represented using the rotary impact test result as the abscissa. This showed clearly that there is no significant correlation between the single run PDI values of the two standards (tumbling box and Ligno tester) and PDI values of the rotary impact tester, figure 5.10. Especially in the region of industrial interests (> 97.5 %) there are very scattered points. The R^2 values were both below 0.05, indicating no correlation.

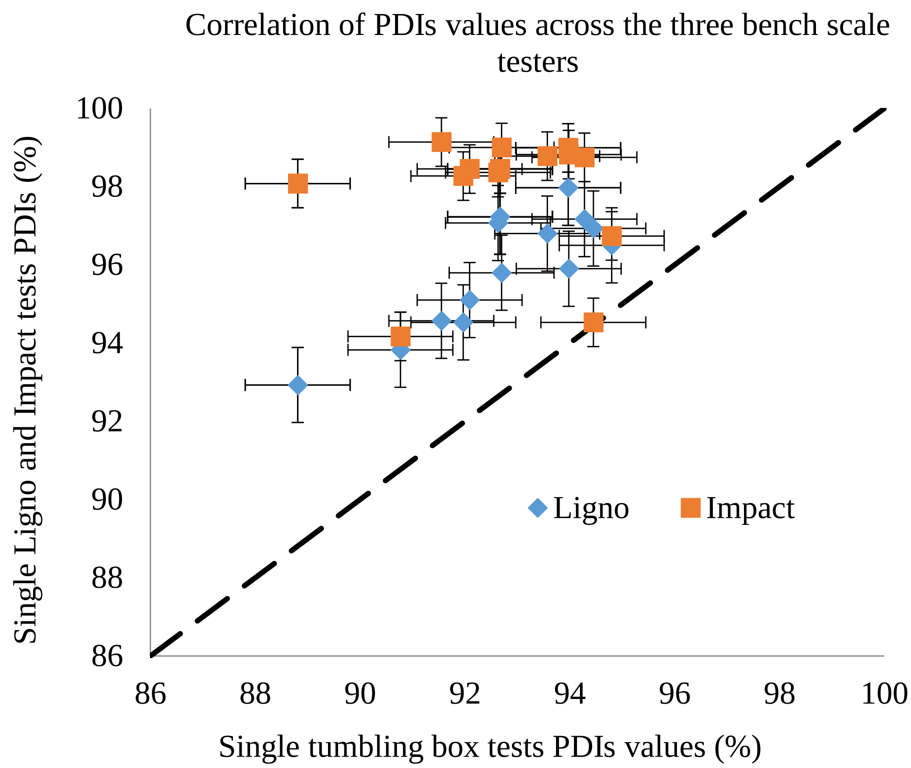


Figure 5.12 Compares the correlation of single run Ligno and rotary impact against tumbling box pellets durability tests PDI values

Observation of the same data using the tumbling box test results as the abscissa simply reinforces the impression gained from the figure 5.9, that the tumbling box and Ligno test have some degree of correlation with lower PDI values (but with significant offset) and poor correlation in the required minimum value for commercial pellets (i.e. ≥ 97.5 %) PDI and that neither correlates significantly against the rotary impact tester. However, the overall poor correlation of the PDI values in the commercially acceptable minimum range (i.e. ≥ 97.5 %) of pellets durability was still a significant contribution to understanding whether the standard testers are comparable in their results, or if either is more consistent than the other. Also, the significant poor correlation of PDI values of standard pellet durability testers (tumbling box and Ligno testers) with the rotary impact durability testers a clear evidence of potentially a major problem with the use of the standard tests, given that previous work to compare the rotary impact test against the breakage in real pneumatic conveying trials showed good agreement (H. J. Abou-Chakra et al., 2004; Bridle et al., 1995), from the Quality in Particulate Manufacturing research project; the rotary impact tester was specifically developed to mimic the mechanisms of breakage in pneumatic conveying pipelines). If the strong correlation between the rotary impact test and real pneumatic conveying system degradation found with materials tested by Bridle hold for pellets, then this suggests that the two standard tests (Ligno and tumbling box) will give a misleading indication of the differences in degradation to be expected in a real pellet delivery between different pellet batches. The anecdotal observation that the pattern of breakage seen in the rotary impact tester was similar to the once seen in real pellet deliveries, gives some support to the belief that the rotary tester better represents the mechanisms at work in real delivery systems.

Other results of the resulting fines (< 3.15 mm) produced from different sets of pellets durability tests are presented in appendix D of this thesis.

5.4 **Summary**

Evaluation of pellet durability index testing techniques: -

- The tumbling box test generates only very fine dust, i.e. small wood particles rubbed off the surface of the pellets. The reduction in a rate of dust production with test duration is very significant and the standard test duration (500 revolutions) finishes while the rate of dust production is still dropping very quickly. This suggests that particles that suffer different rates of surface wear would not display linearly proportional results in the test and that the relative ranking of several different pellets may be different depending on the test duration chosen. Bearing in mind that the test duration appears to have been chosen arbitrarily, this suggests that there would be little correlation between the tumbling box test results and real handling system degradation. The observed degradation trend is clearly the result of unrealistically low velocity of collisions in the test compared to a real pellet delivery operation. Nevertheless, it was found to be the most repeatable of the three tests.
- The Ligno test was slightly less repeatable than the tumbling box test. It also generated a different size class of fines, appearing to be mostly either parts of shattered pellets, or relatively large pieces knocked off the ends of pellets. This might suggest that the impact velocity (currently unknown and hard to measure) in the Ligno tester may be

excessively high compared to the velocity of impact in a real pellet delivery system. It had the advantage that the degradation tended to be much more linear with test duration, which would indicate an expectation that the relative ranking of different pellets would be more likely to remain the same irrespective of the test duration chosen.

- The rotary impact tester generated a different pattern of breakage again. It produced less fine dust than the tumbling box test, but larger broken particles < 3.15 mm than the Ligno tester. Instead, it produced more intermediate sized attrition products (thought to be from damage to the ends of the pellets) but also more pellets being broken down into smaller pieces, but not passing through the sieve that classifies them as "fines". The set-up of this tester to produce a closely controlled impact velocity broadly representative of that in the real pellet delivery system, and the previous work of (Bridle et al., 1995) that successfully related the rotary impact test results to particle degradation in pneumatic conveyors for other materials, leads to the expectation that the breakage pattern of this tester is likely to be more representative of the real delivery system, but this remains to be tested. It was the most repeatable of the three tests.
- The fact that the relative ranking of different pellet batches changes between the rotary impact test and the two standard testers, gives a great lack of confidence that the standard tests are likely to have any realistic meaning in terms of indicating the breakdown to be expected in a real pneumatic delivery.
- The difference in the way the pellets breaks in the three different tests reflects the difference in the impact and collision processes present in them.

Chapter 6. Prediction of Wood Pellets Degradation in a Large Scale Pneumatic Tanker Truck Delivery System

6 Introduction

Pelleted biomass materials are brittle material that often breaks down to generate fines and dust due to moisture interference or impact and wear along the transport chain or handling system. In this chapter, the detailed analysis of the large-scale pneumatic blow pellet degradation experiment conducted were presented. The pneumatic pellet degradation experiment was conducted in accordance with the common industrial pellets delivery practice for domestic use, which is where fines are highly unwanted. The blown delivery experiment was conducted to assess the level of pellets degradation in a large-scale pressurised tanker truck delivery system. The experiments were carried out in two phases: the first phase involves dumping of air from the pressurised tank at lower blow delivery pressures, which occurred in the first delivery tests due to inability of the driver to control the electrically automated valves, during the blow delivery tests. While in the second phase, the pellets blow degradation tests were conducted using the full pressurised tank air (without dumping air from the pressurised tank), even at lower blowing tank delivery pressures. The pneumatic pellets degradation experiment was set-up to investigate the influence of blower operating parameters (i.e. blowing pressures, conveying air and particles velocity, feed rate and pipe length) on change in pellets degradation observed during deliveries. In both cases of the pneumatic deliveries, the targeted tank and manifold blow pressures used were 0.3 bar, 0.5 bar, 0.8 bar and 1 bar.

These values of the blowing pressures were selected for the large-scale pneumatic blow pellets degradation tests, using pressurised tanker truck delivery system, were based on several consultations with the motivated research collaborator (Forever Fuels Ltd), who from time to time receive related problems of pellets degradation and complaints of excessive fines (< 3.15 mm) content in the pellets delivered to their domestic boilers customers. The customers attributed the excessive pellets fines content in their stores to poor quality of the pellets or delivery practices. This has echoed, the needs for an evidence to support the hypothesis that says that optimum blow conditions, that minimises pellet degradation, is to blow as high rate as achievable in the delivery (for any given blower used). This hypothesis was reached based on other previous reviewed work on physical relationship for optimum delivery conditions stated in the bullet points below: -

- Decrease in particles velocity, was a well-known factor that reduces particles degradation (Bridle et al., 1995).
- Increase in blowing pressure reduces the inlet air velocity (and hence pellets velocity) due to air compression, (Boyle’s law); since, the air velocity at the pipe end remain virtually constant and the average particles velocity reduces.
- High transfer rate could leads to high pellet concentration in the pipeline, maximising the “shielding” effect as seen in pipeline erosion test, which was presumed to have a similar effect on particles degradation (Macchini et al., 2013).
- High concentration of particles reduces the particles velocity due to increased “slip velocity” between the particles and air and hence reduces particles breakage (Gorman et al., 2012).

These hypotheses depend on a degree of assumption that similar effects seen in pipe erosion would also occur in degradation. However, this has not been proved in practice; the desire to make the delivery as high a rate as it can be achieved is counter-intuitive to many people that are not versed in the nuances of pneumatic conveying, so many pellet customers often request transfers be made slowly. Evidence from a full-scale simulation of real industrial pellets delivery system would prove the hypothesis and support good practice in the industry.

6.1 The Pneumatic Blown Delivery Experimental Objectives

A significant programme of experimental work will be conducted to examine the difference in blow conditions that varies pellets degradation in full-scale pneumatic blown delivery system. The results obtained from the full-scale pneumatic blown pellets degradation tests would be compared to that of parallel bench scale pellets durability tests conducted, using virgin samples of pellets from the same batches across the three bench scale testers. The outlines of the full-scale pneumatic blown delivery test are given in the following bullets points: -

- To use an existing pressurised pellets pneumatic tanker truck delivery system and design a full scale receiving bin similar to common industry practice
- To determine whether the usual ranges of blown operating conditions have any significant effect on the levels of pellets degradation in real handling
- To undertake parallel tests with the same batch of pellets samples used for the blown delivery, and run them through the three-bench scale pellet durability testers
- Consistence flow and operation of the blow tank was some extend achieved
- The point is that the facilities provided on the tanker for the driver to use, to control the flow rates of solids and air, are not very good and therefore it was hard for the operator to establish known, repeatable and stable conditions. In particular, the flow of air in the pipe could only be adjusted by venting some of the air from the system between the blower and the inlet of the conveying pipeline, but there was no means for measuring the flow rate of the vented air so the flow rate of air in the pipeline under venting conditions was uncertain and probably not very repeatable. Even without venting, there was no means for measuring airflow so the flow rate was dependent on the accuracy of the engine speed governor, for which there was no accurate monitor. Similarly, in regard to solids flow, the control was crude. The driver was forced to try to use the pellet outlet valve to "throttle" the flow of pellets, but this is not a very efficient or reliable means for controlling solids flow rate. On land, based systems the "blow tank air ratio" is normally used, i.e. adjusting the amount of air going into the tank as a percentage of the total air flow, however that means of control was not easily possible on the tanker. Hence, the only means available was to throttle the pellet valve. The positioning of the valve was very crude, from two push buttons on the tanker control panel, which lit progressively a row of lights giving some indication of valve position, but this was not calibrated in any way. In any event, using the position of a butterfly valve to try to control flow of large particles is not very repeatable and likely to lead to hang-ups, surging and unsteady flow.

6.2 Experimental Approach

The following safety precautions measures were observed before and during the actual full-scale pneumatic blown pellets degradation experiments, conducted using a pneumatic pressurised tanker truck delivery system.

- An initial safety blow tests were conducted on the pressurised tank at 2 bars (gauge) pressures before the actual pellets delivery test. The tanker has an inbuilt pressure relieve valve, which is main for venting out unwanted excessive air pressure from the pressurised blow tank to keep it within ≤ 1 bar (gauge). The initial safety blow test was conducted to determine error margins of the pressurised blow tank.
- The maximum blow tank pressures were limited to 1 bar (gauge) pressure; which is in line with the common industrial standard pellets delivery practice.

6.2.1 Material and Methods

The following test facilities and material specification were procured for designing and building of the test rig and blow testing:

- Receiving hopper plate type: stainless steel with 2 B finishing (giving smoother inner surfaces that can ease retrieving of the entire degraded pellets).
- Pipe bore diameter (4 inches) including the flexible pipe, approx. 6 m long and 1-meter-long Perspex pipe with the same 4 inches' diameter (to allow inspecting and filming of the pellet flow velocity), before the 90˚rigid pipes bend.
- An existing 6-wheel pressurised blow tanker truck (from Forever Fuels Ltd)
- Rotex screening machine (small industrial scale)
- Impact mat, which was hung at about 50 cm away from the wall inside the receiving hopper.
- Approximately, 28 tonnes of wood pellets from similar batches were used.
- Pressure gauge: Two inbuilt pressure gauge attached to the rear end of the tanker. Another one pressure gauge was also installed along the blowing pipeline, for measuring the blow line pressures.

- Load cells: a load cell was mounted under the receiving hopper to record the weight of the pellets received in the hopper during the blow test.
- Instrumentation and data logging equipment: pressure gauges, air flow meter and stopwatch for measuring displayed manifold and tank pressures. The airflow velocity will be measured at 20 seconds' intervals of the entire blow delivery period.

6.2.2 **Receiving Hopper Design (Pellet Store Design)**

A receiving hopper was designed and constructed using 2B finishing stainless steel in accordance with the guideline provided for small-scale domestic pellets stores designed practices. The geometries of the upper square section of the receiving hopper area are 1.2 m × 1.2 m. The total volume of the hopper designed is about 2.3m^3. The volume is large enough to accommodate more than 1 tonne of pellets, which is in line with the commercial standard pellet store design practice, that stipulated that the usable space of any wood pellet store must not exceed 2 / 3 of its entire volume (Stelte, 2012). The receiving hopper was equipped with impact mat, suspended 50 cm away from the side wall. The impact mat prevents the blown pellets impinging on the opposite wall, which may lead to increase in pellets degradation, other than the bend, during the blow delivery tests. A single hatch (250 mm × 250 mm door) was also created on one side of the hopper to provide easy access to the entire lot of blown degraded pellets (including all the fines and dust), retrieval from the receiving hopper. The access to the entire blown degraded pellets has also eliminated any form of sampling errors that could occur in the data or difficulties in reclaiming the adhered dust on the walls, which was achieved through manual brushing.

The hopper was suspended directly above the Rotex screening machine inlet (opening), as shown in figure 6.2, to ease the discharging of the whole lot degraded pellets, collected inside the receiving hopper, into the sieving machine. The degraded pellets were fed directly into the sieving machine by controlling the slide valve attached to the hopper outlet. The schematic diagram of the hopper designed for the pneumatic blow pellets degradation experiment is shown in a figure 6.1. Details of the hopper design are also shown in appendix E.

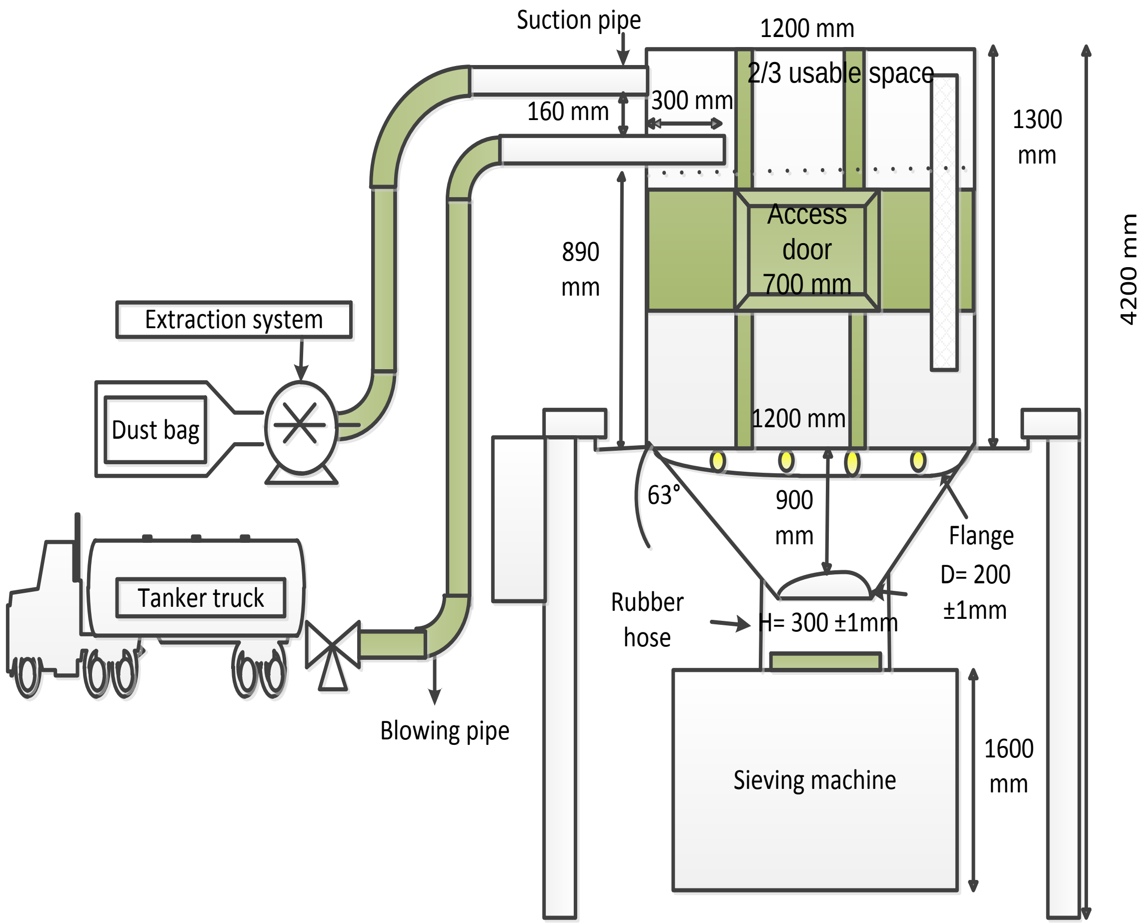


Figure 6.1 The schematic diagram of the receiving hopper design geometry and the set-up for full-scale pneumatic pellets degradation experiment

6.2.3 Sampling, Loading and Size Analysis Facilities

Sampling is one of the important factors that requires being given an adequate attention if accurate results were to be achieved from bulk particles degradation tests (H. Abou-Chakra et al., 2004). For the fact that wood pellets are regular in shape and sizes (6 mm or 8 mm diameter and ≤ 40 mm length), the smaller fines within the pellets could segregate during loading to cause sampling problems or inside the pressurised tank during transport or discharge. Pellets can segregate within the tank to inconsistencies between the input and outputs batches of the same pellets. Therefore, samples of wood pellets were taken on a regular basis during screening and loading of the tanker truck in accordance with the ASTM E300-03 standard, at the site of forever fuel Ltd. The samples of the pellets (14 samples with each sample bag containing 4 - 5 kg per bag) taken during loading, were further screened and sample in accordance with EN 14778:2011 and used for parallel bench scale durability tests across the three bench testers. The sampling procedure for the first and second batch of the pellets used in the blow tests were the same. However, the entire bulk of degraded pellets received in the hopper, after each blow test, was subjected to machine screening to separate the surviving (> 4.75 mm) from the broken fines (< 4.75 mm diameter) fractions. The broken fines were further screen into smaller size fractions using smaller sieve diameters of the same Rotex screening machine.

6.2.4 **Connections**

All the pipeline was connected in accordance with the industrial standard pneumatic pellets delivery practices. The vertical section of the blow rigid pipe (2.3 meters long) was connected to the 90-degree bend (with 300 mm radius) leading to the attached flange on the receiving hopper. A 1 m length transparent Perspex pipe, of the same diameter, was also installed within the rigid pipeline and the two ends of the Perspex pipe was connected using a "Eurac" connectors (which ensures perfect concentricity of the pipe ends) between the two half ends of the rigid blow pipelines, that fed in the pellets into the receiving hopper as shown in figure 6.2. A single 4-inch bore and 6.5 m long flexible hose pipe was then connected between one end of the pressurised tanker truck to the other end of the rigid blow pipe, using male and female cap lock Storz 110A connectors.

The suction line rigid (2 meters long and 100 mm bore steel) pipe attached to the second rigid bend and flange on the receiving hopper have similar connections flexible pipe dimension to the suction to the mobile dust extraction system. A large dust collection bag was also connected to the dust extraction machine to capture all the dust during blowing, in accordance with the commercial pellets delivery practice as shown in figure 6.2. The mass of the dust collected in the bag was determined, after each blow test, using a weight balance with 0.001 g precision.

A single bend was installed on the blow pipeline for understanding how each bend contributes to pellets degradation during the deliveries, at different blower pressures, and allows scaling of the damage, contributed by one bend to several numbers of bends in a large-scale blow system. The used single bend would also allow comparisons of the results to that of single breakage events that seems to occur in a rotary impact tester. All the connections were broadly consistent to the most frequent practice in a normal pellets delivery site. Photograph of the pneumatic pellets degradation experimental set-up are shown in figure 6.2.

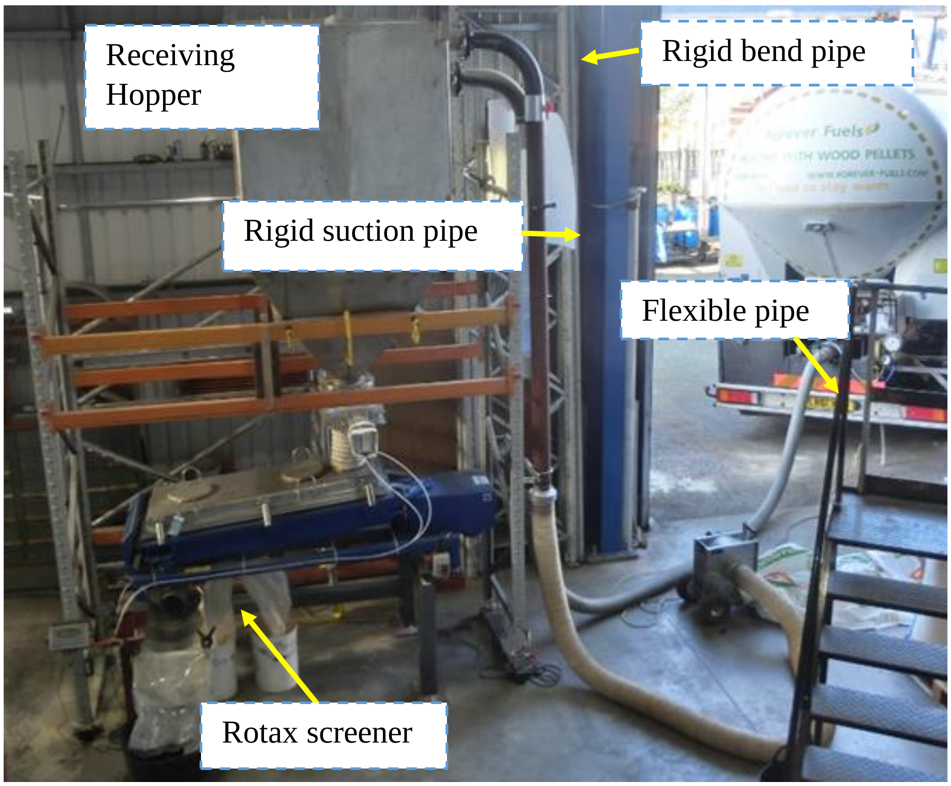


Figure 6.2 Experiment layout for the pellets pneumatic blow degradation test

6.2.5 Pre-Conveying Operational Factors

The following operational factors were considered in setting up the conveying blow test rig. The factors considered are part of the commercial pellets pneumatic blow delivery guide stipulated by Bradley (2014) which states as follow:

- The conveying pipeline geometry, i.e. flexible pipe length (6 m) and number of bends etc.
- Process conditions, such as conveying air velocity and solids concentration in the pipe.
- The overall transients process i.e. brief start-up and shut down processes.

The first two variables have been considered to some extent during the test rig setup; while the third option was taken into account during the actual conveying of the pellets.

6.2.6 Conveying Processes

The following guidelines were observed before the actual pellets conveying processes to ensure consistency in the pellets quality before discharging it into the pipeline. The guidelines are part of the important prevent measures against problems that are likely to occur in any biomass pellets blow deliveries due to:

- Improper screening of fines during loading, which can increase the chances of having more fines fed into the tanker.
- Variation in batches of pellet quality loaded, which can consequently affect the breakage behaviour.
- The level of pellets or fines segregation during loading and unloading of the pressurised tank. This was one of the most difficult tasks to achieve because of limited access to the interior part the tanker.

An only limited sampling of the pellets from the tanker outlet was undertaken to ensure consistency in the pellets due to possible problems of segregation that might have occurred during transport. The sampling was limited because it was very difficult to achieve without losing some of the required usable pellets. However, it is important to note that the samples of pellets collected during loading were used for parallel bench scale pellets durability tests, for comparisons the bench scale results and the corresponding full-scale pneumatic blow degradation tests.

The actual pneumatic pellets blow degradation test was conducted based on the experimental plan shown in table 6.1, after undergoing all the pellets quality satisfactory inspections. The key variable was the blowing pressure used to make the delivery.

Table 6.1 Shows the experimental plan for the sixteen runs pneumatic blow pellets degradation tests

Pellets layers	Pot 4	Pot 3	Pot 2	Pot 1
Top	0.8 bar	1 bar	0.5bar	0.3bar
Middle 2	0.8 bar	1 bar	0.5bar	0.3bar
Middle 1	0.8 bar	0.8 bar	0.8bar	0.8bar
Bottom	0.8 bar	1 bar	0.5bar	0.3bar

The term "pot" refers to the outlet from the tanker, of which there were 4 in number.

The experiments were designed to explore the cause of variation in pellets degradation due to change in positive blown deliveries pressures from pressurised tanker trucks. Each part of the experiment was designed to explore some key factors that were anticipated to be responsible for changes in pellets degradation due to change in different blowing pressures. The main factors to be considered in this test included pellets segregation in the tank, blowing pressures effect, tank delivery pot variation and pipe lengths (the latter would be explored in further tests by changing the number and length of delivery pipes). This would help to explore the ‘‘counterintuitive behaviour’’ of pellets degradation expected in an industrial tanker truck delivery system, based on theories of material pneumatic blowing systems as stated by the earlier researchers.

(a) Pellets segregation in the tanker: to investigate how pellets or fines segregates within a pressurised tank might vary the amount fines observed in the receiving end hopper after delivery. The pellets inside the pressurised tank were assumed to be arranged in descending order of top, middle 2, middle 1 and bottom layers. The assumption is that the little fine that manage to escape through the sieve aperture corners during screening or created due to pellets to pellets attrition inside the tank, would eventually descend down to the bottom layer through the voids created within the pellets during transportation from production point to the users (so-called "spontaneous segregation" of fines) (H. Abou-Chakra et al., 2004). Based on this assumption, the pellets in the tank pot number 1 (where all the screened pellets are fed into the tanker may possibly have the highest fines concentration due to sedimentation). Therefore, the pellets in that pot were blown at similar presumed standard blowing pressure (0.8 bars) as shown in table 6.1. Also, the same blowing pressure was used across all the pots in the “middle 1” layer, to explore the difference in fines levels between delivery pots.

(b) Delivery tank pressures: The desirable to explore the hypothesis that optimum pellets blowing conditions could be achieved at the highest blowing pressures, due to the expected high density of the pellets in the pipeline, which could result in shielding along the bend and in return reduced pellets degradation. As discussed above, this is a contentious issue with pellet customers for domestic pellets use, where fines content is highly undesirable due to the resulting problem of poor efficiency in the boiler. Often, customers express a preference for longer delivery times, which occur at lower blowing pressures. Their assumption is that low blowing delivery pressure and corresponding low delivery rate should result in low impact velocity of the pellets, which would decrease pellets degradation during the delivery. This misconception arises because of a natural tendency to compare with the delivery of oil; in a single-phase liquid, a lower delivery pressure and longer time do indeed result in slower movement of the fuel in the pipeline. By contrast, in a pneumatic delivery of particles, the mass flow rate of the fluid is unchanged when the fuel delivery rate is reduced, and the lower pressure causes the volume flow rate to increase. Previously, there was no definitive data available to evidence optimum minimum blow pressures or maximum blow pressures for pellets deliveries using pressurised a tanker truck. Although 0.8 bar blowing pressure recommend in most standard guides on industrial tanker delivery (UK Pellet Council, 2012), this was not based on any experimental evidence specific to pellets. Therefore, four different blowing pressures (1 bar, 0.8 bar, 0.5 bar and 0.3 bar) were selected to be tested across the tanker pots. The choice of the blow pressures was based on extensive consultation with tanker truck drivers that constantly deliver pellets to domestic stores and large pellets users.

(c) Pots arrangement: the pots were numbered in ascending order (1, 2, 3 and 4) from the driver’s cab, such that most of the high blow delivery pressure were carried out in the long-distance pots (1 and 2), so that the distance may be compensated with low blow pressure that are mostly within tank pots number (4 and 3) which are closer to the receiving point. However, in the second batch of the repeat test, the blow pressures were reversed in the bottom layer pots, to explore the same effect.

(d) Effect of delivery distance on pellets degradation at different blow pressure was also experimented using the pressurised tanker truck delivery at Forever Fuel Ltd main site due to absent of large store and sample required. One of the driver that took part in first blow test at The Wolfson Centre undertook longer blow delivery trials to explore other variable (increase in delivery distance) that were not achieve in the first set of blowing pellets degradation tests and to clarify whether the results from the first trials showed consistent and useful data. The longer blow pellets degradation tests were conducted by adding or increasing the numbers of blow pipes lengths and blowing the same blow pressures used in the first short delivery tests conducted at the Wolfson Centre. The lengths of the flexible pipes were increased in the order of 1 pipe = 9.5 m, 3 pipes = 20.8 m, 5 pipes = 38.6 m and 7 pipes = 47.4 m pipes respectively.

6.2.7 Instrumentation and Data Acquisition

The readings of the blow tank, manifold and pipe inlet air pressures were monitored from their respective gauges and recorded at 20-seconds intervals of the entire delivery period, using a stopwatch. The mass flow rates were determined based on the quantity of pellets received in the hopper at 20-second intervals of the same entire blowing period, measured using stopwatch. The mass of the pellets received in the hopper was monitored and recorded from the weigh-beams balance attached to the receiving hopper frame.

The air flow rate was also measured and recorded at every 20 second interval of the entire pellets blow period, using PCE - 423 air flow meter. Some of the data were recorded manually by four different individual co-researchers and extreme care was taken to avoid the error of parallax or zero errors from the meter gauges' readings during the data collection in each delivery.

The pellets velocity was filmed through the transparent section of the Perspex pipe installed within the rigid blow pipeline using a high-speed digital camera (CASIO EXILIM EX-ZR200), set at 1000 frames per second. The average velocity of the pellets recorded videos tracks at different blowing pressures (0.3 bar, 0.5 bar, 0.8 bar and 1 bar) were analysed using Mat lab software. The results obtained from the analysis were compared to the level of pellets degradation observed at corresponding blowing delivery pressures.

6.2.8 Determination of Degraded Pellets Fractions after Each Full Scale Pneumatic Pellets Degradation Tests

The entire batch of the degraded pellets blown at each tank delivery pressures (0.3 bar, 0.5 bar, 0.8 bar and 1 bar) were retrieved in a receiving hopper for sieving. The degraded pellets, in the hopper, were screened into different sizes using a Rotex (Model 112) screening machine in accordance with EN15149-1:2010 standard. The first part of the screening was to separates the whole lot degraded pellets into surviving (> 4.75 mm diameter) and broken fines (< 4.75 mm) pellets fractions. The broken fines fractions were further separated into smaller size ranges of particles in the order of 4.75 - 3.15 mm, 3.15 mm - 2.36 mm, 2.36 - 1 mm and < 1 mm diameters. The screening was performed using 4.75 mm, 3.15 mm, 2.36 mm and 1 mm wired-mesh diameters sieves. During the screening process, the stocked finer and dust along the corners of the receiving hopper were manually brushed down to pass through the sieving process. The manual brushing process was aided by the present of the hatch (small door) provided on one side of the receiving hopper. The mass of the screened surviving and broken pellets fractions (including fractions of each fine, under 3.15 mm diameter) was measured using a large weigh balance with 0.05 kg precision. The pellet durability index (i.e. percentage mass of the surviving over the broken pellets frictions) was calculated using the bench scale formula, for calculating pellet durability index (PDI) shown in equation 3.5. The calculated PDI values of the surviving and broken pellets fractions were analysed and presented in the results and discussion section.

6.3 Results and Discussion

The data obtained from the pneumatic blowing pellet degradation experiments were analysed and results were presented. The results obtained were analysed based on the effect of the tank and manifold blowing line pressures, particles and conveying air velocity, mass and volumetric air flow rates on pellets degradation.

6.3.1 The Effect of Conveying Blow Air Pressures on Wood Pellets Degradations

The original plan of this experiment was to use the full output of the blower on the tanker truck, for the conveying and adjust the conveying pressure by controlling the flow rate of pellets in the pipeline. However, in the first series of tests, there was a misunderstanding; because it was quite difficult to control the flow rate of pellets out of the tanker (the discharge valve was positioned by an electric positioned with a very imprecise adjustment). The driver vented some of the blower output to the atmosphere as a more convenient means of achieving the two lower conveying pressures (0.3 and 0.5 bar). This is referred to as "dumping air" but in the second series of tests, no air was vented (no air dumping). The results of the two tests condition differ, not surprisingly. The targeted tank and manifold blower conveying air pressures during the blow tests are (1 bar, 0.8 bar, 0.5 bar and 0.3 bar). The resulting levels of pellets degradation versus blow delivery pressurise, of the two-pressurised tank air condition are presented in figure 6.3 (vented) and 6.5 (unvented).

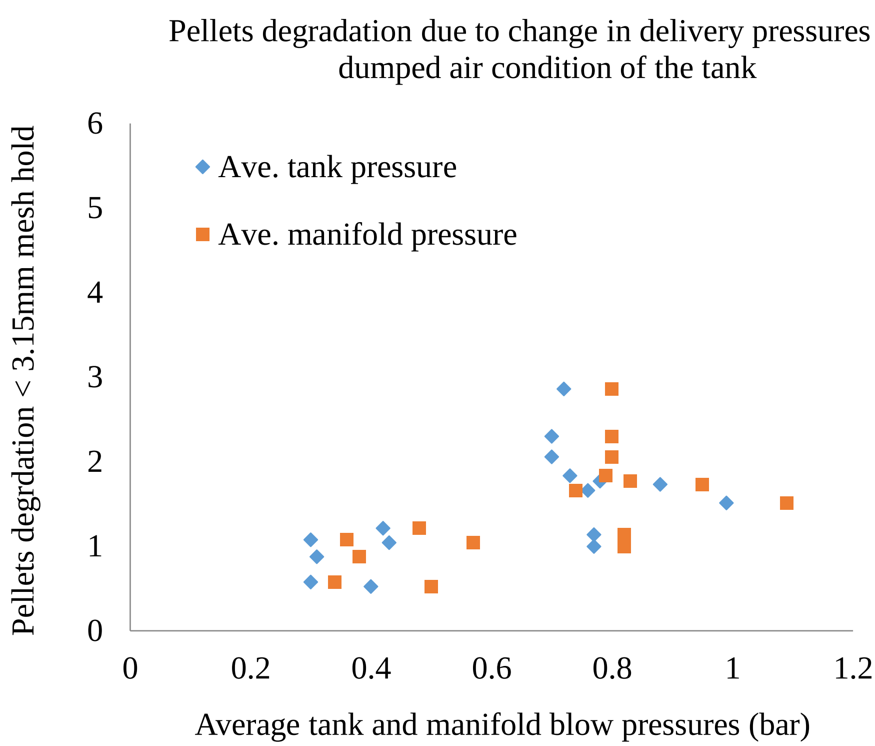


Figure 6.3 The change in pellet degradation due to corresponding change in tank and manifold blow pressures *(in an air dumping condition of the pressurised tank)*

Note that the "manifold pressure" is the pressure in the air manifold between the blower and the tank. Neither of the pressures shown is the same as the pressure at the inlet to the pipeline.

The result shown in figure 6.3 depict changes in pellets degradation due to change in the average conveying tank and manifold air pressures, in an air dumping condition of the pressurised tank. The level of pellets degradation observed in the lower region of the average blow pressures between (0.3 bar - 0.5 bar) appears to be slightly lower than that of some pellets blown at high delivery pressures. This benefit was attributed to excessive air dumping from the pressurised tank that resulted to lower pellets impact velocity at lower blowing pressures deliveries. Though, in some instances, the pellets degradation appears to be low at high blowing pressures, with some points across the high blowing pressures. The scattered nature of the results was believed to have occurred due to transient or occasional slugging flow condition of the pellets along pipeline before impacting bend. The level of pellets degradation observed in this case was a bit counterintuitive because the expectation is that high pressures reduces the air velocity at the line inlet, reduce pellet velocity in the pipeline and more "shielding". The occasional slugging that occurred at the highest pressures was because of air velocity becoming too low to keep the pellets properly suspended. Then, when the slug clears, the tank pressure drops suddenly, giving high air velocity for a period.

Similarly, the change in pellets degradation due to a corresponding change in average blowing pressures (in an air dumping condition of the pressurised tank) was analysed based on delivery tank pot numbers and the result obtained are shown in figure 6.4. The analysis was carried out to understand the degradation of pellets blown from each specific tank pot varies with the change in the blowing tank and manifold air pressures. This might possibly give an information of pellets fines segregation tendency within the pressurised tank.

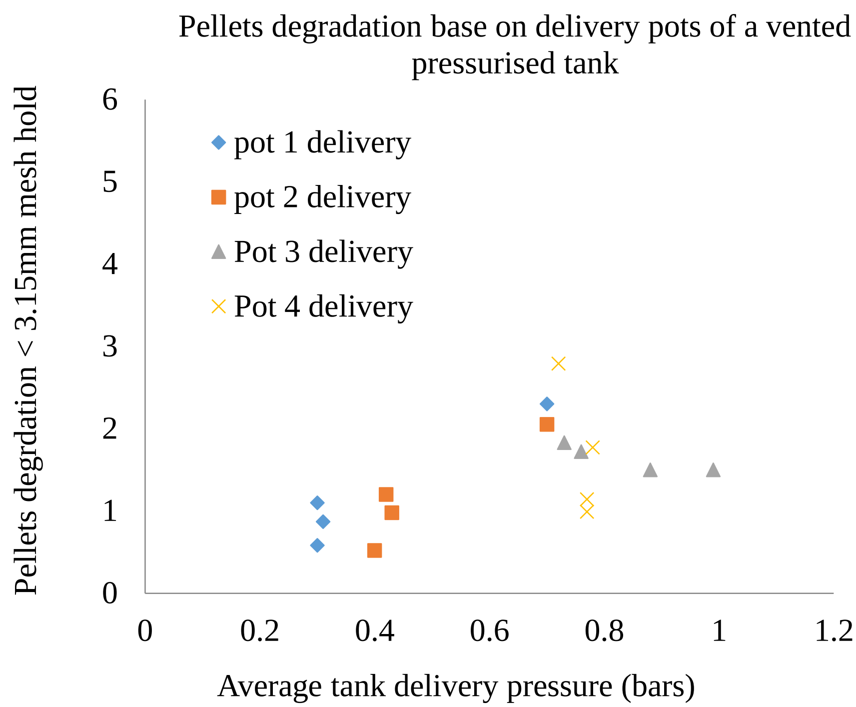


Figure 6.4 The percentage of pellets degradation from different delivery tank pot versus change in blowing pressures *(in an air dumping condition of pressurised tank)*

The change in pellets degradation from different pressurised tank pots was compared to their corresponding change in average blowing pressures as depicted in figure 6.4. The pattern of pellets degradation observed in figure 6.3 appears to correlate significantly with the mode pellets degradation analysed specifically based on delivery tank pots number as shown in figure 6.4. The two results were achieved in an air dumping condition of the pressurised tank during the pneumatic deliveries. However, the pellets blown from pot 1 and pot 2, at lower average delivery pressures clearly appears to have the lower level of pellets degradation compared to pellets blown at high delivery tank pressures (0.8 bar & > 1 bar) from the same pots. Similarly, some level of decrease in pellets degradation was observed from the pellets blown at high flowing pressures in pots 3 and 4, with exception of pellets degradation observed in the 16th run at pot 4, which was believed to have higher concentration of fines and dust due to settle proportion of segregated fine along tank bottom that got discharged when the tank is about to be total emptied. The believed is that the low level of pellets degradation observed at the lower blowing pressures was due to excessive air venting that seems to occur at lower blow tank deliveries pressures.

6.3.2 Change in Pellet Degradation Due to Corresponding Change in Tank Blowing Pressures (In an Unvented Air Condition of the Pressurised Tank)

In this case, the same batch of wood pellets was also blown at different delivery pressures (in an unvented pressurised tank conditions). The results obtained were analysed based on pellets degradation versus change in an average tank and manifold blow pressures across the entire delivery tank pots numbers and the second result was analysed based specific delivery tank pot numbers, of the tanker truck, in which the pellets were blown. The results obtained in both case is depicted in figure 6.5 and 6.6 below.

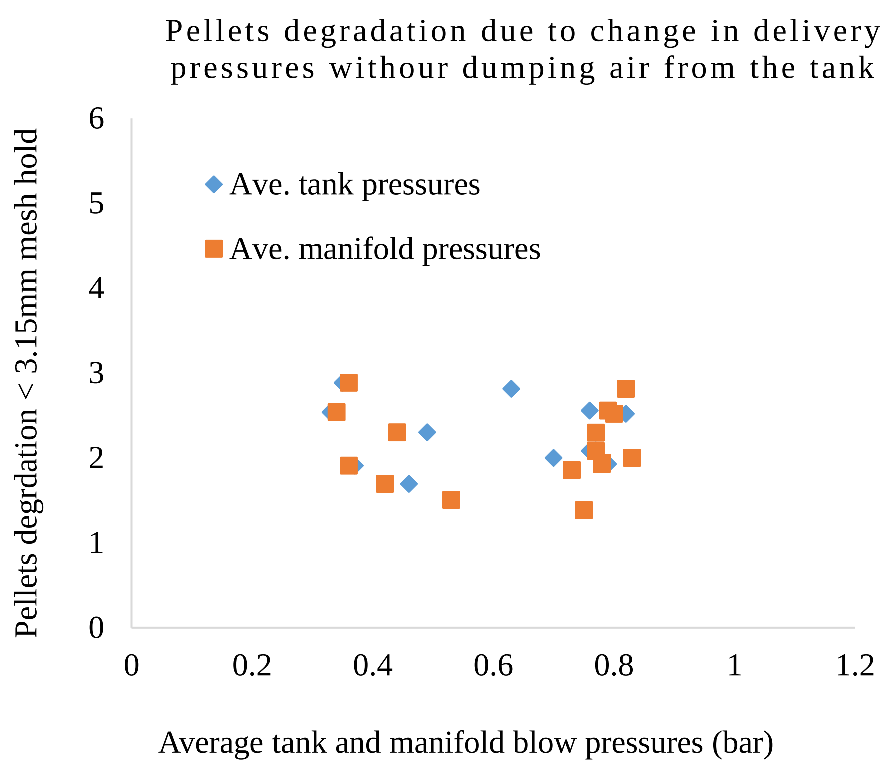


Figure 6.5 Percentage of pellets degradation due to change in the average tank and manifold blow pressures

(Without dumping air from the pressurised tank during deliveries)

The result shown in figure 6.5 was differs from the result shown in figure 6.3 only in terms of air venting conditions of the pressurised tank during the blow deliveries. The result shown in figure 6.5 was achieved without venting air out of the pressurised tank during the blow deliveries and the pellets degradation appears to be scattered across the average blowing pressures. The optimum pellets degradation, in an unvented pressurised tank blow condition, appears to occur between 0.4 bar to 0.75 bar blower pressures, because the set of pellets blown at 0.3 and above 0.8 bar blowing pressures appears to have suffered the more manages compares to pellets blown between 0.4 bar to 0.7 bar blow delivery pressures. This simply means that low pellets degradation may possibly be achieved in an unvented air condition of the pressurised tank, if the pellets were blown between 0.4 - 0.75 bar pressures. This could also vary with the feed rate and solid flow rate in the pipeline, which seems increases the dense flow rate leading the shielding along the bend, without slugging.

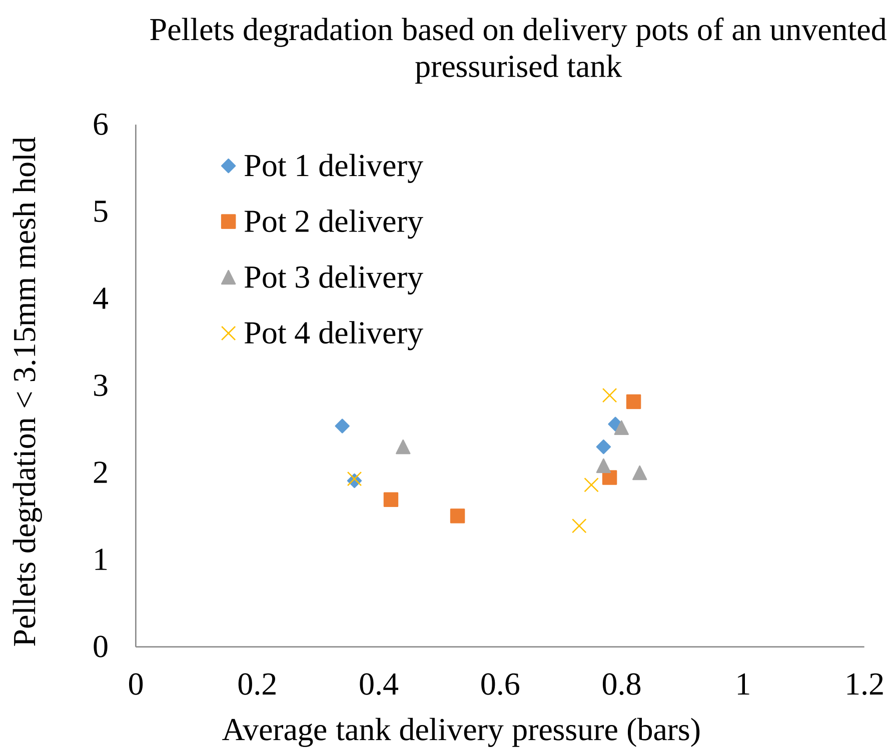


Figure 6.6 Percentage of degraded pellets from different delivery tank pots versus change in delivery pressures *(in an unvented air condition of the pressurised tank)*

The same result of an unvented blow degradation test in figure 6.5 was further analysed based on specific delivery tank pots numbers of the tank truck. The results obtained were depicted in figure 6.6. The change in pellets degradation due to a corresponding change in the average tank delivery pressures of an unvented pressurised blow tank condition results shown in figure 6.6 have virtually a similar pattern of randomly scattered breakages across the blow pressures as observed in figure 6.5 6.5. The only difference in fig. 6.6 is that most of the high pellets degradation appears to be concentrated in the region > 0.75 bar average tank delivery pressures. Thus, 0.4 bar to 0.75 bar appears to also be the optimum tank and manifold blowing delivery pressures for the same unvented blowing air condition of pellets analysed based on delivery pots, especially, for the pellets that were blown from pot number 2, 3 and 4.

The scattered natures of the results, in this case, were attributed to the duration of transient periods (start up and end of delivery time) during which some pellets experience unsteady impact velocities. The variation may consequently contribute to changes in the actual pellets degradation observed. Since pellets blown at higher delivery pressure (i.e. 0.8 bar and 1 bar) takes about 100 - 120 seconds to deliver 800 kg – 900 kg of the wood pellets and out of 100s or 120 s, first 20 s and possibly the last 20 s of the entire delivery periods may be used for transient actions. Thereby allowing about 200 kg to 300 kg of the pellets to be blown in an unsteady condition of the intended blowing pressures, due to a short transient period that could lead to difficulty in control flow rate and pressure ramp precisely. Consequently, the pellets impact velocity varies during the transients' periods to cause a significant change in the level of pellets degradation expected at the blowing pressure.

6.3.3 Pellets Degradation Due to Change in Delivery Pipe Lengths

In order to have a thorough understanding of how and what are the possible cause of variation in degradation of pellets observed in the first set of short blow distance, pneumatic pellets degradation tests conducted at The Wolfson centre. A longer blow pellets degradation tests were conducted using the same ranges of blowing pressures deployed for the short distance test, but different pipes lengths. The longer blow pellets degradation test was conducted at the main site of Forever Fuels Ltd Company. The test was conducted by one the driver that participated in the short blow pellets degradation experiments conducted at The Wolfson Centre. The driver took the advantage of large company stores and access to the large pellets in Ret ford site to further investigate pellets degradation due to change in blowing pressures and delivery pipe lengths. Where up to 3.5 tonnes of pellets were blown in each longer blow degradation test compare only about 1-tonne maximum deployed for each single run in the short distance blow test. The targeted tank and manifold blowing pressures (0.3 bar, 0.5 bar, 0.8 bar and 1 bar) deployed are in the longer blow degradation test was similar to that of short pneumatic degradation tests conducted at The Wolfson Centre. However, the pellets blowing periods of each test run differs. The delivery period appears to be decreasing with corresponding increase in blowing delivery pressures. The longer blow tests took about 25 minutes: 10 seconds, 11 minutes: 30 seconds, 7 minutes: 21 seconds and 6 minutes: 57 seconds to deliver 3.5 tonnes of pellets at 0.3 bar, 0.5 bar, 0.8 bar and 1 bar blowing pressures. While, the short blow pellets degradation test, it took just about 6 minutes: 40 seconds, 5 minutes: 6 seconds, 1 minute: 20 seconds and 1 minute to delivery 800 kg - 900 kg of pellets at the same corresponding 0.3 bar, 0.5 bar, 0.8 bar and 1 bar blow pressures.

The lengths of the flexible pipes from the tank truck to the receiving end store were increased in the order of 1, 3, 5 & 7 pipes. The pipe length increment corresponds to: 1 pipe = 9.5 m, 3 pipes = 20.8 m, 5 pipes = 38.6 m and 7 pipes = 47.4 m respectively. The distance (length) to the receiving hopper (store) variation also depends on the pressurised tanker truck delivery outlet position (i.e. tank pot number). The resulting change in pellets degradation attained at different blow pressures and pipes lengths are depicted in figure 6.7. It is clear from the results obtained that the longer the pipes lengths, the higher the level of pellets degradation observed, especially in the region of the highest and lowest blowing pressures 0.3 bar and 1 bar values. The optimum pellets blowing pressures for long blow deliveries, especially in longer pipe deliveries, appears to occur between 0.5 bar to 0.8 bar.

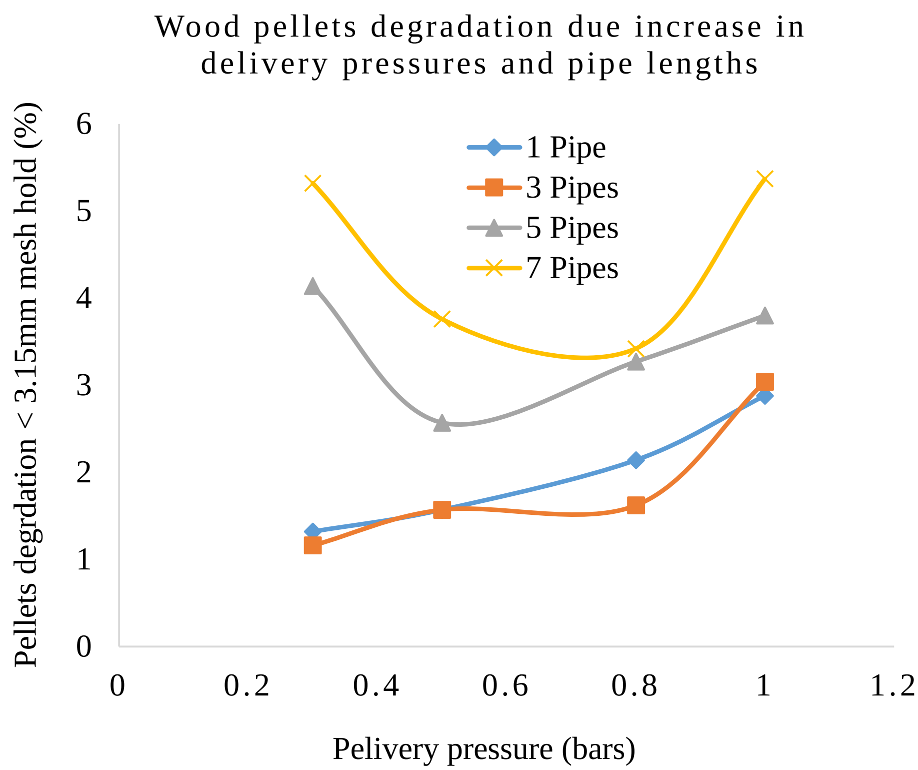


Figure 6.7 Percentage mass of degraded pellets due to change in blowing pressures and pipe lengths (numbers) *(in an air dumping condition of pressurised tank)*

The result has also shown that, the longer the blowing pipelines, the higher the pressure at which minimum pellets degradation occurred, in a vented pressurised tank blow condition. The low pellets degradation observed at short distances blow deliveries (limit 20.8m length) was attributed to a large flow of air dumped from the pressurised tank during the deliveries. It was also apparent that the results in figure 6.7, (i.e. for the longer duration tests) appeared to be rather more consistent. The level of consistency observed in these results was an indication that the relatively more dominant transient actions that occurred in a short blowing time (the small delivery batches used in the tests at The Wolfson Centre), might well have contributed to the irregular pattern of pellet degradation observed in figures 6.5 and 6.6.

6.3.4 **Effect of Velocity on Pellet Degradation**

Particles velocity was known to have direct influence on particles degradation in a pneumatic blow delivery system. However, particle concentration, density and solid flow rate could also vary the velocity of particles in a pipelines due to change in blowing pressure; therefore, it was suspected that the particle velocity would not be the same as the air velocity. In the small batch tests undertaken at The Wolfson Centre. The velocities of the pellets blown at different blowing pressures (0.3 bar, 0.5 bar, 0.8 bar and 1 bar), were filmed using a high-speed video camera along the transparent section of the Perspex pipe. The camera was adjusted to record the velocity of the pellets at 1000 frame per second. The recorded video images of the pellets velocities at different blow pressures were analysed using MATLAB software. The average velocities of the pellets blown at different delivery pressures were plotted against the corresponding level of pellets degradation observed and the results were depicted in figure 6.9.

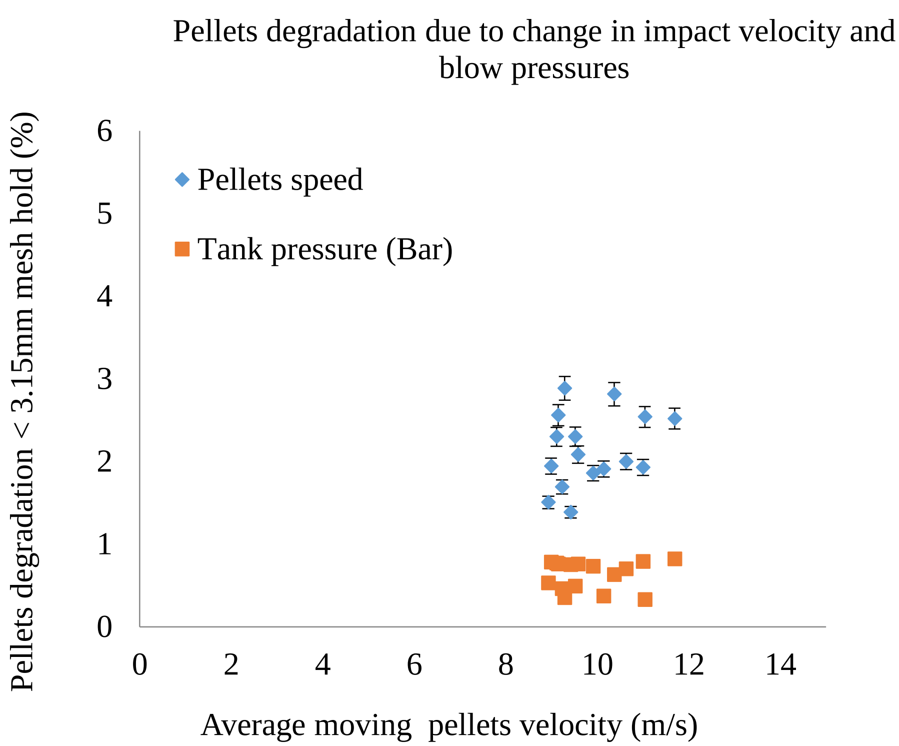


Figure 6.8 Shows the percentage pellets degradation due change in moving pellets velocities at different blow delivery pressures

It is apparent from fig. 6.9 that the average moving pellets velocities were approximately about 12 m/s for the short blow delivery period. The pellets degradation appears to increase randomly with a corresponding increase in pellets velocities. It is important to note that the scattered nature of pellets degradation, in this unvented air blow condition of the pressurised tank, was attributed to the short transient at the beginning and end of the short blowing times, which might have consequently altered the pellets impact velocity due to change in solid feed rate or mass flow rate, particles concentration and density long the pipeline bends.

6.3.5 The Relationship between Average Moving Pellets Velocities, Air Velocity and Tank Delivery Pressures

The average air velocity through 8 inches' diameter pipe was measured using an air flow velocity meter, during the unvented pressurised tank blow deliveries. The results were calibrated base the delivery pressures and scaled to 4 inches' pipe diameter, which is the actual conveying pipeline diameter.

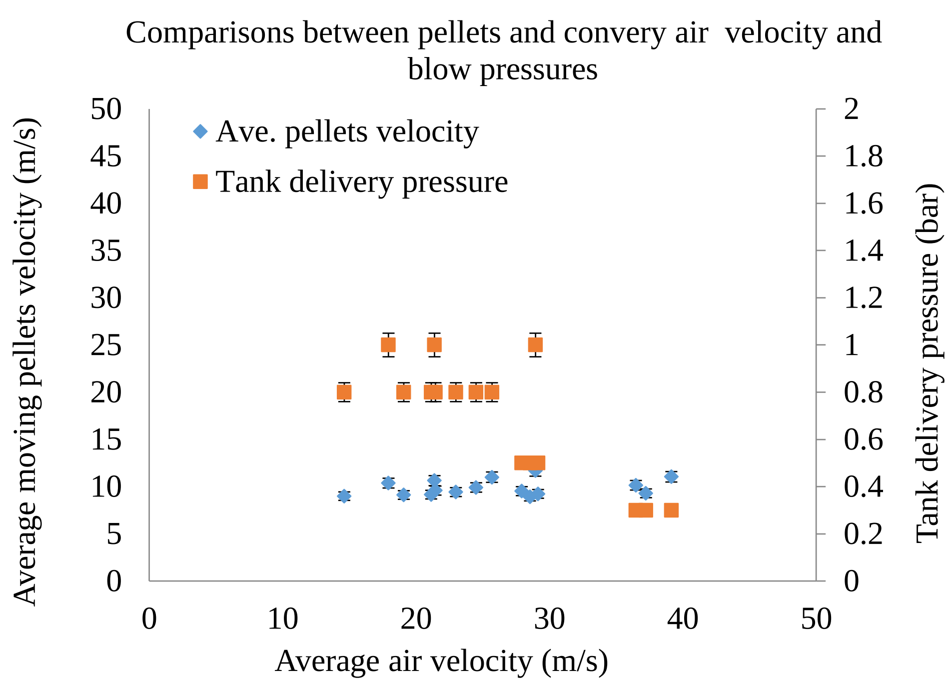


Figure 6.9 The comparisons between the average blow tank pressures, moving pellets velocities and air velocities in a 4 inches' pipe diameter

(In an unvented air blow condition of pressurised tank)

The results obtained were compared to the average moving pellets velocities analysed using Mat-lab software, and the average blowing delivery pressures as shown in figure 6.9.

As observed in figure 6.9 there is a very loose correlation between averages moving pellets velocity increment with the corresponding increase in conveying air velocity, up to about at 30 m/s. However, there it is a large scattered correlation and less clear with further increase in the average air velocity beyond 30 m/s for the next about 10 m/s as shown figure 6.9. Notwithstanding the poor correlation between pellet velocity and air velocity, this data is interesting as it showed that the maximum average pellet impact velocity in this pipeline at the location of measurement, with 0.3 bars - 1 bar blowing pressures, did not exceed 15 m/s even with the increase in air velocities up to 30 m/s, but was not much lower with lower air velocities.

6.3.6 **The Relationship between Average Pellets and Inlet Air Velocity versus Conveying Line Pressures**

The relationship between the average pellets and conveying inlet air velocity at different blowing line pressure during the pneumatic pellets degradation test was determined. The investigation was carried out to understand how the conveying air velocity changes with the pellets degradation, at different delivery pressures. The results obtained are shown in figure 6.10.

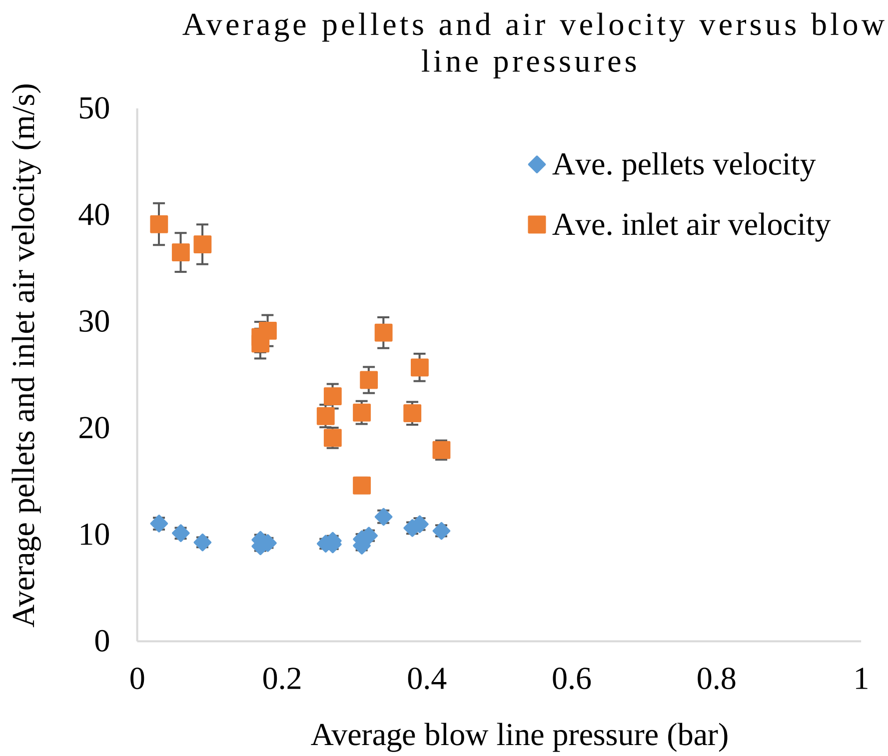


Figure 6.10 The relationship between the average pellets and air velocities versus conveying line delivery pressures *(in an unvented air condition of the pressurised tank)*

The result shown in figure 6.10 depicts a progressive decrease in average inlet air velocities with an increase in line blowing pressures between up ≤ 0.3 bar. The linear decrement in average inlet air velocities have suddenly diminished to a scattered increase in the regions of high blowing line pressures. The sudden instability of the air velocity along the high line air pressures was due to change in blow tank pressures and pellets flow ‘‘slogging’s in the pipeline during the delivery. However, the average pellets velocities appear to have a similar trend across the average blowing line pressures.

6.3.7 The Relationship between Averages Conveys Line and Blow Tank Delivery Air Pressures

The relationship that exists between the line and blow tank air pressures (which are the two-main tanker truck conveying pressures), during pellets delivery, was investigated to understand their influence on mass flow rate or solid loading ration during pellets delivery, in an unvented pressurised tank blowing condition. The averages line and tank delivery air pressures at the targeted blowing pressures (0.3 bars, 0.5 bars, 0.8 bars and 1 bar) were calculated and the results are shown in figure 6.11.

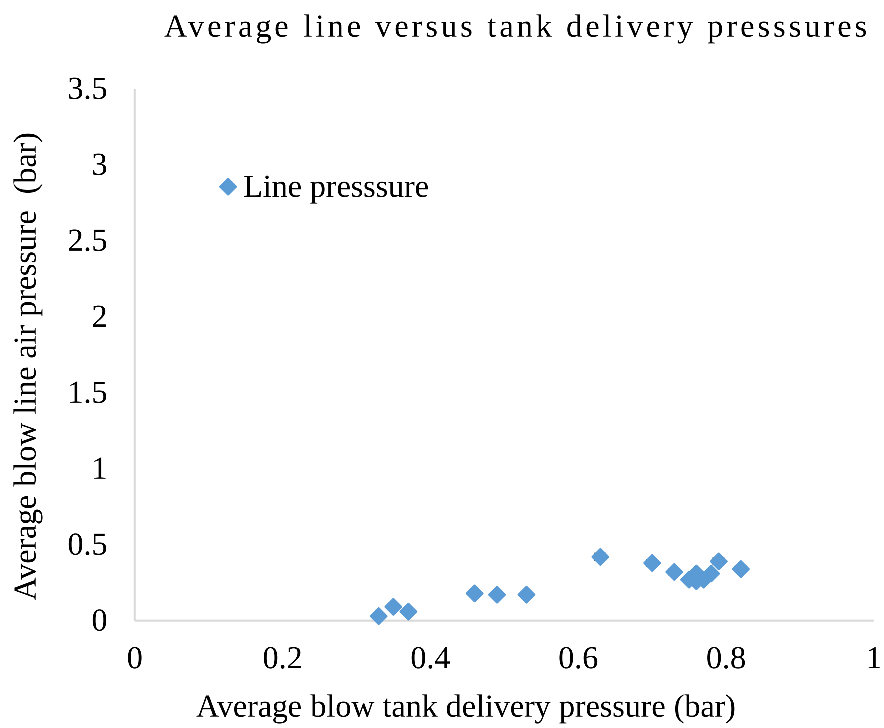


Figure 6.11 The change in average blowing line pressure due to change in tank delivery air pressures

The average tank delivery pressures were found to increases with the corresponding increase in average line pressures. However, the linear relationship between the average line and tank delivery air pressures diminished after about 0.7 bars tank delivery pressure. The average tank delivery pressure was almost twice the line blow pressures. The blow line pressured appears to be scattered at high blowing tank delivery air pressures, which was presumed to occur due to transient.

6.3.8 Relation between the Blow Tank Pressures and Pellets Delivery Time Durations

Understanding how long it takes to deliver a certain quantity (tonnes) of wood pellets from a pressurised tanker truck could be an important way of determining the solid flow rate, which is sometime use to presumed pellets degradation of a blow delivery pressure.

The concept in this analysis is that high blow pressures could increase the solid loading ratio due regular feed rate at achievable tank delivery valve opening. High feed rate may also result in low pellets degradation, where material shielding occurred along the bend. The possible reduction in particles degradation may be lost suddenly due to collapse arched pellets within the pressurised tank or slogging along the blowing pipeline, which could change the density and impact velocity of the pellets. The change pellets blow pressure and delivery period results are shown in figure 6.12.

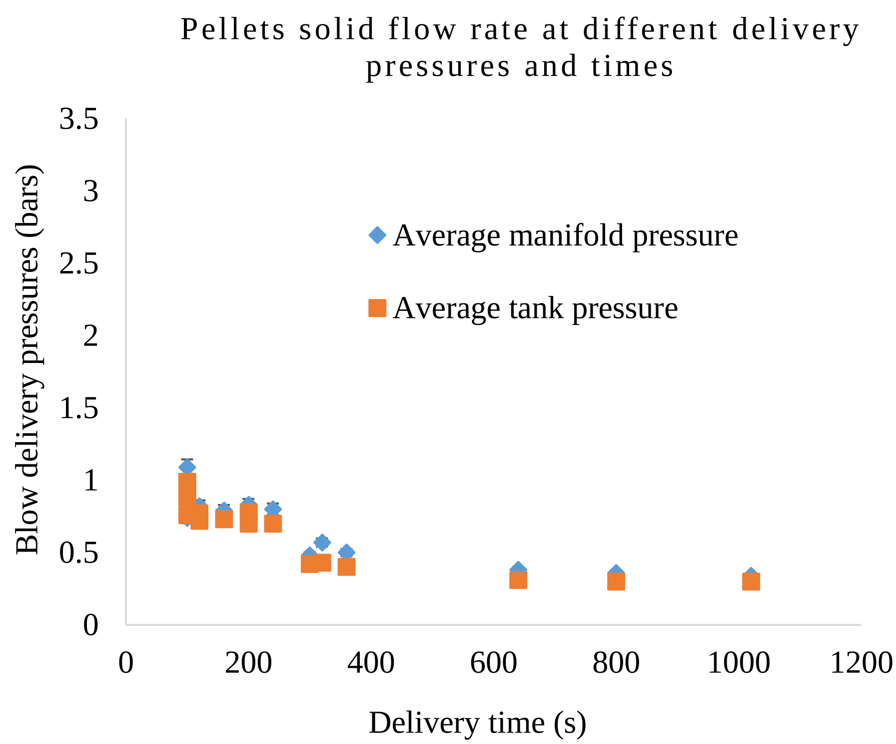


Figure 6.12 The effect blowing pressures on pellets delivery periods

The result shown in figure 6.12 depict the longer delivery periods the lower the blowing pressures. While the higher the blowing pressures (0.8 bar and 1 bar) the shorter the delivery time it takes. This proportional relationship was possibly achieved because high blowing pressure results in pushing more of the material out of the tank and along the blow pipeline.

6.3.9 The Relationship between Pellets Mass Flow Rate, Pressurised Tank and Manifold Delivery Air Pressures

The relationship between the two delivery pressures (manifold and tank pressures) of a pressurised tanker truck and pellets mass flow rates at different delivery pressures (0.3 bars, 0.5 bars, 0.8 bars and 1 bar) was studied and shown in the following figures (6.13, 6.14, 6.15 & 6.16) respectively.

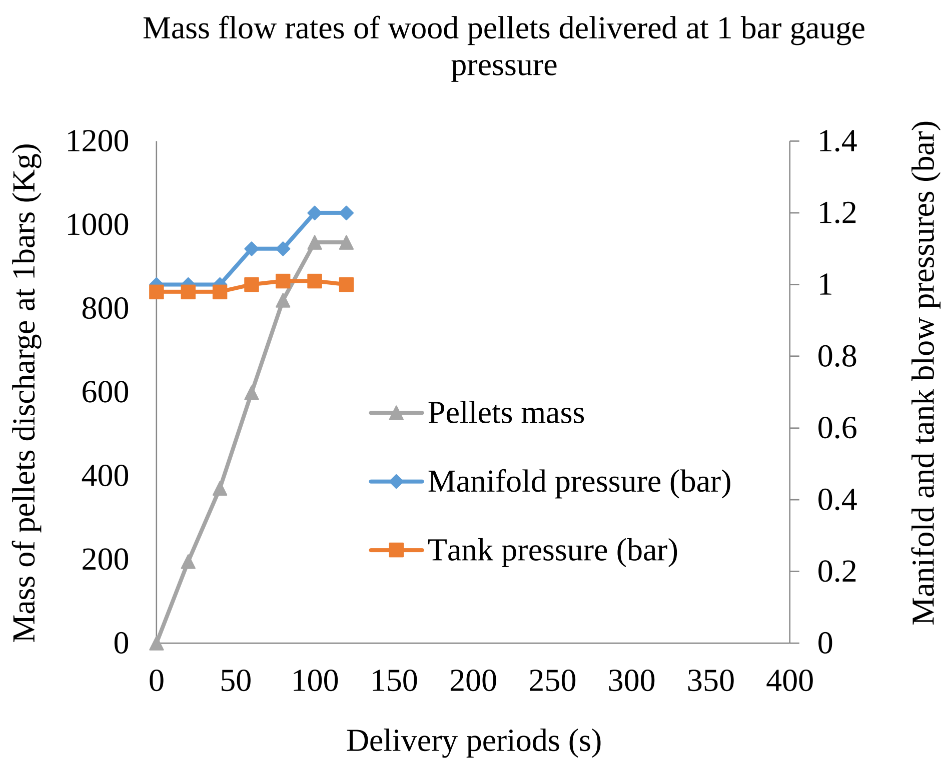


Figure 6.13 Show the maximum delivery period and increase in pellets mass flow rates at 1bar delivery pressures *(in a vented pressurised blow tank condition)*

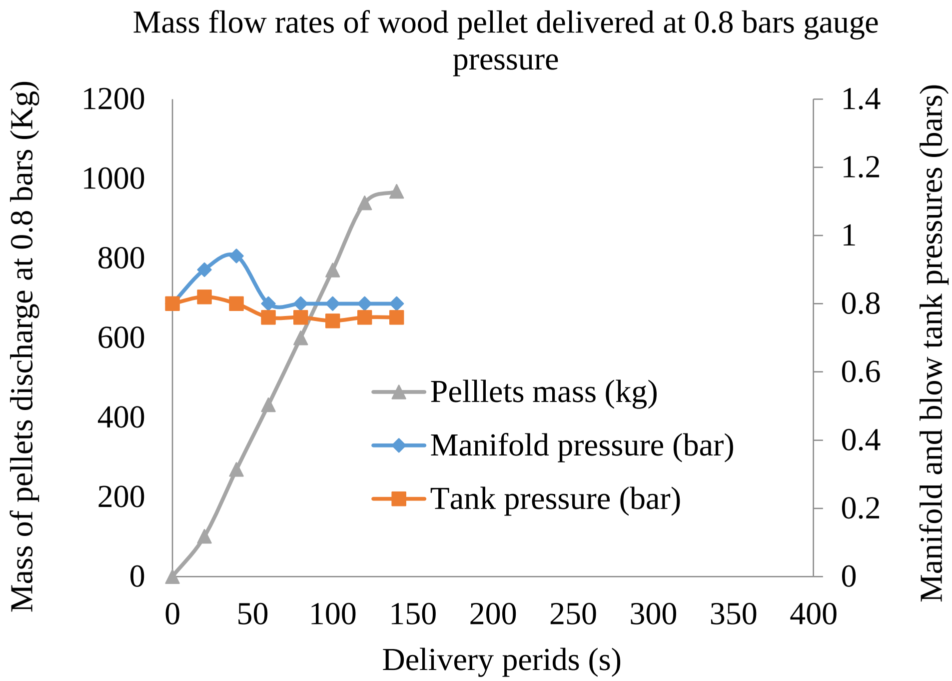


Figure 6.14 Show the maximum delivery period and increase in pellets mass flow rates at 0.8 bar delivery pressures *(in a vented pressurised blow tank condition)*

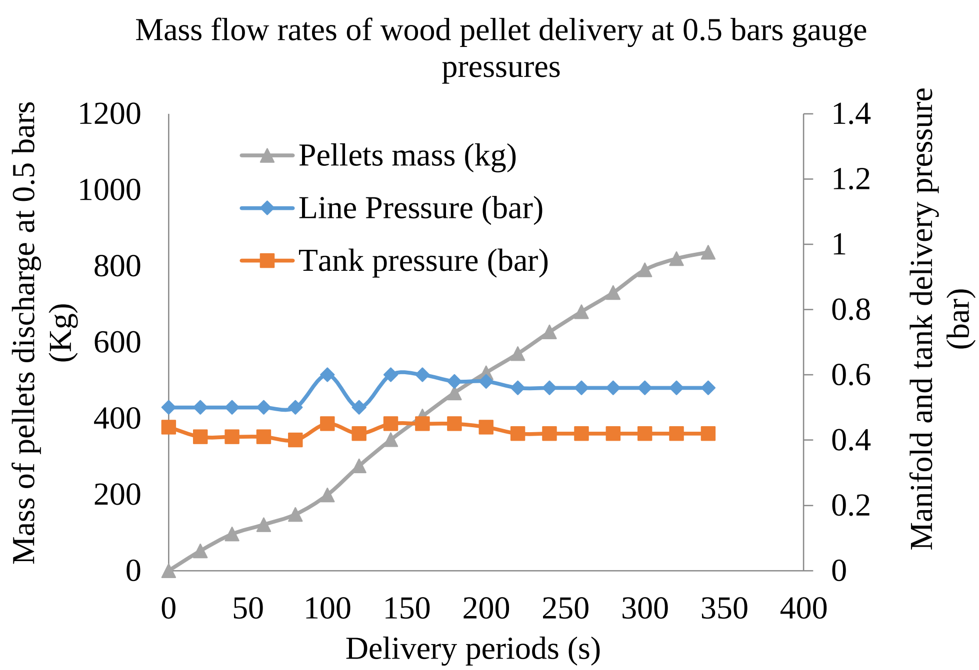


Figure 6.15 Show the maximum delivery period and increase pellets mass flow rates at 0.5 bar delivery pressures *(in a vented pressurised blow tank condition)*

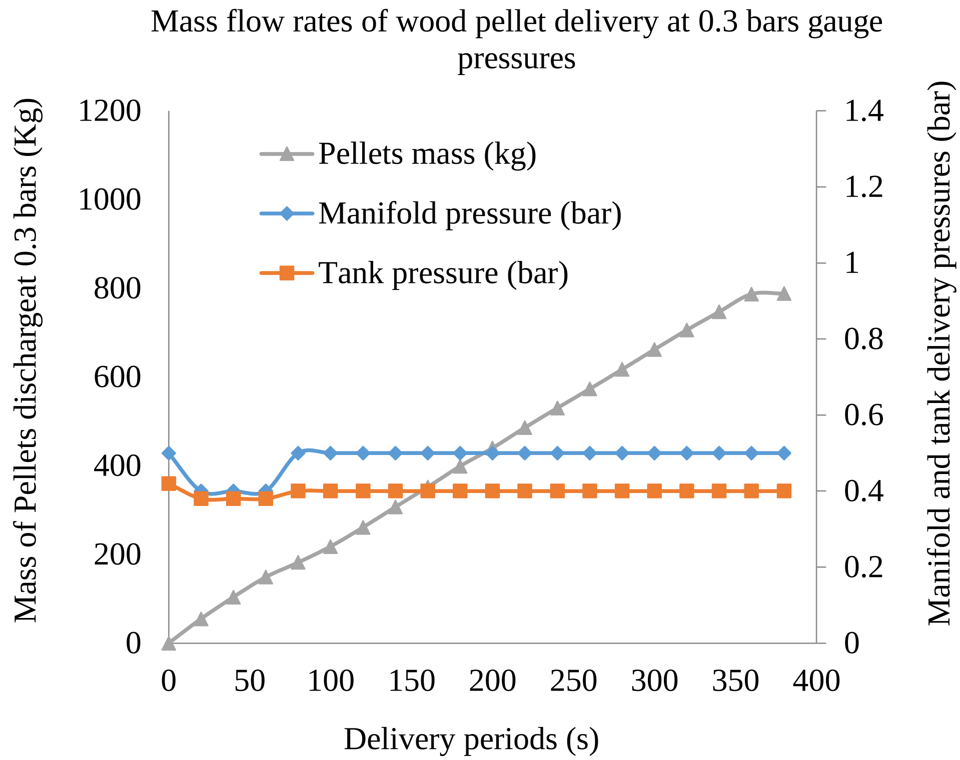


Figure 6.16 Show the maximum delivery period and increase pellets mass flow rates at 0.3 bar delivery pressures *(in a vented pressurised blow tank condition)*

The investigation was carried out to gained more sight on the pneumatic pellet handling practices and the achievable delivery periods of each blowing pressure because this could be used in filling or refilling of domestic small pellets silos or stores to prevent over filling. The variation in the delivery periods and pellets mass flow rates during each set of pellets blow degradation test, conducted at different blow tank and manifold delivery pressures (0.3 bar, 0.5 bar, 0.8 bar and 1 bar) were depicted in

The delivery periods were found to increases with the corresponding decrease in the specified tank and manifold delivery pressures. However, there were certain fluctuations along the pressure trends which indicate the occurrence of some irregularities in the pellets flow along the blow line. The irregular flow of the pellets was presumed to be occurring due to slugs or transients along the blow pipeline during the deliveries.

The transient blow behaviour of the pellets flow within the pipeline was more pronounced in the 1 bar and 0.8 bar blowing pressures, where the manifold blowing pressure suddenly increased toward the end of the delivery. Similarly, in the 0.8 bar blow test, the manifold blowing pressure suddenly increases to 1 bar before it finally stabilised at the required 0.8 bar.

6.4 Summary

The summary and key finding of this chapter are detailed as follow:

The study showed that a significantly lower level of pellet degradation could be achieved by dumping some of the excess air from the pressurised tank where pellets are blown at either 0.3 bar or 0.5 bar manifold and tank delivery pressures of a pressurised tanker truck, especially when pellets are blown at a short delivery distance. The decrease in pellets degradation was not due to the low delivery pressures used, the benefit was simply due to air vented out from the pressurised tank during the delivery, which reduces the conveying air velocity in the pipeline.

Considering the results of pellets blown at 1 bar blowing pressure, it was clear that this was on the verge of not transporting the pellets steadily, resulting in occasional slugging and clearing of the line. This instability led to high pellet degradation, presumably because the unstable pressure meant that every time slugs were cleared the falling pressure gave rise to high air and pellet velocity. The level of pellets degradation observed at 1 bar blowing pressure should only be used as an extreme worst case scenario for all the delivery conditions, both in a long or short delivery distance. That 1 bar blowing pressure may be used if pellets degradation is not a concern in the delivery at all cost.

The lowest pellets damage appears to occur at the intermediate blowing pressures (0.5 bar and 0.8 bar). However, the argument between the preferable delivery pressures might depend on the delivery distance and tanker operator as well. This conclusion was supported by the extended pipes pellet delivery result shown in figure 6.7, which also indicated low pellets degradation at these specified intermediate blow pressures in contrast to those of 0.3 bar and 1 bar delivery pressures.

The average inlet air velocity appears to have influence on the corresponding pellets velocities in the blown pipeline and the blowing tank pressures were inverse related to the pipe inlet air velocities.

Pellet mass flow rates correlated strongly with pressure. The higher the blowing pressure the lower was the required blowing period. As the manifold or tank blow pressures increased from 0.3 bar, 0.5 bar, 0.8 bar and 1 bar the corresponding duration of the delivery time decreases 380s, 340s, 140s and 120s for every 900 - 1000 kg of pellets delivery from the pressurised tanker truck.

One of the most important findings, particularly with the smaller deliveries, was the high level of variation of the degradation between deliveries made under very similar conditions. Even though the same blowing pressures and delivery times were successfully achieved in the repeat tests, the level of degradation was far from repeatable. The degradation level did not correlate with the tank delivery pot number (outlet number) and neither did it correlate with the discharge number from one pot. The level of variation was such that it seriously clouded the correlations, being as large as the difference between the average results for different conditions.

The reason for the high level of variation was unclear. The most likely explanation seems to be segregation of pellets during loading of the tanker. Although the pellets were screened during loading, which should have led them to be free of fines inside the tanker, “free surface” segregation would have led to a distribution of pellet lengths in different parts of the tanker contents, and therefore in the different deliveries. This could conceivably have led to the differences in degradation, as shorter pellets have a greater number of ends within a given mass, and the ends are susceptible to being damaged. Alternatively, longer pellets might break initial half more easily, leading to fines generation. It could even be that shorter pellets are shorter at the point of tanker loading because they were initially less strong when produced at the mill, and so suffered more breakdowns in the extensive handling chain from the mill to warehouse via land shipping, ocean shipping and further land shipping with all the handling steps involved. A distribution of pellet strengths should be expected at the point of manufacture, due to the use of multiple pellet presses in parallel and the impossibility of achieving identical conditions on them.

The result of this variation is that customers must expect to see very significant variation in the nett levels of fines they ultimately receive in batches delivered to their stores, even with the greatest care taken over control of delivery conditions. This is especially so with smaller deliveries. Though, the variation appears to be less in the larger blow deliveries.

Chapter 7. Comparison of bench scales pellets durability testers and large scale pneumatic blow pellets degradation test

7 Introduction

The objective of the work in this chapter is to answer part of the principal research question as to whether or which of the bench scale durability testers might be used to predict the actual pellets degradation in real handling system (i.e. pneumatic delivery). Several experiments were conducted to resolve the present controversy and concern in the industry, especially anecdotal stories of pellets with high pellet durability index (PDI), as tested in popular standard bench scale testers (tumbling box and Ligno testers), that turn out to produce high volumes of fines in real handling systems. The cause of the counterintuitive behaviours of pellet degradation between the bench scale testers and full-scale industrial handling system (i.e. pneumatic pellet delivery) were yet to have any substantial scientific evidence or study.

Therefore, samples of the same batch manufactured wood pellets durability were tested using the three bench scale testers (i.e. standard tumbling box and Ligno testers and newly introduced rotary impact tester). The average PDI values of each bench-scale durability tester results were compared to the average level of pellet degradation observed in the full-scale pneumatic pellets delivery test, conducted using a pressurised tanker truck delivery system, at different blowing pressures and pressurised tank conditions.

The breakage patterns of pellets in distinct pellet degradation tests conducted were compared to examine whether there is a realistic chance of such scaling being reliable, from the resulting pattern of pellets breakages between the two tests. The consideration is that if the pellet breakage pattern between one of the bench test and the full-scale delivery tests appeared to be qualitatively similar, then it would be reasonable to presume that similar breakage mechanisms may exist between the two tests, so that a simple scaling of that particular bench scale tester results could form a basis for prediction of pellet degradation in a full-scale handling systems, albeit with some scaling to allow for different numbers of bends, blowing distance etc. Conversely, any of the testers showing a degradation pattern that is not qualitatively similar to that of full-scale tests would imply that the tester is probably a poor basis for prediction of full-scale degradation, even with scaled results. The flow charts illustrating procedures for comparing the two-distinct pellet degradation test experiments are shown in figure 7.1.

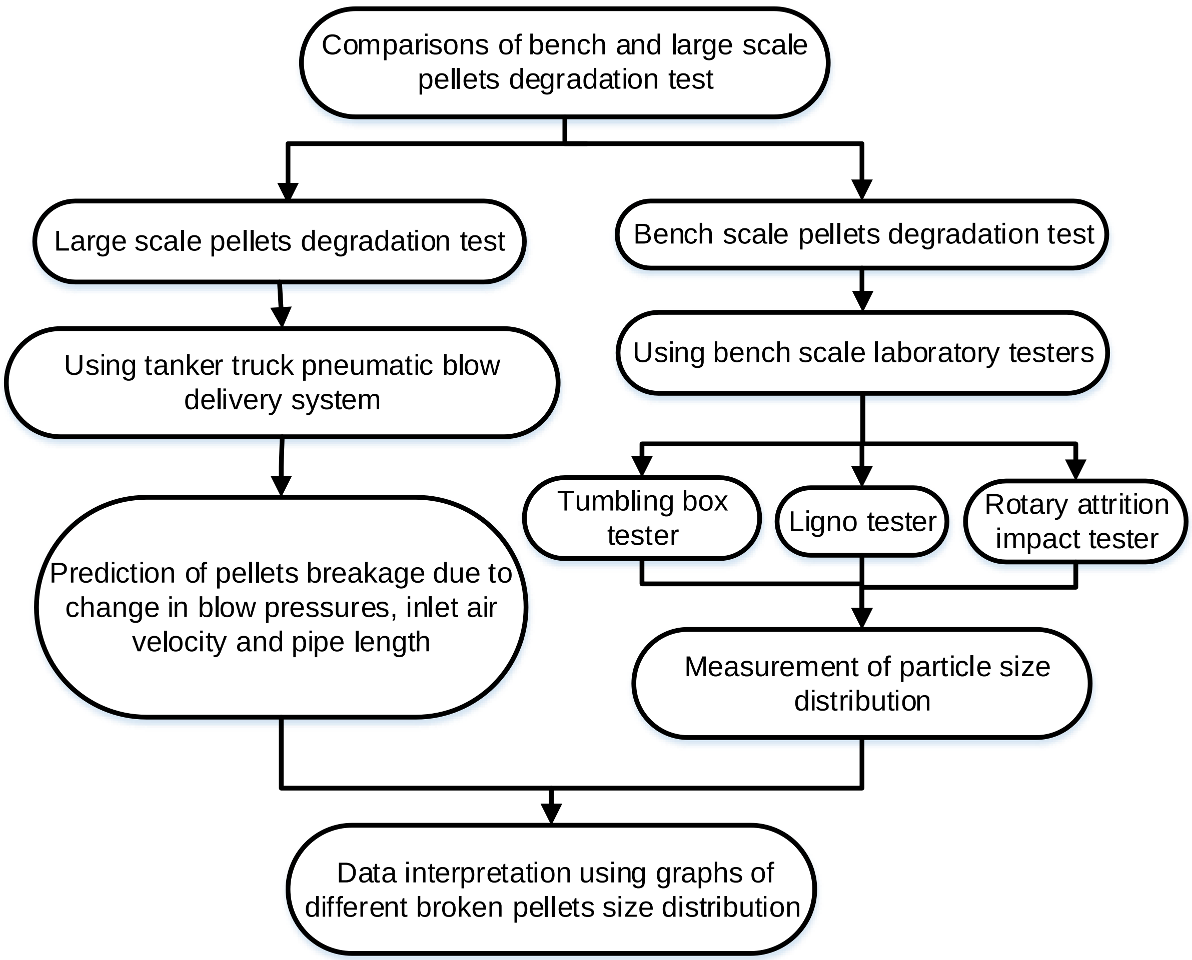


Figure 7.1 The experimental flow chart comparing bench and large scale pellets degradation tests

7.1 Methods

Parallel bench-scale pellet durability tests were conducted using the three bench scale testers and samples of fresh pellets from the same manufacturing batch collected during loading of the pressurised tanker truck. The results of the full-scale pneumatic pellets degradation tests, conducted at targeted different delivery pressures (i.e. 0.3 bar 0.5 bar, 0.8 bar and 1 bar) and pressurised tank conditions, see section 5.6.2 for more detail were compared to the bench scale test results. The two-standard bench scale pellet durability tests were conducted using the tumbling box, Ligno test were conducted in accordance with (EN 15210 - 1), and the rotary impact tests were conducted in a similar way. The particles size distributions of the degraded pellets fractions (broken pellets) from the benches and full-scale pellets degradation tests were analysed accordance with EN 15149-1 standard. The degraded pellets size fractions were categorised into different sizes ranges from 4.75 - 3.15 mm, 3.15 - 2.36 mm, 2.36 - 1 mm and < 1 mm all in diameters. Particles below 3.15 mm sieve size are regarded as fines at stated in the EN 14961 - 2 standard. The pellet durability index (PDI) values of the degraded pellet fractions were calculated using equation 3.5. The damage incurred by the pellets tested in each of the bench scale testers was compared to those of the full-scale pneumatic pellets degradation tests, by using the percentage mass of the broken pellets fractions to plot the breakage patterns.

7.2 Result and Discussion

In this section, the results of single run pellets durability tests, from the three bench-scale pellet durability testers (tumbling box, Ligno and rotary impact testers), were compared to that of the actual full-scale degradation tests. Each of the single run bench-scale pellet durability tests was conducted using fresh separate samples of pellets per tester. The fractions of the broken and degraded pellets size distributions after every single durability test was determined (4.75 - 3.15 mm, 3.15 - 2.36 mm, 2.36 - 1 mm and < 1 mm diameters). The mass within each size range was measured using an electronic balance, and the results were compared to those from the full-scale pneumatic degradation tests as shown in figures 7.2 to 7.4.

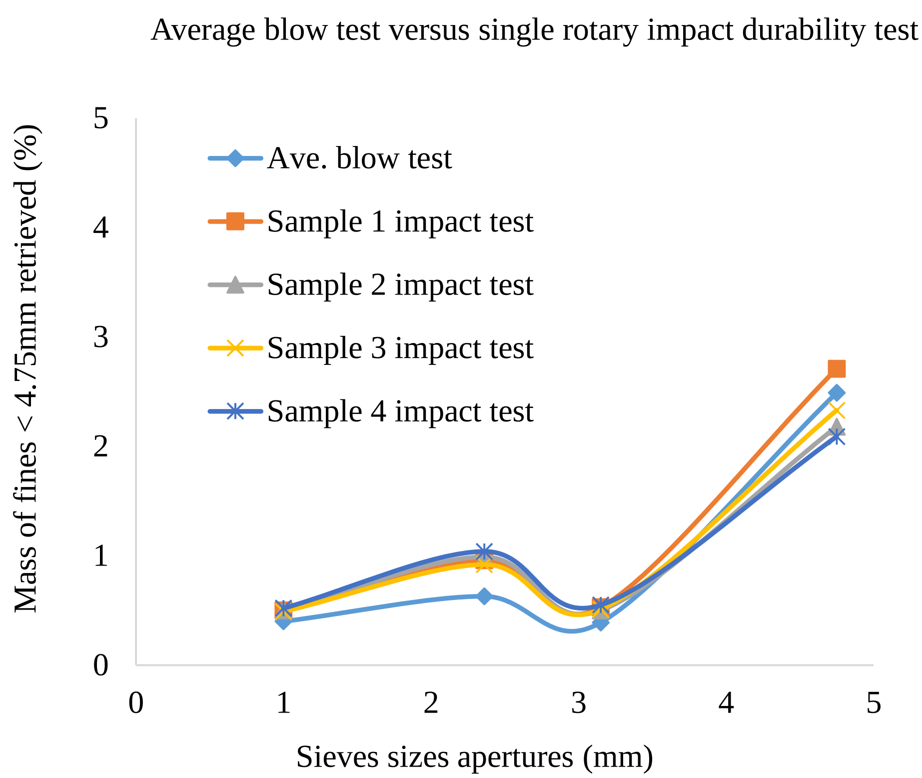


Figure 7.2 Compares the breakage pattern of pellets in every single rotary impact pellets durability test versus average full-scale pneumatic blow tests

The breakage patterns of the four-separate single run wood pellets rotary impact durability tests were compared to that of average full-scale pneumatic degradation test are shown in figure 7.2 above. The breakage pattern of the four-separate rotary impact durability tests appears to be very similar to that of the average full-scale pneumatic degradation test, although broken particles between >1 mm and < 3.15 mm appeared to be slightly high in the rotary impact tester compared to that of average full-scale pneumatic test. The four repeated runs of the rotary impact durability test showed high repeatability (reproducibility).

Similar single repeated tumbling box durability tests were also conducted and the pellet breakage patterns were compared to that of the average full-scale pneumatic degradation tests, shown in figure 7.3.

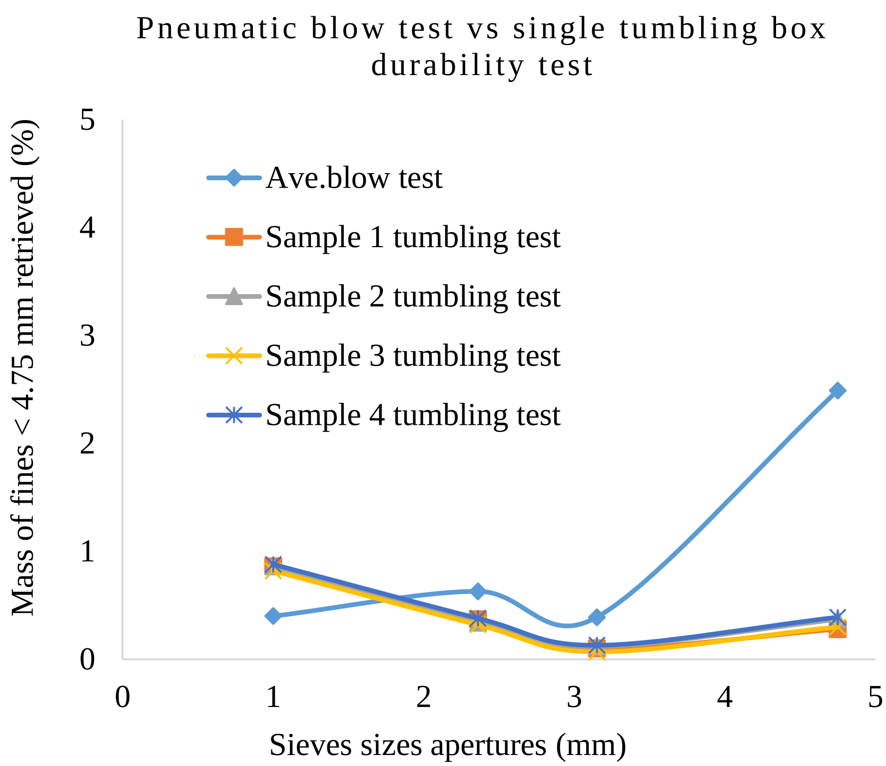


Figure 7.3 Compares the breakage pattern of pellets in every single repeated tumbling box durability tests versus average full-scale pneumatic blow tests

The four-repeated independent single run tumbling box durability tests were conducted using fresh samples of pellets for each test (all from the same manufacturing batch again). The resulting breakage patterns of the pellets in the four repeated tumbling box tests differs very widely to the pattern of pellets of degradation observed in the full-scale pneumatic blow degradation test, as shown in figure 7.3. The implication is that tumbling durability test is unlikely to replicate or predict similar level of pellet degradation in a full-scale pneumatic blow delivery system or any real handling, because the wider difference in breakage pattern implies a wide difference in breakage mechanism, which is, therefore, unlikely to be scale in the same way.

In addition to tumbling box and rotary impact test, a similar sample of the pellets from the same batch tested in tumbling box and rotary impact test was used to conduct repeated Ligno durability tests. The Ligno repeated durability test were conducted using four separate fresh pellets samples (100 g) for four consecutive times and the resulting patterns of pellet breakage were compared again the full-scale pneumatic degradation test as shown in figure 7.4 below.

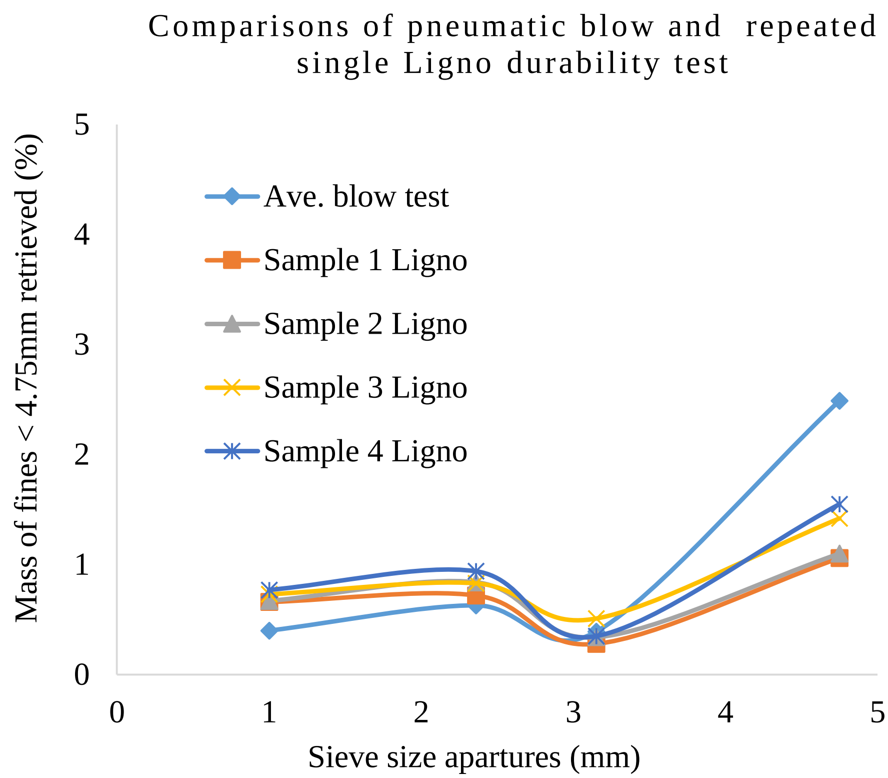


Figure 7.4 Compares the breakage pattern of pellets in every single repeated Ligno durability tests versus degradation in a full-scale pneumatic blow tests

The breakage pattern of the pellets in the Ligno tester was to some degree similar to that of the average full-scale pneumatic degradation test, especially between 2.36 - 3.15 mm diameters. The similarity in breakage pattern of pellets between Ligno tester and average pellets degradation in the full-scale test was an indication of the better potential tendency of the Ligno tester to predict pellets degradation in full-scale pneumatic blow system, compared to the tumbling box tester. The negative side of the Ligno tester results was in terms of less repeatability in comparisons to other bench scale testers.

The breakage patterns of each bench scale single pellets durability test, across the three-bench tester, was compared to that of average full-scale pneumatic degradation test in figure 7.5 below.

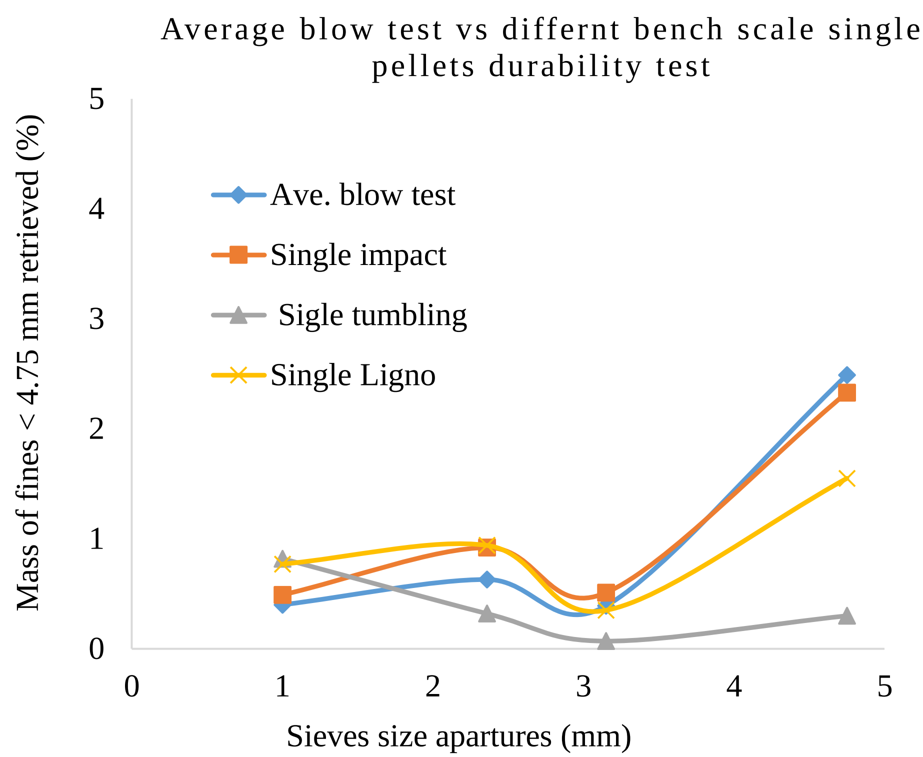


Figure 7.5 The comparisons of pellets breakage in the three bench scale durability testers versus average pellets degradation in full scale pneumatic blow tests

The single rotary impact durability test shown in figure 7.5 appears to have the most similar pattern of pellet breakage to that of full-scale pneumatic degradation test in comparison to tumbling and Ligno testers. However, Ligno tester has also shown some degree of similarity in breakage that seems to be similar to that of full-scale blow test, especially in the region of broken pellets fines between 2.36 - 3.15 mm diameters ranges. By contrast, the breakage pattern of pellets in tumbling box was very different to that of the full-scale pneumatic degradation test.

By implication, it means that rotary impact tester has high tendency to predict similar pattern of pellet degradation observed in real handling system compare to Ligno tester.

However, in comparison, the standard tumbling box test was of no use because is just exposing the pellets to breakage mechanism other than that of real blow delivery system, so it is unlikely to produce results that may correlate to pellet degradation in real handling systems.

7.3 The Comparisons of Broken Pellets Sizes Distribution of Bench and Full Scale Pneumatic Blow Degradation Tests

Having seen how each of the single run bench scale pellets durability tests result relates with the average pellets degradation in full-scale pneumatic test, it was therefore taken on board to understand the relationship that could exist between the average pattern of degraded pellets fractions derived from each bench scale and full-scale degradation tests. It is important to note that the pneumatic pellets degradation tests were conducted using different delivery pressures (0.3 bars, 0.5 bars, 0.8 bars and 1 bar) and pressurised tank conditions. Therefore, the first set of the pneumatic degradation tests results denoted with [A] expresses the condition of pellets degradation achieved under excessive air venting condition of the pressurised blow tank at low delivery pressures. Whilst in the second part of the blow degradation test result denoted with [B] represent the full blow tank pellets degradation attained without venting air from the pressurised blower tank during most of the deliveries. The fractions of broken pellets fines size distributions between 4.75 - 3.15 mm, 3.15 - 2.36 mm, 2.36 - 1 mm, and < 1 mm diameters ranges were analysed after the bench scale tumbling box, Ligno and rotary impact tester and the full-scale pneumatic degradation tests conducted in an air vented condition of the pressurised tank [A].

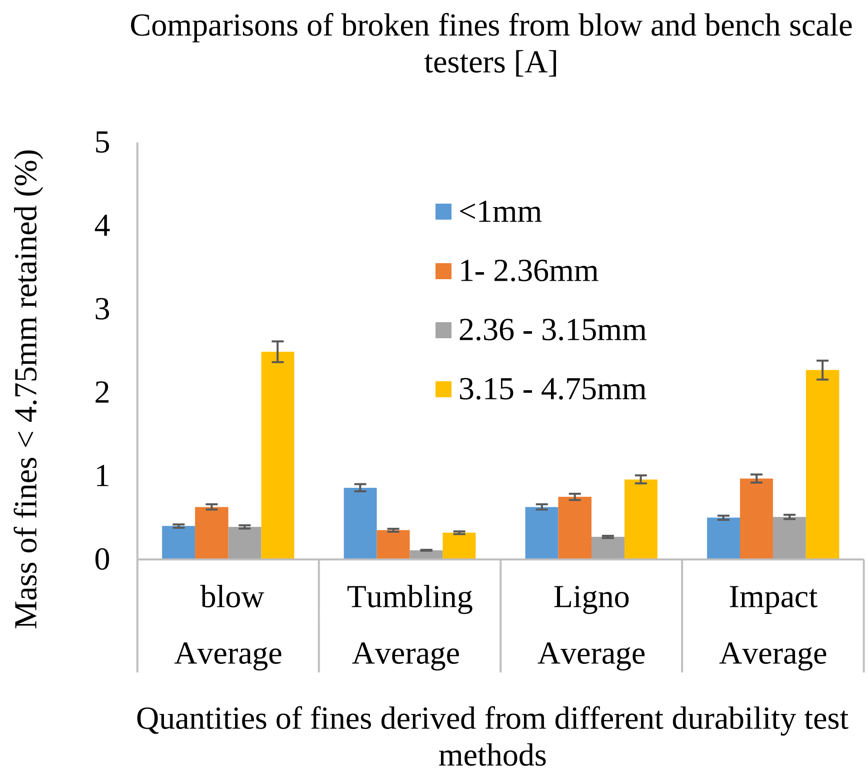


Figure 7.6 Compares the average pattern of pellets degradation in a vented air full-scale pneumatic blow test to those of the three bench-scale pellets durability testers

The bar chart in figure 7.6 compares the average mass of broken pellets of different size fractions arising from full and bench scale degradation tests. In comparisons, the breakage pattern of rotary impact durability tester was very similar to that of the full-scale pneumatic test, especially in range of large broken particles size column (3.15 - 4.75 mm). Likewise, the Ligno tester demonstrated some degree of similar breakage pattern observed in the full-scale blow degradation test. Conversely, columns representing the breakage pattern of pellets in standard tumbling box durability tester were totally opposite to that of full-scale pneumatic blow pellets degradation tests. The most significant difference seems to occur in the finer class range column of broken particles below 1 mm diameter, which is sometime regarded at wood dust.

Similar resulting ranges of average broken pellets fractions derived from the three bench scale durability testers, shown in figure 7.6 were also compared to the average ranges of broken pellets arising from the unvented pressurised tank pneumatic pellet degradation tests [B] shown in figure 7.7.

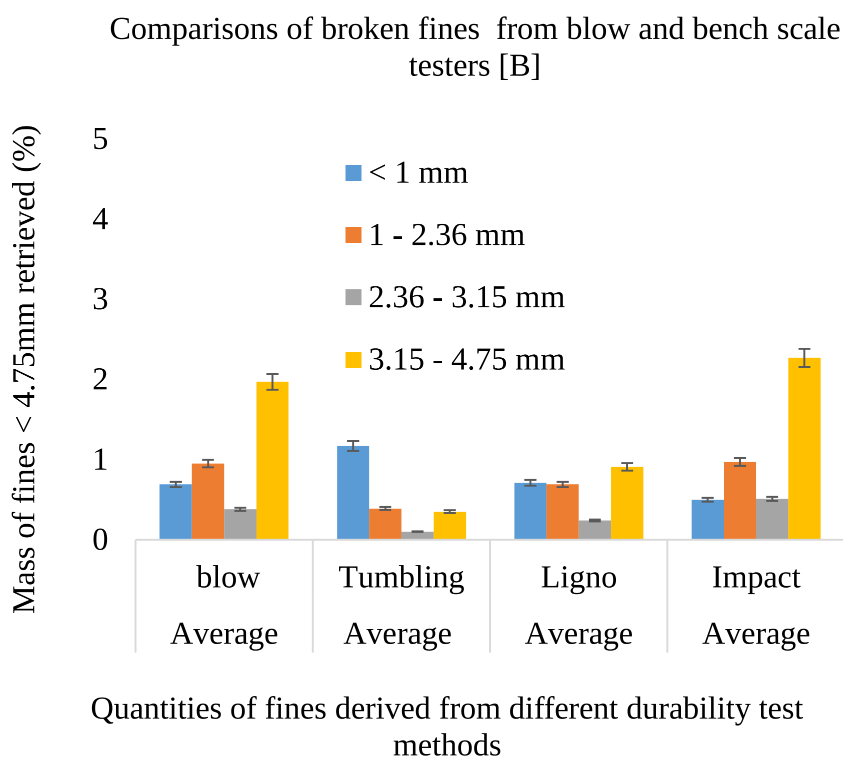


Figure 7.7 Compares the average pattern of pellets degradation in an unvented full-scale pneumatic blow to those of the three bench-scale pellets durability testers

The trends of pellets degradation observed in figure 7.6 and figure 7.7 were very similar in comparisons, even though in this case, the full-scale pneumatic degradation tests, was conducted in an unvented pressurised tank condition. The rotary impact tester retained the highest breakage correlation to that of full-scale pneumatic tests, followed by the Ligno tester, which also showed similar degree of correlation with the full-scale test, especially in the columns of broken particles sizes between 4.75 - 3.15 mm, and 1 - 2.36 mm diameters. By comparison, the average breakage pattern of pellet degradation in tumbling box durability tester remains with the reverse pattern of degradation in comparison to that of full-scale pneumatic blow degradation test. The biggest differences seemed to occur in the finer class ranges of broken particles size fractions below 1 mm diameter.

7.4 Comparison of Average Pellets Degradation in Bench and Full Scale Pneumatic Blow Delivery System

The average mass of degraded ranges of broken pellets fractions from the three bench scale durability tests was compared to the average mass of degraded pellets derived from full-scale pneumatic blow degradation tests. The results for the vented and unvented blow conditions of the pressurised tank are shown in figure 7.8 and figure 7.9.

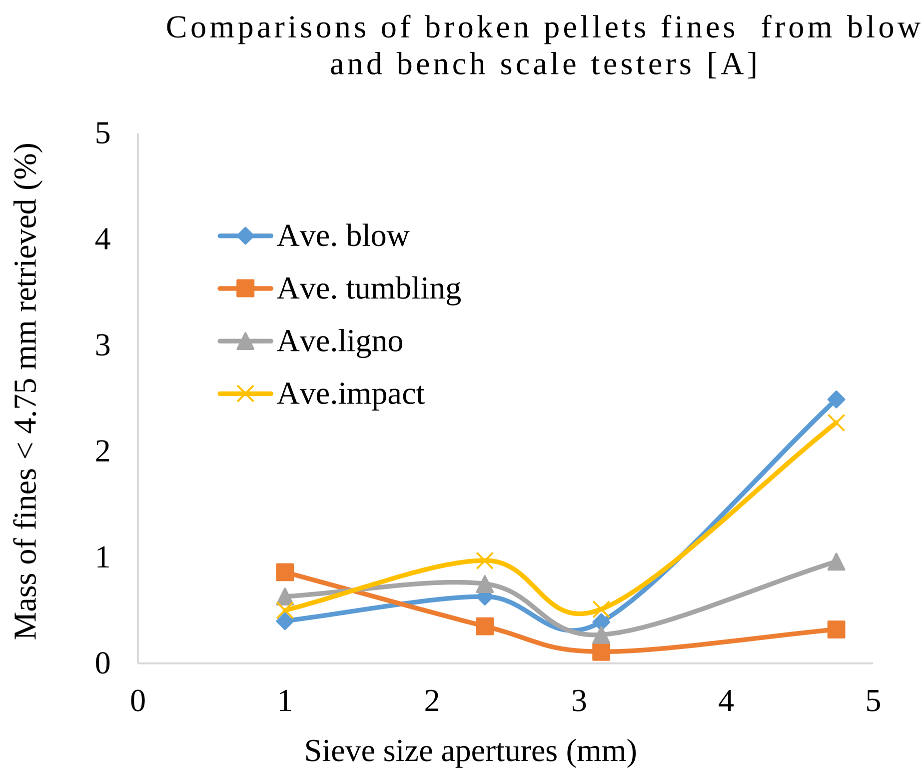


Figure 7.8 Compares the average pattern of pellets degradation in a vented full-scale pneumatic blow and the three bench-scale testers

Similarly, the pellets breakage pattern of the three bench scale testers was compared to that of average unvented pressurised pneumatic degradation tests and the results are shown in figure 7.9.

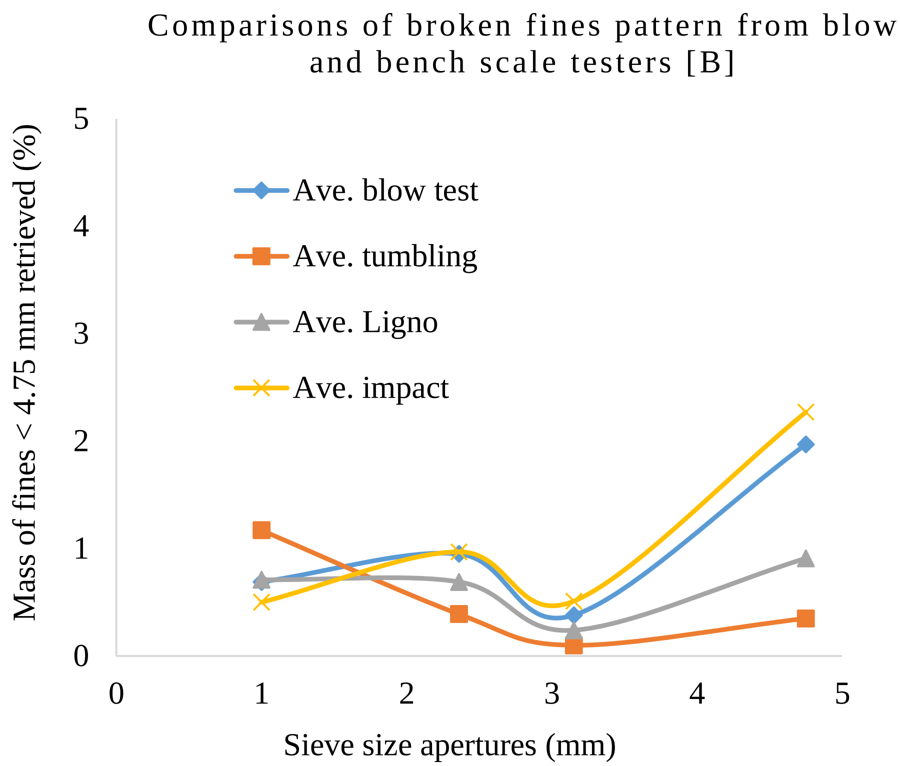


Figure 7.9 Compares the average pattern of pellets breakage in an unvented full-scale pneumatic degradation test and the three bench-scale testers

In both case, the results shown in figure 7.8 and figure 7.9 comparing the average mass and breakage patterns of pellets degradation in a vented blow (fig.7.8) and unvented (fig.7.9) full-scale pneumatic blow pellets degradation tests to the resulting breakage in the three bench scales pellets durability tests. The result has also shown that rotary impact tester appears to have the most similar trends of breakage to that of full-scale pneumatic degradation tests. Likewise, the Ligno tester, have also shown some degree of similarity in the mode of breakage observed in full-scale pneumatic blow degradation test, especially, in the region between 2.36 - 3.15 mm diameters. However, the average pattern of pellets degradation observed in tumbling box durability tester was in contrast to that of full-scale pneumatic blow pellets degradation tests.

The difference in pattern of pellets degradation relationship observed between the three testers reinforces the view that the rotary impact tester has the highest potential to predict pellets degradation in full-scale pneumatic delivery systems, followed by the Ligno tester, whereas the tumbling box tester is most unlikely to produce relevant data except perhaps for pellets dustiness tendency.

7.5 Scaling of Different Bench Scale Pellets Durability Test Results to Predict Pellets Degradation in Full Scale Pneumatic Blow Delivery System

Having seen how the resulting breakage characteristics of the average and single pellets durability tests conducted using the three bench scale testers relates with the pattern of pellets degradation in full-scale pneumatic blow test. An additional investigate on how long a sample of pellets needs to be tested continuously in any of the bench scale testers to produce an equivalent number of pellets degradation that could be observed in full-scale pneumatic pellets delivery systems. Therefore, a required quantity of fresh pellets sample (i.e. 500 g for Tumbling box, 100 g for Ligno and 2000 g for rotary impact testers) were tested consecutively, in each of the bench scale durability tester for four times. The tumbling box durability tests were conducted in accordance with the EN 15210-1 standard as described in section 3.4.3 and the Ligno test as described in (ÖNORM M 7135) standard see section 3.4.4. Likewise, the rotary impact test as described in section 3.4.5. After each test, the broken pellets fine (< 4.75 mm diameter) were removed and the remaining surviving pellets (> 4.75 mm diameter) were returned into the tester for the next subsequent durability tests and this was repeated using the same tester for four times. The fines were removed to expose the surviving pellets surfaces to a fresh contact area and prevent any form of cushioning effect that could alter the breakage behaviours of the pellets because this was what seems to be happing in the rotary impact tester. Similarly, in a lean phase pneumatic blow delivery systems where the material is suspended in air, a lower level of cushioning is expected to occur in the blowing pipeline.

The particle size distributions of the entire retrieved degraded pellets, after each test, were separated in accordance with ISO 3310-2 standard. The particle size distribution of the broken pellets fines was further analysed into different ranges (4.75 - 3.15 mm, 3.15 - 2.36 mm, 2.36 - 1 mm and < 1 mm diameters) and the respective mass of each size range was measured and determined as the percentage of the surviving pellets in each subsequent test, not the initial mass of the pellets before the first test. The measured masses were used for calculating the corresponding pellet durability index (PDI) using equation 3.5. The resulting PDI values (i.e. percentage degradation in each size range) obtained from the first four consecutive rotary impact, Ligno and tumbling box durability tests and the results were compared to that of full-scale pneumatic degradation test as shown in the following figures 7.10, 7.11 and 7.12.

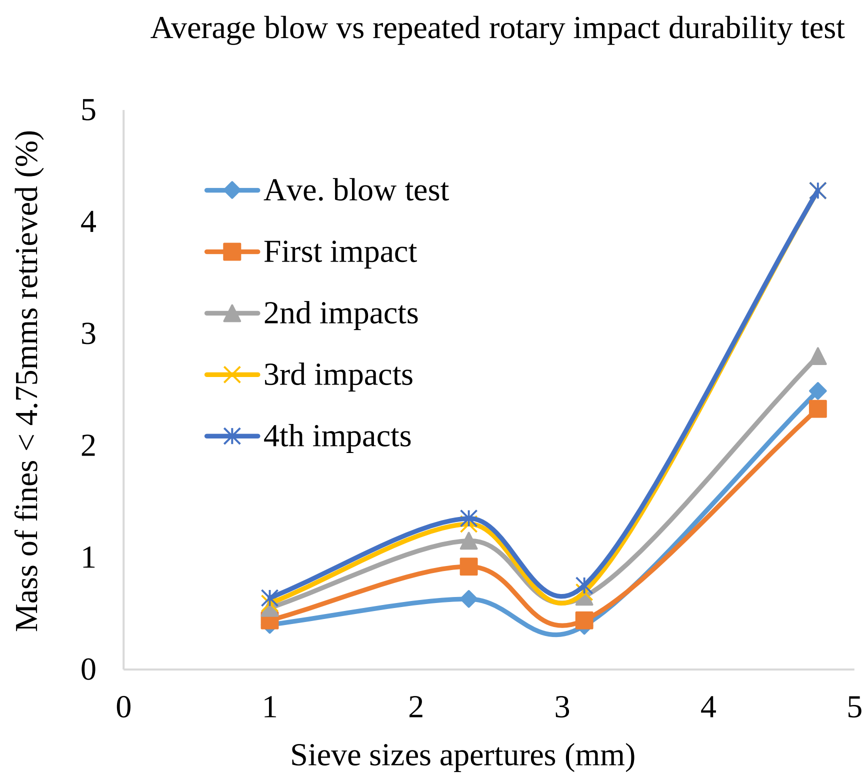


Figure 7.10 Compares the continuous breakage pattern of pellets in a rotary impact tester versus full-scale pneumatic pellets degradation tests

The first rotary impact durability tester shown in figure 7.10 appears to have better correlation and possible tendency to predict pellet degradation in full-scale pneumatic blow deliveries.

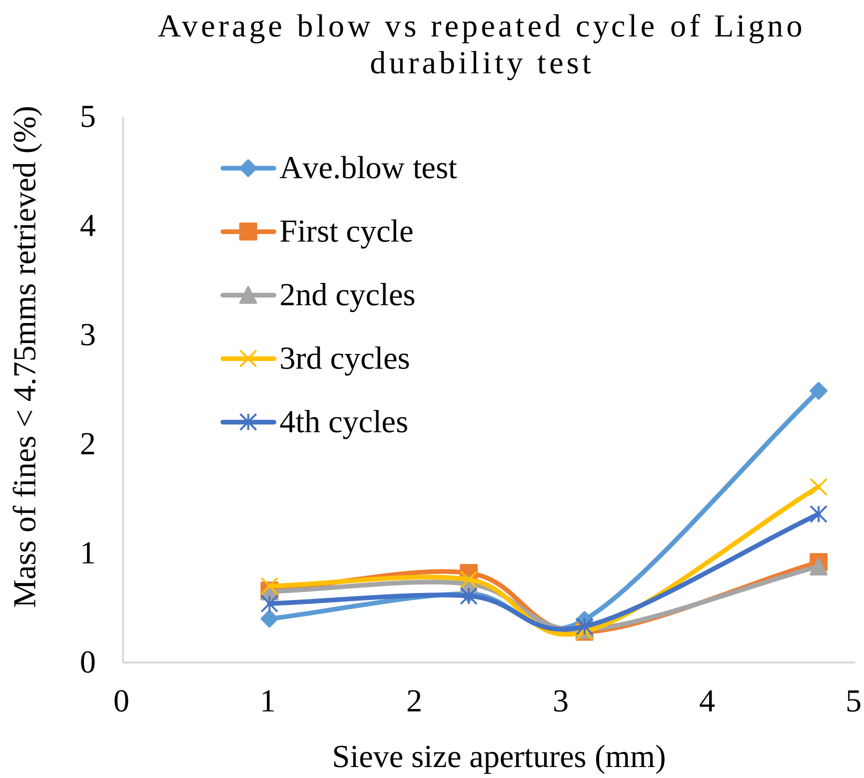


Figure 7.11 Compares the continuous pellets degradation pattern in the Ligno tester versus full-scale pneumatic blow degradation tests

Virgin samples of pellets from the same batch durability were tested using Ligno tester and results were compared to that of full-scale blow as shown in figure 7.11. The degradation of pellets in Ligno tester have also depicted some degree of pellets breakage pattern that are almost similar to that of full-scale pneumatic degradation test, especially in the region of broken pellets fines below 3.15 mm diameters, which is important reference for pellets durability measurement in the European EN 14961-2 standard.

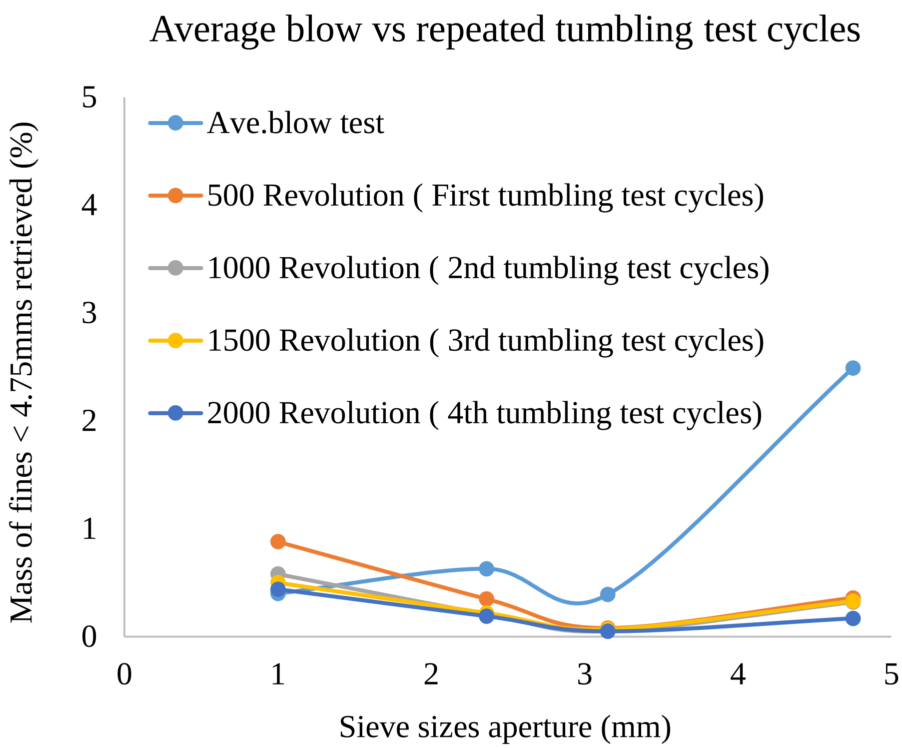


Figure 7.12 Compares the continuous breakage patterns of pellets in tumbling box durability tester versus average full-scale pneumatic blow degradation tests

However, the breakage pattern of pellets observed in the repeated tumbling durability tests conducted using the same batch of pellets sample was negatively correlated to the pattern of pellets breakage observed in full-scale pneumatic degradation tests, even with the continuous decrease in mass of the surviving pellets in the subsequent testing across all the tests runs.

It is important to note that, in this repeated pellets durability tests, one sample of wood pellets are tested consecutively for four times, in the bench scale tester and the surviving pellets (above 4.75 mm wire mesh sieve) was retested again, without adding the broken fine, to get the second PDI value. This process was repeated to achieve the subsequent PDI values, in each additional test runs. The result of the repeated rotary impact tests shown in figure 7.10 also reaffirms the continuous decrease in the pellets strength with subsequent durability testing. While the repeated Ligno pellets durability tests result shown in figure 7.11 appear to have less breakage with further testing which is possibly why the pellets have slight reduction in length in comparisons to the original pellets length before testing in figure 5.6. However, the breakage behaviour of pellets in the tumbling durability test was very different from the two other bench scale testers. The worst part of the tumbling durability tests is that the pellets appear to be more resistive to breakage with increasing number of tumbling test cycle, after the first 500 tumbling rotations. The increase in revolution per minute in the tumbling test from 500, 1000, 1500 and 2000 complete tumbling cycles, for every 10 minutes appears to have no significant impact on the pellets length reduction during the tumbling box tests.

7.6 Summary

A key finding of interest from this part of the work was the comparison between the resulting breakage characteristic of single and multiple bench scale pellets durability testers (rotary impact, tumbling box and Ligno testers), and that of full-scale pneumatic pellets degradation tests:

The single impact pellet durability test using rotary impact tester appeared to have shown the highest potential usefulness to predict pellets degradation in the full-scale pneumatic blow deliveries compare to Ligno and tumbling box tester, the conclusion was made based on similarity of pellet breakage pattern. However, Ligno tester has also shown some degree of pellets breakage patterns that seemed to correlate with the mode of pellets degradation observed in the full-scale pneumatic degradation tests, especially in the broken pellets fractions below 3.15 mm diameters.

The breakage patterns of pellets in the rotary impact tester showed a balance of volume and surface breakage mechanism which seemed to correspond well to that of full-scale pneumatic degradation tests. The second best in this respect was the Ligno tester, in which significant chipping of pellets also appears to have occurred, compared to what was found in tumbling box tester, where the pellets appeared to experience little other than surface wearing. The pellets tested in the tumbling box tester was believed to have suffered for more of surface breakage instead of combine impact and surface wearing because most of the broken finer particles were produced after the first 500 and subsequent tumbling rotations in the tumbling box test remain the highest. The total fines production appears to be reducing and stabilised with a subsequent increase in the number of tumbling rotation of same pellets sample from 500 to 1000, 1500 and 2000 revolutions. The finer broken pellets fractions below 1 mm diameters generated from the tumbled pellets with an increase in the number of rotation or tumbling tests cycles (rpm) appears to be constant. The conclusive summary in this chapter will be re-affirm by the outputs of breakage matrices model that compare the actual experimental data with the predicted results in next chapter.

Chapter 8. Using Breakage Matrices Model to Predict Pellets Degradation in Full Scale Pneumatic Blow Delivery System

8 Introduction

Evidence from the results of single and multiple bench scale pellets durability tests comparisons to those from full-scale pneumatic pellets degradation tests result in chapter seven have depicted the existence of some similarity. However, the extent or degree of the similarity between each of the bench tester pellet breakage mechanisms and that of full-scale pneumatic degradation tests was further investigated using a mathematical modelling approach known as' 'breakage matrices''. The investigation was carried out as an alternative way to explore the relationship that may exist between the bench and full-scale experimental degradation tests results, for clearer understanding. The breakage matrix modelling takes the percentage mass fraction of the initial size distribution of the pellets (before testing) and multiplies it by a matrix that represents the breakage function (for each durability test) to produce the outputs fractions. The outputs of the three bench scale matrices modelling results were compared and scaled-up to test prediction of pellet degradation in a full-scale handling system (i.e. pneumatic blown delivery system). This method of using the breakage matrices model to quantify or predict particle degradation in a full-scale pneumatic conveying system, from bench scale experimental data, has previously been demonstrated by (Baxter, et al. 2004; Abou-Chakra et al. 2004).

8.1 Test Material and Methods

The initial size distribution of the pellets before the bench or full-scale pneumatic pellets degradation tests are 6 mm diameter and ≤ 40 mm lengths. The pellets, at virgin state (before testing), was initially screened using 5.6 mm diameter wire-mesh sieve, to eliminate all the unwanted fines, before sampling in accordance with EN 14778 standards during loading. The samples of the clean pellets were then used to conduct the three bench scale pellets durability test, (one for each tester), repeatedly for ten consecutive times. The bench scale durability tests were conducted using both standard tumbling box, Ligno and the newly modified rotary impact tester. The same batch of pellets used in the bench tests was also used in the full-scale pneumatic pellet degradation tests, conducted using different targeted blow tank pressures (0.3 bar, 0.5 bar, 0.8 bar and 1 bar) of the pressurised pneumatic tanker truck delivery system.

A detailed description of the tumbling box durability tests (in accordance with EN 15210-1: 2009 standard) can be found in section 3.4.3. Likewise, a repeated Ligno durability test was conducted using 100 g of clean pellets from the same batch consecutively for ten times, each cycle being in accordance with the ÖNORM M 7135 standard as described section 3.4.4. The repeated rotary impact durability tests were also conducted using 2000 g of same batch pellets repeatedly for ten consecutive times as described in section 3.4.5. In total, thirty bench scale pellet durability tests, (ten runs per each tester) were conducted repeatedly using fresh one pellets sample on each of the bench scale testers. All the pellet samples came from the same manufacturing batch. All experimental tests were conducted at ambient temperature conditions approximately 23˚C.

The full descriptions of the full-scale pneumatic pellets degradation test are given in chapter 6 of this thesis in detail. However, the entire degraded batch of each blown pellets was treated as a whole, after each blowing test, to avoid any form of sampling errors arising due to fines segregation during screening, and particle size distribution (PSD) analysed. The screening was conducted in accordance with the EN 15149 - 1: 2010 standard (E. V. Alakangas, 2009). A Rotex screening machine was used for the full-scale sieving and manual sieving for the bench scale tests. The degraded pellets were screened using 4.75 mm, 3.15 mm, 2.36 mm and 1 mm wire mesh sieves. During screening the degraded pellets were first separated into surviving (> 4.75 mm diameter) and broken pellets fractions (> 4.75 mm diameter). The broken pellets fractions were further separated into < 4.57- 3.15 mm, 3.15 - 2.36 mm, 2.36 – 1 mm and < 1 mm diameters ranges. Each of the specific single-class ranges presents a unique element of information about the particle breakage characteristic, in the breakage matrices. The weight of each specific single-class range (a portion of either screened surviving or broken pellets fractions) was measured using an electronic balance before using the corresponding value to calculate the pellet durability index (PDI) using equation 3.5. It is important to note that two assumptions were made during the breakage matrix modelling to fit in with the experimental tests data. The first assumption is that the presence of one class of broken particle size in the mixture has no effect on the breakage characteristic of the other class of particles sizes within the mixture, even though, the particles in a tumbling box and Ligno testers are enclosed in a confined box or chambers. The second assumption is that, all the breakage events that took place during each of the degradation test experiment were single breakage event.

8.1.1 Breakage Matrices Modelling and Approach

The breakage matrices present the proportion of degraded particles in a rectangular array form such that the surviving and broken down pellets fractions are arranged in descending column order of each breakage event. The surviving and broken pellets sizes fractions are degraded pellets fractions that remain above and below the 4.75 mm wire-mesh sieve diameters after the screening. The PDI values of each class ranges of the degraded pellets sizes are the building block of each column in the breakage matrices (***M***). The breakage matrices present quantities of degraded pellets in each specific size fractions and breakage characteristics of that class range as shown in table 8.1. The method of generating the breakage matrices from the degraded particles of both the bench and full-scale pneumatic blow tests was similar. The breakage matrices were arranged in rectangular arrays that store the information on the percentage mass of the surviving pellet size distribution, which subsequently decreases with increasing number of impacts through the degradation tests. Such that, the coefficient a_{ij} represent the initial mass fraction of particles j that break down into smaller size fraction of i particles. For example, when the surviving class fraction (> 4.75 mm) broke down into different range of smaller particles size fractions measured between 4.75 - 3.15 mm, 3.15 - 2.36 mm, 2.36 -1 mm and < 1 mm diameters. A typical mathematical relationship that yields the breakage matrices is shown in equation 8.1.

$$B = \begin{bmatrix} \frac{m_1}{m_1} & 0 & 0 & 0 & 0 & 0 \\ \frac{m_1-m_2}{m_1} & \frac{m_2-m_3}{m_2} & 0 & 0 & 0 & .. \\ \frac{m_2-m_3}{m_1} & \frac{m_3-m_4}{m_2} & \frac{m_3-m_4}{m_3} & 0 & 0 & .. \\ \frac{m_3-m_4}{m_1} & \frac{m_4-m_5}{m_2} & \frac{m_4-m_5}{m_3} & \frac{m_4-m_5}{m_4} & 0 & .. \\ \frac{m_4-m_5}{m_1} & .. & .. & .. & 0 & 0 \\ .. & .. & .. & .. & \frac{m_{n-1}-m_n}{m_1} & 0 \\ \frac{m_{n-1}-m_n}{m_1} & .. & .. & .. & \frac{m_{n-1}-m_n}{m_{n-2}} & \frac{m_{n-1}-m_n}{m_{n-1}} \end{bmatrix} \quad \text{Equation (8.1)}$$

The input column vector relates with the mathematical breakage matrices formulas presented as equation 8.1 to produce the output column vector, in decreasing particles sizes manners, as shown in equation 8.2.

$$\begin{bmatrix} a_{11} & 0 & 0 & 0 & 0 & ... \\ a_{21} & a_{22} & 0 & 0 & 0 & ... \\ a_{31} & a_{32} & a_{33} & 0 & 0 & ... \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 & ... \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} & ... \end{bmatrix} * \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ .. \\ I_5 \end{pmatrix} = \begin{pmatrix} o_1 \\ o_2 \\ o_3 \\ .. \\ o_5 \end{pmatrix} \quad \text{Equation (8.2)}$$

Input & output

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ .. \\ I_5 \end{pmatrix} \Rightarrow \begin{pmatrix} o_1 \\ o_2 \\ o_3 \\ .. \\ O_5 \end{pmatrix}$$

$$\sum_{j=1}^{n} I_j = 1$$

$$\sum_{i=1}^{m} o_i = 1$$

$$\sum_{i=1}^{m} a_{ij} = 1 \; for\ each\ j[1, \dots, n]$$

The breakage matrix model was established using equation 8.2 where the input column vector ($I_1, I_2 \dots In$), represented by 1, 0, 0, 0, 0 (having mono size diameter of the particles) was multiplied with the entire columns and rows of the breakage matrices (***M***) on the left-hand side ($a_{11}, a_{22} \dots \dots a_{55}$) of equation 8.2 to produce the outputs column vector on extreme right. The variables in the breakage matrix represent the percentage mass of the pellets or parts thereof that fall into the different size ranges after the breakage event. This simply means that inputs column (***I***) multiplying by breakage matrix (***M***) to produce the output columns matrix (O) ($O_{11}, O_{22} \dots On$) on the right-hand side. The columns of the breakage matrix presented in equation 8.2 were derived from the mathematical relationship between the (overall, time – averaged) input and output column matrix fractions of degraded particles using equation 8.2 such that.

$$\boldsymbol{M} \times \boldsymbol{I} = \boldsymbol{O} \qquad \text{Equation (8.3)}$$

Where **I** and **O** are the input and output column vectors. ***M*** is the breakage matrix transforming ***I*** to ***O*** by rules of matrix multiplication. The elements of the column vectors represent the mass fraction of particles found on each sieve during the sieve analysis of the input and output materials.

The diagonal selective functions $a_{11}, a_{22}, a_{33}, a_{44}$ and a_{55} in the breakage matrices (**M**) shown in equation 8.2 represent the relative mass of the surviving pellets in each size interval from every single durability test run. The lower off-diagonal elements, (fractions below the surviving class range) are the percentage of broken particles falling into the size classes below the starting class size. However, in this case, only the first column of the breakage matrices has non-zero numbers below the diagonal, because when the same pellets were tested repeatedly, the broken fraction was removed and only the surviving "whole" pellets (+ 4.75 mm) were reused again for the ten times consecutive tests. The rest of the sub-diagonal values of the breakage matrix are therefore represented with zeros, and the diagonal values apart from the top left value are set as 1, as shown in table 8.1. The upper off-diagonal elements are all represented by zeros to indicate that there is no size enlargement after each test run. What this means when using it to model the real process is that breakage of the particles that are already below 4.75 mm is ignored.

Using this simplification described above (all diagonal members being unity except the top left value) was a decision made at an early stage to make the system of breakage matrix use more practical to the application being studied. To obtain a fully and accurately populated breakage matrix, the sub-diagonal members in each column can only be determined by undertaking a separate breakage test with a subsample of material in each individual size class. To do this means taking input material across the whole size range (which is not normally available in practical pellet processing), separating it into individual size classes, and then undertaking an individual breakage test then a sieve analysis on each input size class. This is a large amount of work; in a research context, it could be undertaken, but it is not realistic to do this for regular analysis of pellet samples in an industrial setting. However, in reality, it is commonly known from grinding studies that as particles get smaller, the breakage they suffer from the same process drops off dramatically; this means that the diagonal values other than the top left are normally close to unity. Therefore, given the amount of work to be done in a limited time in this project, the need for simple and quick working for potential industrial application, and the known secondary effect of impact in these smaller classes, the decision was taken to test this simplified approach.

The breakage matrix model was achieved by multiplying the input column vector mathematically with the breakage matrices (***M***) of each mono size column elements, of each breakage event, in ascending order of impact test number as shown in a linear regression equation 8.4.

$$|\mathbf{I}| \times |\boldsymbol{M_1}| \times |\boldsymbol{M_2}| \times |\boldsymbol{M_3}| \times \ldots \times |\boldsymbol{M_n}| = |\boldsymbol{o_n}| \qquad \text{Equation (8.4)}$$

Using equation 8.3 the column of breakage matrices events, for continuous re-use of the surviving pellets above 4.75 mm diameters, are shown in equation 8.4.

$$\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ ..n \end{pmatrix} \xRightarrow[\text{1}^{\text{st}}\ \text{Test}]{} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ .a_n \end{pmatrix} \qquad \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_n \end{pmatrix} \xRightarrow[\text{2}^{\text{nd}}\ \text{Test}]{} \begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_n \end{pmatrix} \qquad \begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_n \end{pmatrix} \xRightarrow[\text{3}^{\text{rd}}\ \text{Test}]{} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_n \end{pmatrix} \qquad \text{Equation (8.5)}$$

Table 8.1 below shows this in practice for an example, determining breakage matrices for three successive cycles of testing on a subsample of pellets. The input and output size distribution vector of each test is known from sieve analysis of the samples before and after each test (obviously, the output from one test is the input to the next test) and the values in the matrices are determined to fit, based on the simplification described. The first column of the matrices gives the information on the percentage mass of pellets that survived (a_{11}) and broken downsizes fractions ($a_{21......}a_{51}$) in that matrix column. The second, third, fourth and fifth columns of the breakage matrices arrays were represented by 01000, 00100, 00010, and 00001 as shown in table 8.1, i.e. ignoring further breakdown of the smaller classes. An example, of how the input column vector were multiplied with the breakage matrices to achieve the output column vectors are shown in the following steps below:

Input = 1* matrix = 0.9812, Output = 0.9812

Therefore,

1st Output matric multiplication is equal (1 * 0.9812) = 0.9812

2nd matrix output equal to (1 *0.0036) + (0 * 1) = 0.0036

3rd matric output is equal to (1 *0.0009) + (0 * 0) + (0 * 1) + (0*0) = 0.0009

4[TH] Output is equal to (1 *0.004) + (0 * 0) + (0 * 1) + (0*1) (0*0) = 0.004

5[th] Output is equal to (1 *0.0097) + (0 * 0) + (0 * 1) + (0*1) (0*1) = 0.0097

Table 8.1 Present the mathematical multiplication of breakage matrix model for the repeated tumbling box durability tests results

Class size (mm)	Inputs (mm)	Breakage matrix (mm)					Outputs (mm)
8.0 -4.75	1	0.9812	0	0	0	0	0.9812
3.15-4.75	0	0.0036	1	0	0	0	0.0036
2.36-3.15	0	0.0009	0	1	0	0	0.0009
1-2.36	0	0.004	0	0	1	0	0.004
0-1	0	0.0097	0	0	0	1	0.0097
8.0 -4.75	0.9812	0.9853	0	0	0	0	0.9668
3.15-4.75	0.0036	0.0043	1	0	0	0	0.0078
2.36-3.15	0.0009	0.008	0	1	0	0	0.0087
1-2.36	0.004	0.0025	0	0	1	0	0.0065
0-1	0.0097	0.0061	0	0	0	1	0.0157
8.0 -4.75	0.9668	0.9901	0	0	0	0	0.9572
3.15-4.75	0.0078	0.0017	1	0	0	0	0.0095
2.36-3.15	0.0087	0.0008	0	1	0	0	0.0095
1-2.36	0.0065	0.0021	0	0	1	0	0.0085
0-1	0.0157	0.0055	0	0	0	1	0.0210

The data presented in table 8.1 is to show the sequence of modelling breakage matrices, for a sequence of three consecutive tumbling box durability tests on one pellet subsample, with all - 4.75 mm removed from the subsample between each test, and accumulated aside but accounted for in the vectors. The columns of the matrices are here present the real particles breakage event in actual repeated tumbling box durability test. The same methods were applied to achieve breakage matrices for the Ligno, rotary impact and the full-scale pneumatic pellet degradation (durability) test results as well.

8.1.2 The Predicted Version of the Breakage Matrix Using only the First Pellets Durability Test Breakage Matrices

Table 8.1 demonstrated how the (measured) input size fractions of pellets interacts in sequence the (deduced) breakage matrices to produce the (measured) output column vectors. It is apparent, as shown in table 8.1, that the breakage matrix does not remain constant, but evolves – in table 8.2, all the breakage value gradually reduces. As was shown in previous chapters, this is a trend observed more with the tumbling box test than with other tests.

However, to undertake such a modelling approach to predict pellet breakdown in a practical scenario would involve undertaking repeated tests (impact, tumbling box or Ligno test) and sieve analyses to obtain the evolving breakage matrices, which is undesirable; it is unlikely that industry users would be prepared to undertake this quantity of work. Hence the question was asked; if one was to undertake only ONE cycle of bench testing, with clean input pellets and one sieve analysis after the test, then work out a breakage matrix based on these results and the simplification postulated above (all diagonal values unity except the top left value), and subsequently used this to predict breakdown in multiple tests (representing pipelines with more impact e.g. more bends), would the level of accuracy achieved be good enough to help with practical assessment of different reception systems? To test this, the use of such an approach for predicting the results of multiple test cycles was evaluated.

The input size fractions vector (1, 0, 0, 0, and 0 for the first test) was multiplied by the (deduced) first test breakage matrix to achieve the (measured) output column vector from the first test. The output column vector of this first test then becomes the input column vector for the second test, so is multiplied by the same breakage matrix (deduced from the first test), to achieve an output column vector (predicted) for the second test. Continuing this process, the first breakage matrix remains constant to predict the subsequent output column vectors as shown in table 8.2, for ten consecutive runs of the durability test.

The size distribution modelling was achieved by multiplying the input column vector (I_1), which is either in a virgin or surviving class state of particle size distribution, repeatedly with the breakage matrix (M_1) of the first durability test (which was kept constant) to predict the output columns vectors (MI_n). The mathematical relationship is shown in equation 8.5. Where

$$|\boldsymbol{M_1}|^{n} \times |\boldsymbol{I_1}| = [\mathbf{O}_n] \qquad \text{Equation (8.6)}$$

The sequence of the inputs multiplication with the breakage matrices shown in equation 8.6

$$\begin{pmatrix}1\\0\\0\\0\\..n\end{pmatrix} \xrightarrow[1^{st}]{} \begin{pmatrix}M_1\\M_2\\M_3\\M_4\\M_n\end{pmatrix} \begin{pmatrix}0\\1\\0\\0\\..n\end{pmatrix} \xrightarrow[2^{n}]{} \begin{pmatrix}M_1\\M_2\\M_3\\M_4\\M_n\end{pmatrix} \begin{pmatrix}0\\0\\1\\0\\..n\end{pmatrix} \xrightarrow[3^{rd}]{} \begin{pmatrix}M_1\\M_2\\M_3\\M_4\\M_n\end{pmatrix} \qquad \text{Equation (8.7)}$$

In this case, the particle size distribution (PSD) of the first breakage event, column vector matrices (M_1, M_2, M_3, M_4...Mn) remain fixed throughout the number of predicted breakage matrix outputs. Whereas, the PSD of the input the column vectors appear to be reducing with the subsequent simulated test runs. Since the predicted output column vector of the first run test becomes the input column vector of the second runs matrix multiplications.

The mathematical relationship shows how input column vectors, relates with the fixed breakage matrices (the degraded particles size distribution of the first durability test) to predict the output column vectors using equation 8.7. The breakage matrix of the first pellets durability test (when the pellets are in a virgin condition) was kept constant, throughout the number of predicted matrix outputs runs. During the predicted matrix multiplication, the variables of the first output column vector were used as input column vector, to multiply the fixed breakage matrices (derived from the first run test) which resulted in the production of the predicted second output column vector. The process was repeated to generate ten predicted output column vectors. The assumption was since same pellets sample were tested repeatedly for ten consecutive times to generate the actual experimental data that was compared to the predicted breakage outputs results. A typical example of third runs methodical multiplication relationship between the inputs and the breakage matrices that results in the predicted outputs column vectors were demonstrated in table 8.2.

$$\begin{bmatrix} M_{11} & 0 & 0 & 0 & 0 & \dots \\ M_{21} & 1 & 0 & 0 & 0 & \dots \\ M_{31} & 0 & 1 & 0 & 0 & .. \\ M_{41} & 0 & 0 & 1 & 0 & \dots \\ M_{51} & 0 & 0 & 0 & 1 & \dots \end{bmatrix} * \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ .. \\ I_5 \end{pmatrix} = \begin{pmatrix} MI_1 \\ MI_2 \\ MI_3 \\ .. \\ MI_5 \end{pmatrix} \qquad \text{Equation (8.8)}$$

Table 8.2 Present the predicted input and output breakage matrix multiplications for tumbling box durability tests results

Class sizes (mm)	Inputs (mm)	Breakage matrix (mm)					Outputs (mm)
8.- 4.75	1	0.9812	0	0	0	0	0.9812
3.15-4.75	0	0.0036	1	0	0	0	0.0036
2.36-3.15	0	0.0009	0	1	0	0	0.0009
1-2.36	0	0.004	0	0	1	0	0.004
< 1	0	0.0097	0	0	0	1	0.0097
8. - 4.75	0.9812	0.9812	0	0	0	0	0.9628
3.15-4.75	0.0036	0.0036	1	0	0	0	0.0071
2.36-3.15	0.0009	0.0009	0	1	0	0	0.0018
1-2.36	0.004	0.004	0	0	1	0	0.0079
0-1	0.0097	0.0097	0	0	0	1	0.0192
8. - 4.75	0.9628	0.9812	0	0	0	0	0.9447
3.15-4.75	0.0071	0.0036	1	0	0	0	0.0106
2.36-3.15	0.0018	0.0009	0	1	0	0	0.0026
1-2.36	0.0079	0.004	0	0	1	0	0.0118
< 1	0.0192	0.0097	0	0	0	1	0.0286

The table shows the first three runs predicted breakage matrices modelling procedure for the tumbling box experimental results. The same method was deployed to achieve the predicted breakage matrices results of Ligno and rotary impact durability tests and that of the large-scale pneumatic pellet degradation tests results.

8.2 Results and Discussion

The resulting outputs of the measured (actual experiment) and the predicted versions of the breakage matrices modelled results of the three bench scale pellets durability testers and the scaled bench to full-scale were all presented and discussed in this section. The measured and predicted level of pellets degradation in the three bench scale testers, after ten impacts, were compared and the scaled bench tests to full-scale pneumatic pellets degradation results were also presented.

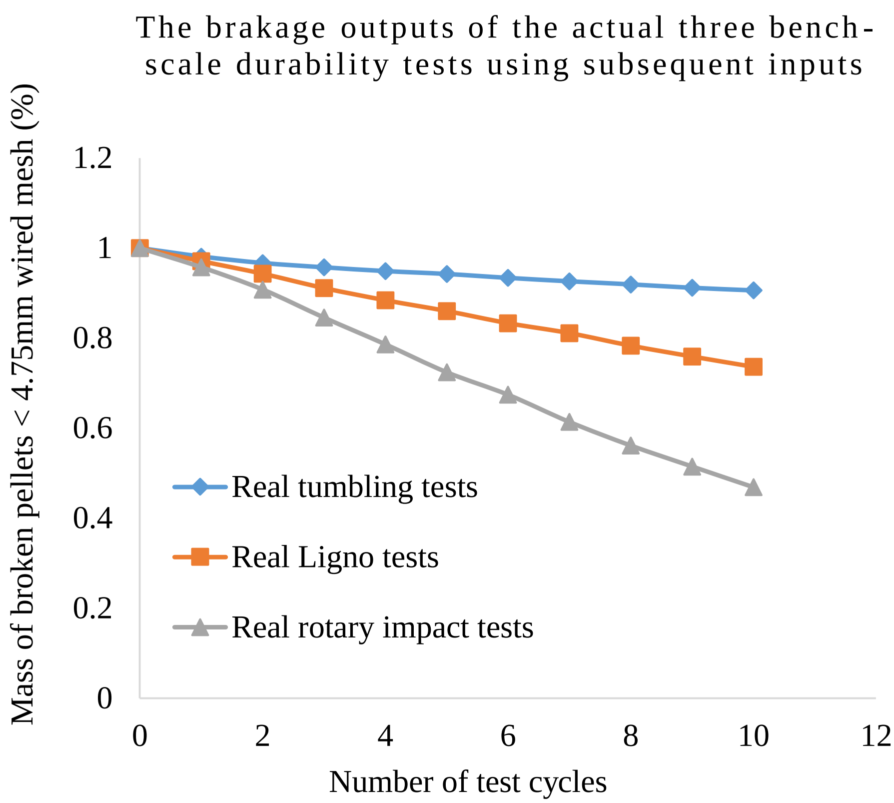


Figure 8.1 The comparisons of actual repeated pattern of wood pellets damage incurred by the three bench-scale pellets durability testers

(Tested for ten consecutive times)

The actual (measured experiment) level of pellets degradation, after testing a fresh single sample of pellets in each of the three-bench scale pellets durability tester, for ten consecutive times, results are depicted in figure 8.1. The pellets in the repeated rotary impact durability tests lost about 53 % 1-PDI of its initial 6 mm size diameter pellets to < 4.75 mm diameters, after the ten consecutive impact durability tests. Likewise, about 25 % of the initial 100 g in Ligno tester and 10 % of the initial 500 g pellets in tumbling durability tests have degraded into < 4.75 mm diameters, after the same ten consecutive pellets durability tests.

The same level pellets damage, after ten consecutive number of durability tests cycles, was predicted using breakage matrix modelling described above, and resulting level of predicted pellets degradation in tumbling box, Ligno and rotary impact testers, after the ten consecutive test cycles were shown in figure 8.2.

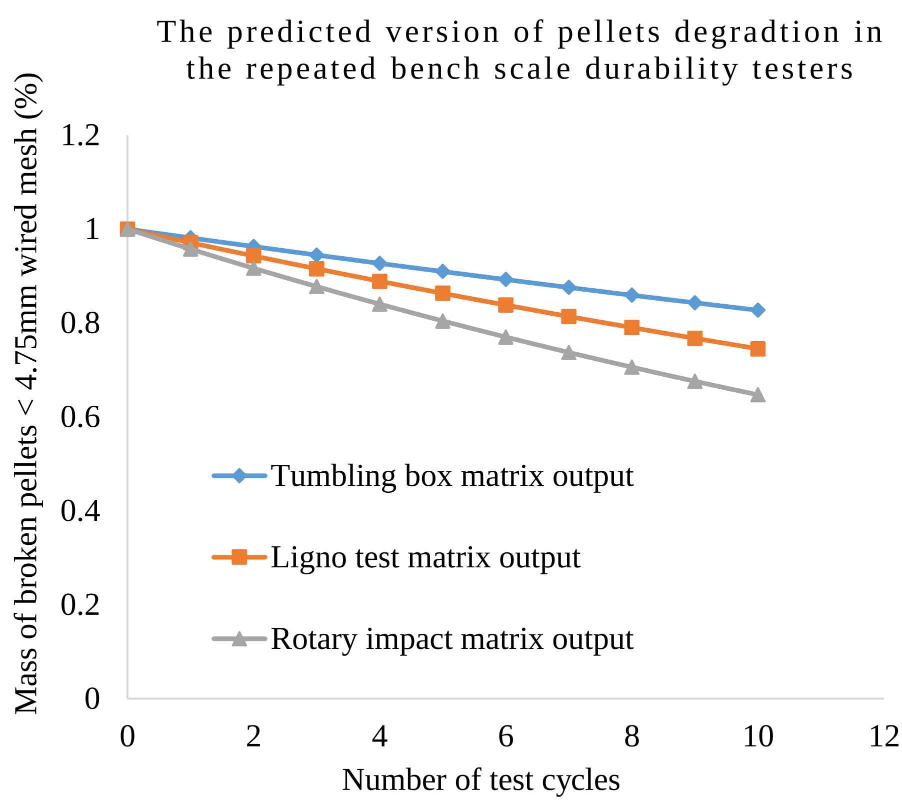


Figure 8.2 The breakage pattern of wood pellets from the three-bench scale durability testers, predicted by the breakage matrices outputs

(By multiplying breakage measured from the first test)

The predicted level of pellets degradation in tumbling box appears to have slightly increased by about 0.5 % in comparisons to the actual experimental tumbling tests result (in figure 8.1), where the percentage mass pellets lost to < 4.75 mm diameters was 0.92 % and the predicted result was 0.82 % breakage, after ten times testing of same single pellets sample.

No significant difference was observed between the resulting levels of actual measured and the predicted matrix outputs degradation of pellets in Ligno tester, after the ten consecutive durability tests cycles. The difference between actual measured and predicted Ligno test results was just about 0.01 % (i.e. 0.74 % to 0.75 %) which negligible. However, the predicted rotary impact pellets degradation was lower than the actual measured experimental tests results by almost about 0.18 %. Cumulatively, the difference between the matrices predicted (0.65 %) and the actual measured (0.47 %) losses of pellets form from initial 6 mm to < 4.75 mm diameters due to degradation is almost about 0.18 %. The variation (about 0.18 %) between the two rotary impact tests results may impose another concern about the confidence in linking the two results.

8.2.1 Scaling 1 Bench Test Real Breakage Matrix to Actual (Average of All Blows at Different Conditions)

A trial was also undertaken to see how the results from each of the bench scale testers (tumbling box, Ligno and the newly introduced rotary impact testers) could be scale to predict pellet degradation in the full-scale pneumatic pellets delivery system. The basic concept to be tested was the use of a single number to capture the tendency for a combination of given pellet delivery pipeline and operating conditions to cause pellet breakage, in relation to the breakage measured in the bench scale test. If this could be achieved then a pipeline layout and operating conditions could be summarised in its attrition effect, by a single number (albeit modified in relation to operating conditions). It would allow, for sufficient further study of the effects of numbers of bends, flexible pipe etc., for any proposed pipeline to be easily assessed and given a “degradation index” based on the layout, and this degradation index would have a useful physical meaning in predicting the effect of blowing the pellets in that pipeline.

To achieve this "calibration" between the bench scale test and the actual blowing line, the degradation caused by the full-size test pipeline (averaged across all the tests at different blowing conditions) was put on the graph of predicted degradation versus number of cycles of tests based on repetition of the breakage matrix in the first test. The reason for using this predicted multi-cycle degradation curve was to enable the pipeline breakage to be predicted from a single cycle of the bench scale tests.

In this case, the - 4.75 mm fraction was used although it would be equally possible to undertake this analysis based on a different size fraction of interest.

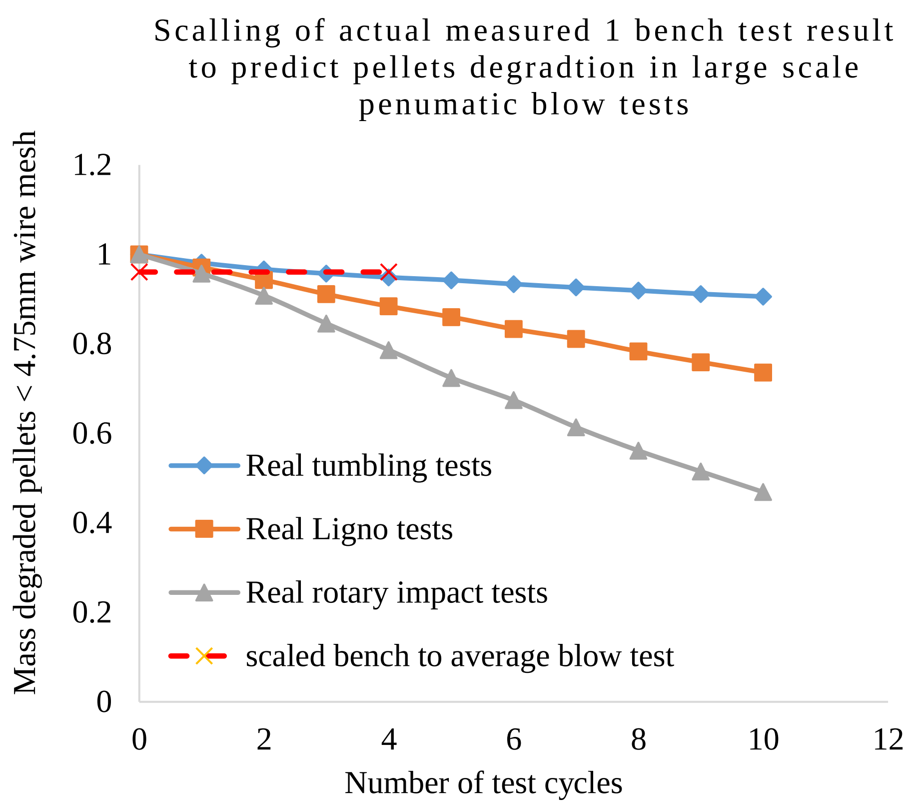


Figure 8.3 Using one actual pellets durability test result of each bench-scale pellets durability tester to predict pellets degradation in full-scale pneumatic deliveries

(The red dotted line shows the required number of actual bench-scale pellets durability tests required to predict same batch pellets degradation in real pneumatic delivery system).

The average pellets degradation attained after the pneumatic blow pellets degradation tests conducted, conducted using four different blowing pressures (0.3 bar, 0.5 bar, 0.8 bar and 1 bar) was divided by the first PDI value of each bench scale pellets durability test result. The ratio between the two tests was determined as (0.9607 %) and is indicated by the red dotted horizontal line across the three actual and predicted bench scales pellet durability tests results, shown in figure 8.3 and figure 8.4. The dotted red line crosses each bench scale test indicates, the estimated number of possible bench scale pellets durability tests cycles that is likely to predict same degree of pellets degradation in a full-scale pneumatic delivery. The red dotted line across the rotary impact test result shows that one rotary impact test cycles, Ligno tester shows about two test cycles and tumbling box shows four tumbling tests cycles may be used, on the same batch wood pellets, to predict pellets degradation in a full-scale pneumatic blow delivery system.

For comparison, the outputs of the first predicted level of pellets degradation in each bench scale testers (tumbling box, Ligno and rotary impact testers) results were also scaled in the same way (dividing each first PDI value with average blow test PDI) to predict pellets degradation in a full-scale pneumatic blow delivery system. The estimated number of predicted bench scale tests required were also shown in figure 8.4.

The red horizontal dotted line across the axis of the three predicted bench scale pellets durability result in figure 8.4 indicates the estimated number of predicted bench scale durability tests require to predict same batch wood pellets degradation in a pneumatic blow delivery system. The predicted version of the first rotary impact bench scale durability test appears to have high tendency to predict pellets degradation in the pneumatic blow delivery system compare to Ligno and tumbling box testers. As evidence in figure 8.4, a single rotary impact, two Ligno and three tumbling box predicted bench scale pellets durability tests cycle may be used to predict pellets degradation in full-scale pneumatic blow delivery system, provided the blowing pressures is $\leq$ 1 bar.

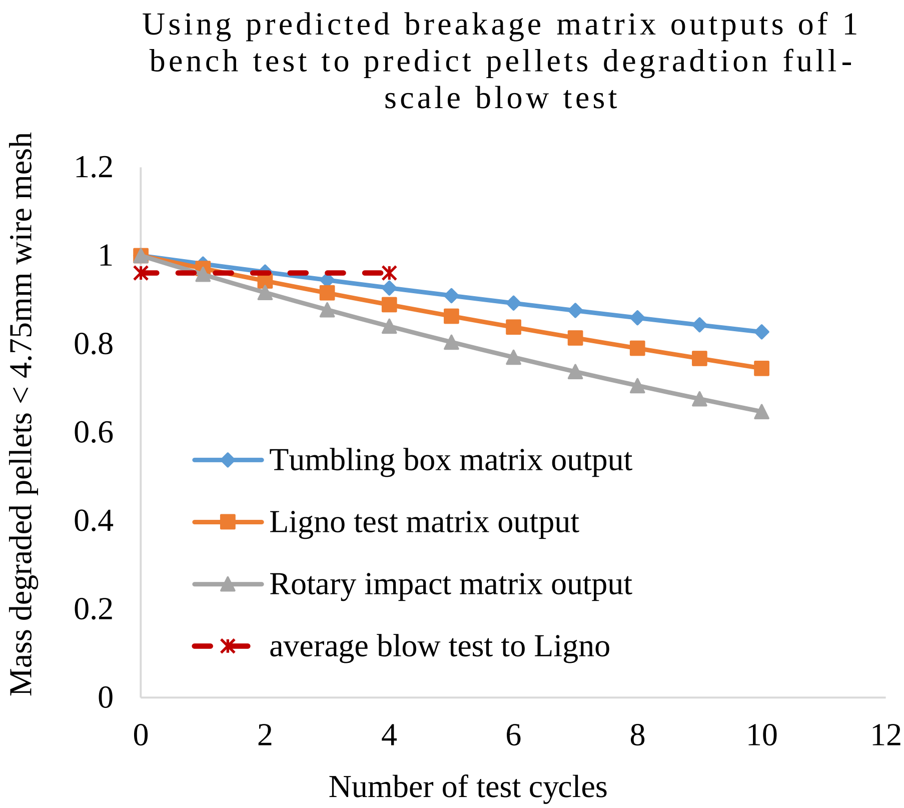


Figure 8.4 Using one predicted bench-scale pellets durability test result of each bench-scale tester to predict pellets degradation in full-scale pneumatic deliveries

(The red dotted line shows the required number of predicted bench scale pellets durability tests required to predict same batch pellets degradation in real pneumatic delivery at ≤ 1 bar).

8.2.2 Scaling Factor 1 Bench Test to Actual Blow at 0.8 bar Average Conditions of All Blows Pressures

While the above scaling study was based on the average of all blowing tests under different conditions for the one pipeline, it was clearly indicated from the tests that the blowing condition also has a strong influence on the degradation in the pipeline. Therefore, it is reasonable to suppose that the effect of a different blowing condition could be represented by a change in the “degradation index”, determined in the same way as shown above but averaged for a particular blowing condition rather than over the average of all tests.

Therefore, the results of each predicted bench scale level of pellets degradation were scaled to examine the number of predicted bench scale pellets durability tests require to predict an equivalent level of average pellets degradation observed in all the pneumatic blow deliveries that took place at 0.8 bar blower pressure. In this case, the average PDI of all the pellet blown at 0.8 bar blowing pressures degradation (about 95.91 %), in all the pneumatic deliveries that took place was divided by the average PDI values of each first predicted bench scale pellets durability tester outputs to achieve the ratio between the benches and full-scale tests. The ratio was used to determine the number of predicted bench scale pellets durability tests required to give a possible estimated equivalent level of pellets degradation in all the 0.8 bar blowing delivery pressure was calculated and presented in a dotted red horizontal line across the axis, as shown in figure 8.5.

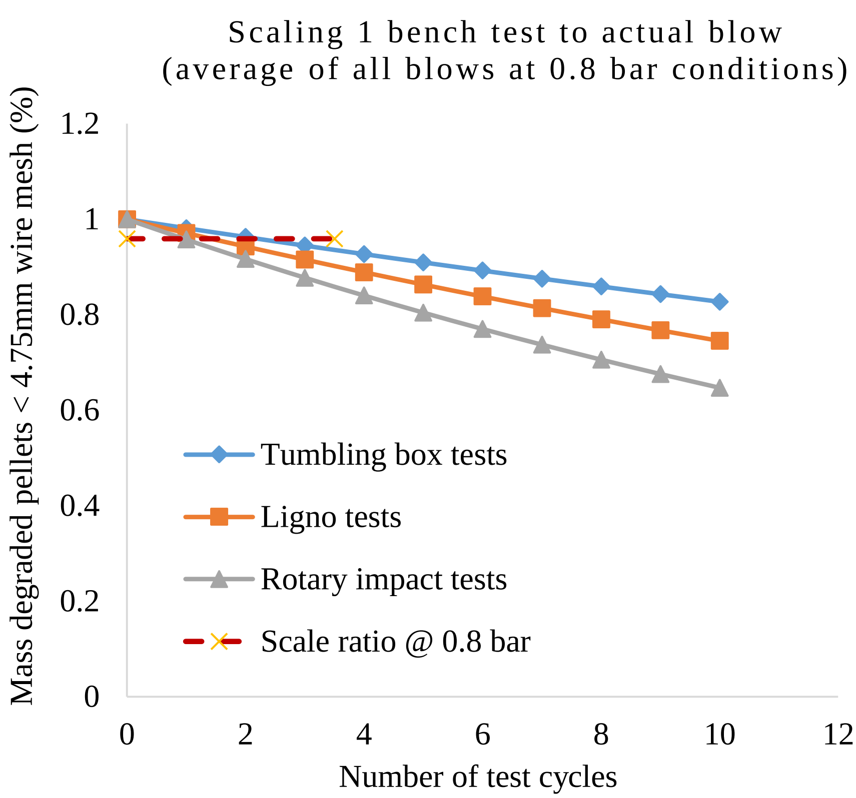


Figure 8.5 Using one predicted bench-scale pellets durability test result of each bench-scale tester to predict pellets degradation in full-scale pneumatic deliveries

(The red dotted line shows the required number of predicted bench scale pellets durability tests required to predict same batch pellets degradation in real pneumatic delivery at 0.8 bar blowing pressure).

The scaled result in figure 8.5 indicates that sample of fresh pellets from the batch may have to be tested once in a rotary impact tester, or twice in a Ligno tester or trice consecutive times in a tumbling box tester, to achieve similar possible breakage characteristic of the pellets in real blow delivery at 0.8 bar pressure.

8.3 Summary

The predicted breakage matrix modelling results of pellet degradation in all the bench scale testers were achieved based on scaling the breakage in one test to a higher power bench-scale tests. The level of damage incurred by the sample of pellets tested in the tumbling durability tester, for ten consecutive times, was slightly lower than the predicted level of pellets degradation predicted using breakage matrix modelling.

For the Ligno tester, no significant difference was found between the predicted levels of pellets degradation predicted using breakage matrix model and the corresponding actual measured pellets degradation in multiple experimental tests.

The level of pellet degradation observed after the actual repeated rotary impact durability testing of one wood pellets sample for ten times, was somewhat higher than the resulting predicted level of pellets degradation observed in the breakage matrices modelling result.

In the case of comparisons between the actual and the predicted bench-scales level of pellets degradation simulated using the simplified breakage matrix modelling, developed by taking a single test cycle and multiplying it multiple times to predict the degradation in the real handling system. Ligno tester and rotary impact testers appeared to have offered the best potential correlation, followed by rotary impact testers. Tumbling box tester seems to be useless in terms of predicting real pellets degradation in full-scale blow system. However, the results were based on a single measurement point, (i.e. the quantity of material passing through a 3.15 mm round-hole sieve).

Chapter 9 Overall Conclusions and Future Work

9 Introduction

The following conclusions were drawn from the research outcomes against the objectives, which were to investigate the effect of pellet physical properties on handling pelleted biomass material in practical use. The findings were linked to the outcomes of pellet degradation in different bench-scale testers and full-scale pneumatic degradation tests. The first part this chapter discusses findings of pelleting process parameters and feedstock variability on the strength and durability of the pellets with different production histories. The subsequent sections cover the resistance to breakage characteristics of the pellets produced and other batches of high-quality wood pellet durability tests in bench testers, including comparisons against full-scale pneumatic degradation tests. The last part of this chapter covers remarks on the use of a breakage matrix approach to relating the breakage of pellets in bench scale testers to the breakage in a full-scale pneumatic delivery system and recommended future work areas.

9.1 Effect of Feedstocks and Pelleting Process Parameters on Pellets Quality

Evidence from effect of feedstock variability and pelleting process parameters on pellets strength and durability study.

The finding on feedstocks steam conditioning showed that steaming could be used to increase pellet quality because the strength and durability of pellets produced using 70˚C steam conditioned feedstocks was higher than pellets of non-steamed feedstock produced at 20˚C. However, the increase appears to be at the expense of total energy used in the pellet production.

Similarly, heterogeneous pellets containing 20 % alder to pine wood content could be produced, since the pellets showed an acceptable threshold pellet durability index (PDI) value (≥ 97.5 %), when it was tested in both Ligno and rotary impact tester, though the PDI values from the tumbling box test were slightly lower in comparison to those of the two other bench testers. This suggested that up to 20 % alder to pine feedstock could be used to maximise renewable energy production. This conclusion was based on similar range of PDI values observed between the heterogeneous pellets containing 10 % to 20 % alder to pine contents.

Increase in initial feedstock moisture content to some extent, before steam conditioning or pelleting, appeared to have improved the pellet strength and durability. The influence was observed across the PDI values of the three bench scale testers, deployed in the measurement of both steam-conditioned and non-steamed conditioned pellets durability.

Similarly, the PDI values of the pellets produced with different production histories were compared to examine where correlation seems to exist between the three-different bench-scale testing techniques: -

The finding from the correlation results showed that, irrespective of the pellets production histories, the pellets breakage in the Ligno tester was slightly less repeatable than that of tumbling box tester but different in breakage mechanism. The limited repeatability observed in Ligno tester results were attributed to the random impact velocity of the pellets during the standard Ligno durability test. However, the two standard pellet durability testers appear to show a very poor correlation in PDI values, especially at the lower region. The breakage pattern of pellets in the rotary impact tester was highly repeatable, but the PDI values derived from the rotary impact durability testing appears to have poor correlation to that of tumbling box but slight correlation to the Ligno tester.

The relatively poor correlation between the PDI values of the three bench scale testers' results is a major cause for concern. Had there been a close correlation but just with an offset, the test results could be subjected to a "correction" for the difference, or the test could have been subjected to an adjustment of duration to obtain equivalence. However, the high scatter and lack of correlation in the most important range (97 % to 100 % PDI for commercial acceptability), even for the two testers accepted as the "standard" and widely used for industrial quality control measurements, together with the much poorer correlation against the rotary impact test that was designed to simulate conditions of particle degradation in a real conveying system, is a clear evidence that industry should expect very little correlation between the PDI reading for a batches and the actual pellet breakage observed in real deliveries. The findings in this chapter suggest that at the moment, the best recommendation is to use the rotary attrition impact tester for evaluation of pellet strength and durability because it produces highly repeatable results as well as being specifically designed to simulate the impact velocity of particles in a pneumatic transport system.

9.2 Assessment of Repeated Pellet Degradation in the Three Bench-Scale Durability Testers

Having seen the interactive behaviours of the surviving pellets (> 4.75 mm diameters PDIs) in each bench-scale durability tester, it was therefore decided to understand the rate and pattern of degradation, and behaviours of the broken pellets fines from each bench-scale tester, which was achieved by taking the percentage mass of broken pellets fines (< 4.75 - 3.15 mm, 3.15 - 2.36 mm, 2.36 - 1 mm and < 1 mm (wire mesh sieve)) generated from each durability tests techniques for ten consecutive times. The finding from each bench-scale tester's pellets degradation pattern are:

- Evidence from the ten-consecutive standard tumbling box durability tests conducted showed that pellets experience more surfaces rubbing or wear type attrition in tumbling tests, instead of combined chipping and wearing actions that seem to be occurring in the real blow or other conveying handling systems. This remark was based on the high level of very fine dust, (i.e. small wood particles < 1 mm diameter) observed to be generated during the tests. Similarly, the first tumbling box test (500 revolutions) appears to be the most significant test in tumbling, with a big drop in fines production, the drop between the first and second tumbling tests, as clearly depicted the difference in figure 5.1 a. The amounts of fines generated appear to be decaying with an increase in the number of tumbling cycles for the same pellet sample during the durability test. This trend of degradation suggested that the pellets are clearly suffering far more surface wear attrition due to unrealistically low-velocity collisions of particles in the tester during tumbling, compared to a real pellet delivery operation. Nevertheless, it was found to be a highly repeatable test in terms of result for multiple samples of pellets from the same batch.

- The continuously repeated testing one pellets sample (100 g) in the Ligno tester showed that pellets degradation in the Ligno tester was slightly less repeatable from sample to sample, in comparison to the tumbling box tester. However, the pattern of broken pellets fines generated from Ligno test, are more of partly shattered fines or relatively large pieces knocked off pellets ends. This pattern of pellets degradation suggests the existence of possibly irregular impact velocity (currently unknown and hard to measure) occurring during the Ligno durability tests and the impact velocity in the Ligno tester was higher than that of tumbling box testing. The Ligno tester demonstrated a linear degradation trend with the increase in test duration, indicating it has more chance of ranking pellets degradation in relation to real handling systems in which it would be expected that pellets would degrade more with more bends in the delivery pipeline.
- Similarly, the samples of pellets from the same batch were tested repeatedly using the newly introduced rotary impact tester, for ten consecutive times. The degradation behaviours of pellets in this tester, shown that it produces less fine dust compared to the tumbling box tester, but produces larger broken fines particles (< 3.15 mm) than the tumbling and Ligno tester. The pattern of pellets breakage in the rotary impact tester was more of intermediate sized attrition products (thought to be from pellets ends damage). The tester also showed a distinct advantage of controlled impact velocity that is broadly expected to be a representative of pellets degradation in a real delivery system, as observed from the previous successful work of using the rotary impact tester to predict particulate material degradation in large-scale pneumatic conveying systems (Bridle et al., 1995).

The difference in breakage behaviors of the pellets in the three bench-testers is a reflection of the difference in impact and collision processes present in them. The fact that the relative ranking of different pellet batches changes between the rotary impact test and the two standard testers, gives a great lack of confidence that the standard tests are likely to have any realistic meaning in terms of indicating the breakdown to be expected in a real pneumatic delivery. Therefore, full-scale pneumatic pellets degradation tests were conducted for further comparisons to bench scale testers.

9.3 Findings from the Industrial Full-Scale Pneumatic Pellet Degradation Tests Conducted Using Pressurised Tanker Truck Delivery System

The key findings from the large-scale pneumatic pellet degradation tests were conducted to examine which of the bench-scale testers might predict the actual pellet degradation in a real handling system. However, a long-standing argument over preferable delivery pressures (the use of lower or higher pressure for lower degradation) was also to be explored, together with an exploration of the effect of the delivery distance and the tanker operator as well.

- The blown pellets degradation study showed that when using a short delivery pipeline, a significant decrease in pellet degradation could be achieved by dumping of some of the air from the blower before it reached the pressurised tank, when pellets were blown at lower tank delivery pressures (0.3 bar or 0.5 bar) on the short delivery distance. This decrease in pellet degradation was not due to the reduced blowing tank pressures, but a result of air vented out of the pressurised tank which results in reduced conveying air velocity through the blowing pipeline.
- The intermediate blowing tank pressures (0.5 bar and 0.8 bar) appeared to the optimum blowing conditions for achieving the lowest level of pellets degradation in an unvented pressurised tank condition, and longer distance deliveries. A similar decrease in pellet degradation was also observed in the extended pipes pellet deliveries, where most of the pellets degradation appeared to occur at the lowest pressure of 0.3 bar and the highest pressure of 1 bar tank blowing pressures. The high pellet degradation observed across all the 1 bar blowing pressure deliveries, was clearly because this was on the verge of not transporting the pellets steadily, resulting in occasional slugging and clearing of the line. The instability led to high pellet degradation, presumably because the unstable pressure meaning that every time slugs were cleared the falling pressure gave rise to high air and pellet velocity. Therefore, pellets should only be blown at 1 bar blowing tank pressure, from a pressurised tanker truck, in both long and short delivery distance if pellets degradation is not a major concern in a tanker truck delivery. The average inlet air

velocities were also found to have direct influence on the corresponding change pellets velocities in the blow pipeline, while the blowing tank pressures had an inverse relationship with the pipe inlet air velocities as expected.

One of the most important findings, particularly with the smaller deliveries, was the high level of variation in degradation between deliveries made under very similar conditions. Even though the same blowing pressures and delivery times were successfully achieved in the repeat tests, the level of degradation was far from repeatable. The degradation level did not correlate with the pressurised tank pot numbers (delivery outlet number) and neither did it correlate with the discharge number from one pot. The level of variation was such that it seriously clouded the correlations, being as large as the difference between the average results for different conditions. The consequence of this variation is that customers must expect to see very significant variation in the nett levels of fines they ultimately receive in batches delivered to their stores, even with the greatest care taken over control of delivery conditions. This is especially so with smaller deliveries. This variation appeared to be slightly less in the larger blown deliveries (several tonnes rather than one tonne), suggesting that variation in the start-up and shut-down transients probably contribute significantly to the degradation, especially in smaller deliveries.

9.4 Assessment of Pellet Degradation Associated with Comparisons between the Bench-Scale and Full-Scale Pneumatic Delivery Tests Results

- The pattern of pellets degradation in the rotary impact durability tester was found to be almost identical to the pattern of pellets degradation observed in full-scale pneumatic degradation tests. This indicated that the rotary impact tester has a high potential to predict pellet degradation in full-scale pneumatic deliveries, at least when the pellets are not blown beyond 1 bar delivery pressures as tested. The rotary impact tester appears to be the only tester that produces a similar pattern of large broken pellets fines (4.75 - 3.15 mm diameter) observed in the full-scale pneumatic pellets degradation tests.
- Similarly, the standard Ligno tester has also shown some, though lesser, tendency to produce similar degradation pattern to the full-scale test, therefore suggesting a fair

tendency to predict pellets resistance to degradation in full-scale pneumatic deliveries. Particularly, the broken pellets fine above 3.15 mm diameter, which is not considered as fine in the EN 14961 - 2 standard but is nevertheless the largest part of the degradation in real deliveries, does show some similarity in this test to the full-scale pneumatic blow degradation test, although not as good as the rotary impact test.

- The most contrasting case is the pattern of pellets degradation observed in standard tumbling box durability tester, which although highly repeatable, was totally opposite to the pattern of pellets degradation observed in full-scale pneumatic delivery tests and the other tests; it produced only very fine dust and no larger broken particles, and the dust production dropped dramatically with extended testing. The breakage mechanism was clearly utterly different from the real delivery system or the other tests, meaning that the tumbling box durability test is most unlikely to have any relevance to the mechanical resistance to degradation of pellets in a full-scale pneumatic delivery or other methods of handling system. However, the tester might possibly be used for understanding the dustiness tendency of pellets in real handling systems.

- Using Breakage Matrix Modelling to Relate Experimental Bench Scale to Full-Scale Level of Pellets Degradation in a Pneumatic Delivery System

The rotary impact tester successively degraded almost 70 % of the original +6 mm size fraction to < 4.75 mm diameters, in ten consecutive actual durability testing cycles of the same pellets sample. By contrast the Ligno and tumbling box durability testing resulted in degrading just about 30 % and 10 % of the same 6 mm into < 4.75 mm sizes diameters, after the same ten repeated actual experimental pellets resistance to breakage testing. However, the predicted breakage matrix results of the rotary impact tester showed a bit less in the predicted cumulative degraded fines (about 38 %) compared to that of the actual experimental testing. But no significant change appeared to occur between the actual experimental and predicted breakage matrices outputs results for repeated degradation of pellets in the Ligno tester (predicted by taking the breakage matrix for the first cycle and raising it to the power of the number of cycles). Conversely, the cumulative mass of broken pellets fines < 4.75 mm diameter generated have increased from about (10 % actual testing to almost 19 % as seen in the predicted breakage matrices outputs results), of the ten-consecutive tumbling box durability testing.

In the case, modelled prediction results, Ligno tester appears to have the most similar outputs of pellets degradation in real to predicted breakage matrix modelling. However, in terms of scaling bench scale test to predict pellets degradation in full-scale pneumatic delivery system, or indeed to rate full scale delivery systems for their degradation potential, the use of a multiplier applied to the breakage matrix obtained by a single bench scale test to arrive at a prediction for a full scale delivery seems like a promising way forwards; the multiplier is different for different bench scale tests, and for different pipeline layouts and operating conditions. For a single-bend infeed line with one length of flexible operating at 0.5 to 0.8 bar, the multiplier is around 0.9 for the impact test and 1 for the Ligno test but it higher for 0.3 bar and 1.0 bar and will be higher for lines with more bends and flexible hoses. A very important finding, however, is that there is a wide margin of variation between degradation levels in successive discharges, even for the same pipeline, same driver, same nominal operating conditions and same manufacturing batch, and this must be borne in mind in terms of the user's expectation.

9.5 Key Contributions to Knowledge

The overall goal of this research project is to make contribution to knowledge in handling of pelleted biomass material in relation to pneumatic delivery of small batches, and recommend or come up with a particular bench-scale tester and usage protocol that seems to predict the actual degradation of pellets in real industrial handling systems, specifically for the pneumatic blown delivery systems.

Similarly, the shortfalls report of the commonly used existing standard pellet degradation testers, which had not been successfully used to predict pellet degradation in real handling systems, another known particle degradation tester (i.e. rotary impact tester) that has often been used successfully at The Wolfson Centre for degradation prediction with other materials in pneumatic conveyors, but has not been used extensively for pellets, was tested.

As a result of this work, a number of previously unknown but important findings have been produced, as follows.

The three bench-scale pellets degradation test results were compared to that of full-scale pellets degradation test conducted using a tanker truck pneumatic blow delivery system, to simulate pellets breakage in real industrial handling, which is the main interest of the industrial sponsor. The correlation of the resulting pellets degradation in each of the three-bench scale tester to the pneumatic blow deliveries tests results were determined and the potential to use breakage matrix modelling to link the bench tests results to full-scale has also been demonstrated. The simplified novel breakage matrix model approach has been pioneered and was determined from different size distribution of broken pellets derived from the first pellets durability test, which represent the first column matrices (a single breakage event, detailing the mass fractions of both the surviving and broken pellets size distributions), and assumed other subsequent columns based on a *priori* knowledge of the commonly found behavior of many materials degradations. Notwithstanding, this simplification method proved to be very promising as a novel means of "scaling" (extending a single bench test result to multiple member of tests) the results of bench-scale tests to predict degradation in full-scale deliveries.

Evidence from the research has shown that, the newly introduced rotary impact tester and the standard Ligno tester were the two bench-scale testers that seem to have high potential to predict the actual resistance of pellets to degradation in real industrial handling system (i.e. full-scale pneumatic delivery system). This is because the rotary impact durability test produces highly repeatable results and showed a similar pattern of pellet degradation observed in full-scale pneumatic degradation tests; the review showed that similar testers have been specifically designed to simulate the impact velocity in the real delivery system. Likewise, the existing standard Ligno tester also showed some promising results that indicate its potential tendency to predict pellets degradation real handling system. However, it was important to find out that the tumbling box tester, which is one of the industrially acceptable means of predicting the actual mechanical strength and durability (resistance to breakage) of pellets in real handling systems appeared to produce a result that was of no relevance whatsoever to the degradation of the pellets blown in a pneumatic delivery system. However, the tester may be used to gain more insight on pellets dust tendency.

Similarly, a useful novel guidance for delivery truck operation has been produced in the UK Pellets Council. The large-scale blowing tests indicated that, the optimum pellets delivery that yielded the least pellet degradation occurred between 0.5 bar – 0.8 bar delivery pressures. That 1 bar blowing pressure should only be used in a blow delivery when pellets degradation is not a major concern issue, in any tanker truck delivery system. However, there are instances where lower blowing pressure of about 0.3 bar resulted to decrease in pellets degradation due to air venting from the pressurized tank into the atmosphere. The vented air resulted to low pellets impact velocity as the conveying air velocity decreases along the blow pipeline. This method of blowing pellets comes with other implications in tanker operation and conveying energy wastage. It should also be noted that the optimum pressure values may vary with the tanker truck blower sizes in different form during the tests, but the general principles would still need to be applied.

Another important novel finding is the level of variation in pellets degradation between deliveries was very substantial, even when every possible step was taken to achieve consistencies in material, system details and operations. The reasons for this were discussed, but it has important implications for the expectations of system users.

9.6 Recommendations for Further Work

The key recommended areas to investigate are:

The current study has investigated the effect of pellets physical properties on handling pelleted biomass material in real practical use. However, it was apparent from current findings that further investigation is required for more understanding of pellets degradation in full-scale pneumatic blown deliveries.

- Further research on change in degradation due to change in blowing pressures is indicated.
- Use of the same pressurised tanker truck to examine repeatability based on tanker delivery pots (outlet) numbers.
- Further repeatability studies should be carried out using the same values of blowing pressures and pressurised tank conditions, to detect the causes of the wide variation found.
- The use of a tipper-blower in place of a tanker should be investigated for its effect on degradation; bearing in mind that around half of the wood pellet delivery industry uses tipper blowers and half uses tankers.
- A wire-mesh 3.15 mm diameter should be tested in Ligno tester instead of the existing 3.15 mm diameter round -holed sieve, because broken pellets have an irregular shape.

9.7 Published Research Work

Abdulmumini, M.M., Bradley, M.S.A., Berry, R.J., (2013). The Effects of Fine Content and Length on Wood Pellets Bulk Density. The 11^{th} International Conference on Bulk Materials Storage, Handling and Transportation, the University of Newcastle, Australia 2^{nd} – 4^{th} July.

Abdulmumini, M.M., Bradley, M.S.A., Zigan, S., (2015). Comparative Study of Pelletizing Process Parameters on Wood Pellet Durability. The 8th International Conference for Conveying and Handling of Particulate Solids Tel-Aviv, Israel, 3^{rd} – 4^{th} May.

Abdulmumini, M.M., Bradley, M S.A., Zigan, S.,Wadige, L.L,. (2016). Comparative Method of Investigating the Resistance of Biomass Pellets Degradation through Repeated Impact. International Congress on Particle Technology, April 19 -21; Nurnberg; Germany.

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11 Appendix A

A.1 The step by step procedure for conducting the large scale rotary impact test

- The procedure for conducting the large scale rotary impact test are short listed in following bullets points below:
- Use 5.6 mm wire mesh diameter sieve to manually separate the clean pellets from the broken fines.
- Use Hoffman R89P Riffle divider to randomly riffle the clean pellets into different sub-samples (Hoffman MFG, Jefferson, and O.R).
- Take one of sub-divided portion of the clean pellets sample and use weigh balance to measure 2000g.
- Place a 40-cm height plastic bucket below the test rig outlet, where the tested pellets will be reclaimed after the impact test.
- Place the top lid and fastened the bolts and nuts
- Gently discharge the 2000g clean pellets sample into the feeding hopper
- Switch on the accelerating disc motor and adjust the table feeder to 8 m/sec to feed in the clean pellets from the hopper into the rotating accelerator disc, where the pellets travel with trajectory speed to hit the target at fixed predetermined speed of 18.8 m/sec for 120 seconds.
- Unscrew the bolt and nuts to remove the top lid and use manual brushing to brush down the debris content, and a vibrator to facilitate the retrieving process.
- Weigh the sample again after test to determine the difference between the pellets before and after test masses.
- Subject the retried pellets to manual sieving with 3.15 mm round-holed sieve again and record the weight. Use equation 3.4 to calculate the pellet durability index (PDI) values of the surviving (coarse) and broken fines below 3.15 mm diameter.
- Take the latter picture of the tested pellets sample, where possible and compared it to the earlier appearance of the pellets before testing, to examine the difference between the two pellets states.

- Always start a new test with fresh pellets sample, except otherwise for a continuous repeated impact test.

A.1.1 Three points pellets strength bend test

The few results of the three points bend pellets compression tests were presented in figure Fig. A1 –A4. The results were present to how show the level of variation in pellets strength measured using the texture analyser could be, despite the pellets are from the same batch and the chosen pellets have similar mass and length. The wide variation in the applied load require to breakage pellet is one of the major limitation of this particular method measuring pellet strength.

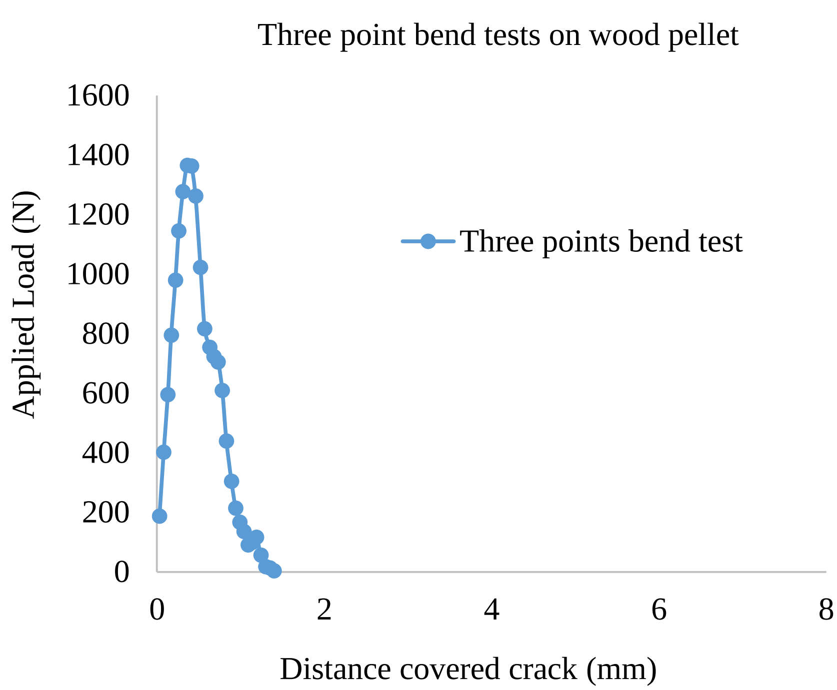

Fig. A1

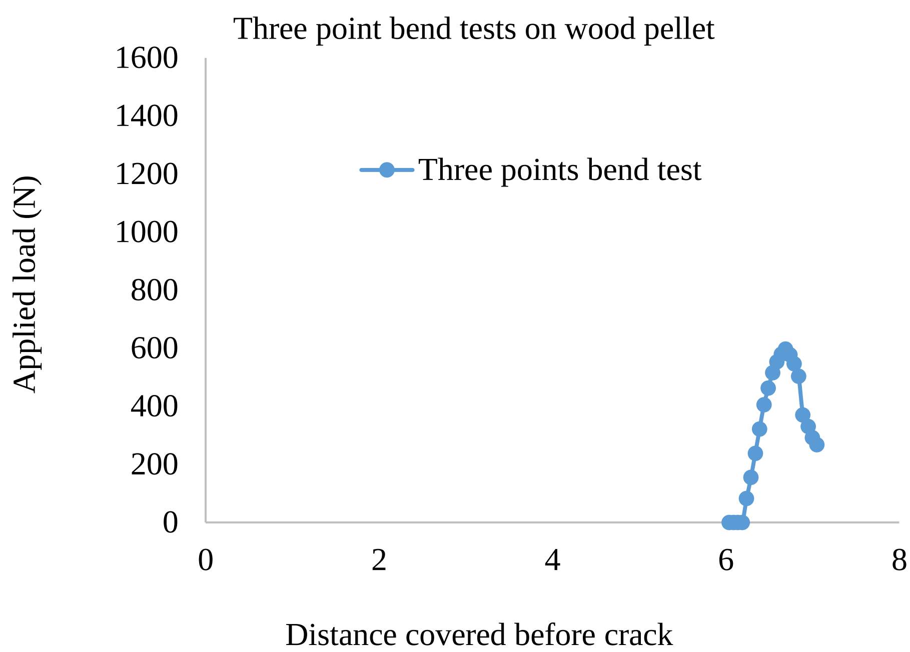

Fig. A2

Another set of pellets of same mass and length were chosen for the three-point bend tests and two out the results achieved were presented in fig. A3 and A4.

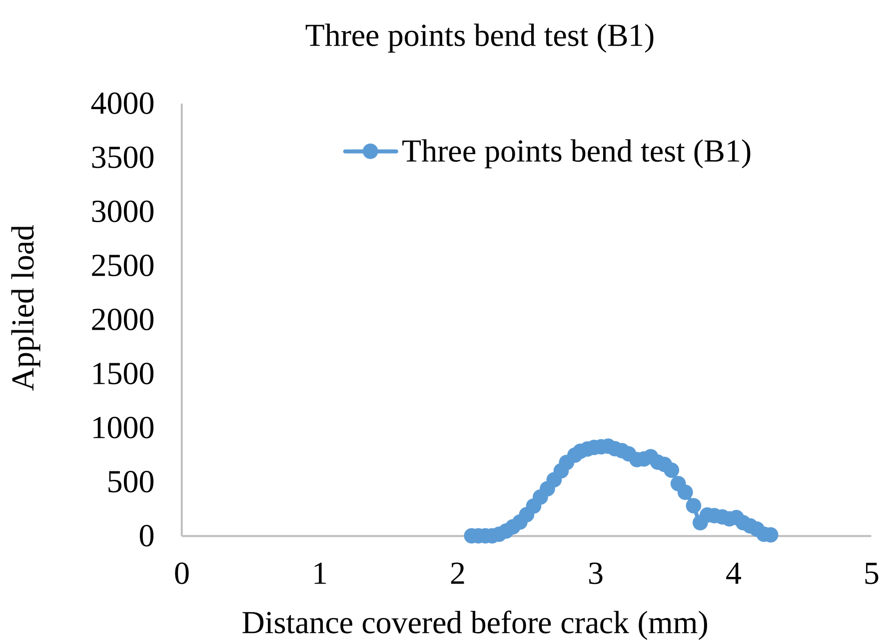

Fig. A3

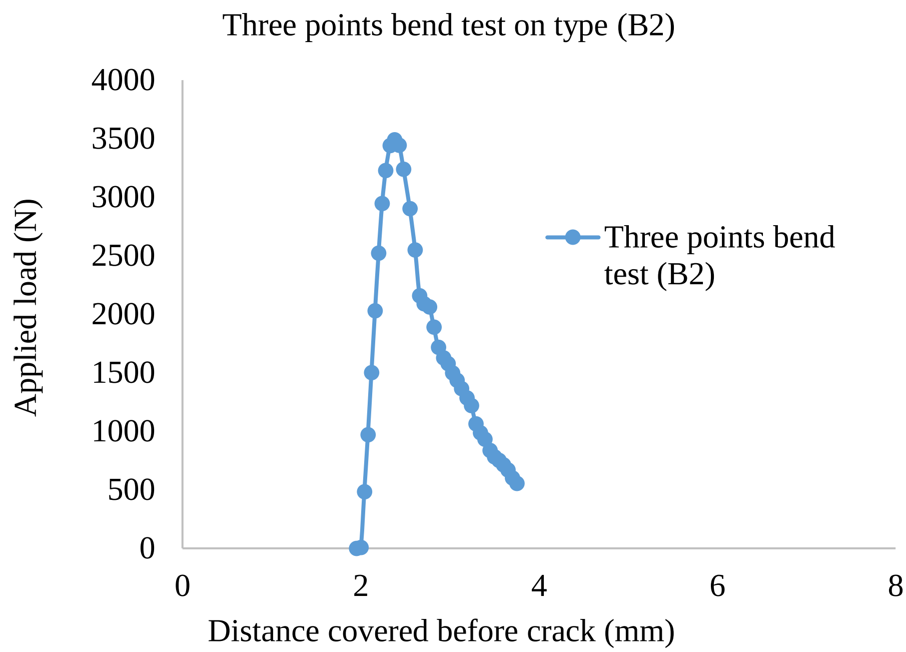

Fig. A4

12 Appendix B

B.1 Additional results on the effect of feedstock moisture on pellets strength and durability

In these section, additional results on effect of variation in feedstock moisture content on pure pine wood pellets strength and durability are presented. The pellets strength and durability was evaluated using standard tumbling, Ligno and modified rotary impact tester. The pellet durability index (PDI) calculated values of the surviving (> 3.15 mm diameter) and broken fines (< 3.15 mm diameter) were compared as shown fig. B1 – B3.

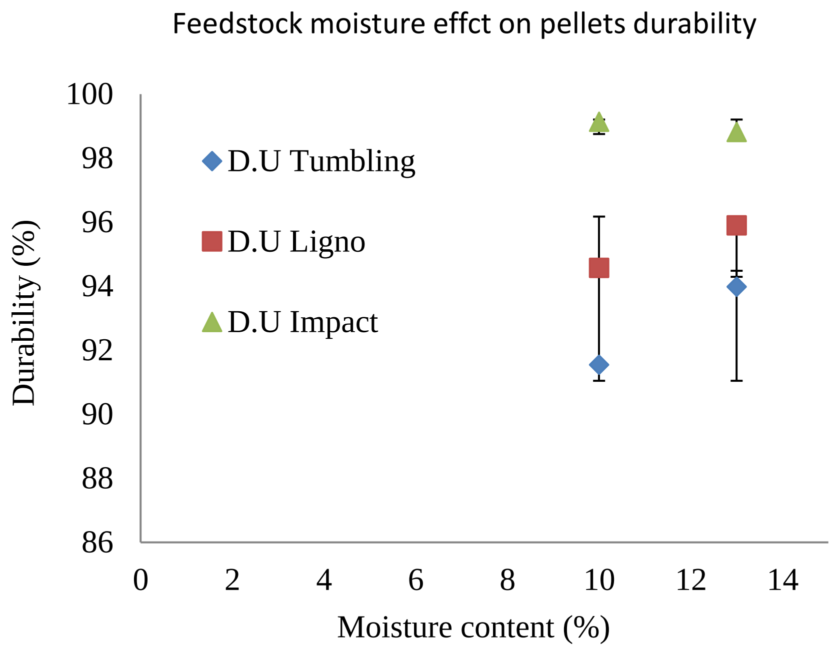

Figure B.1

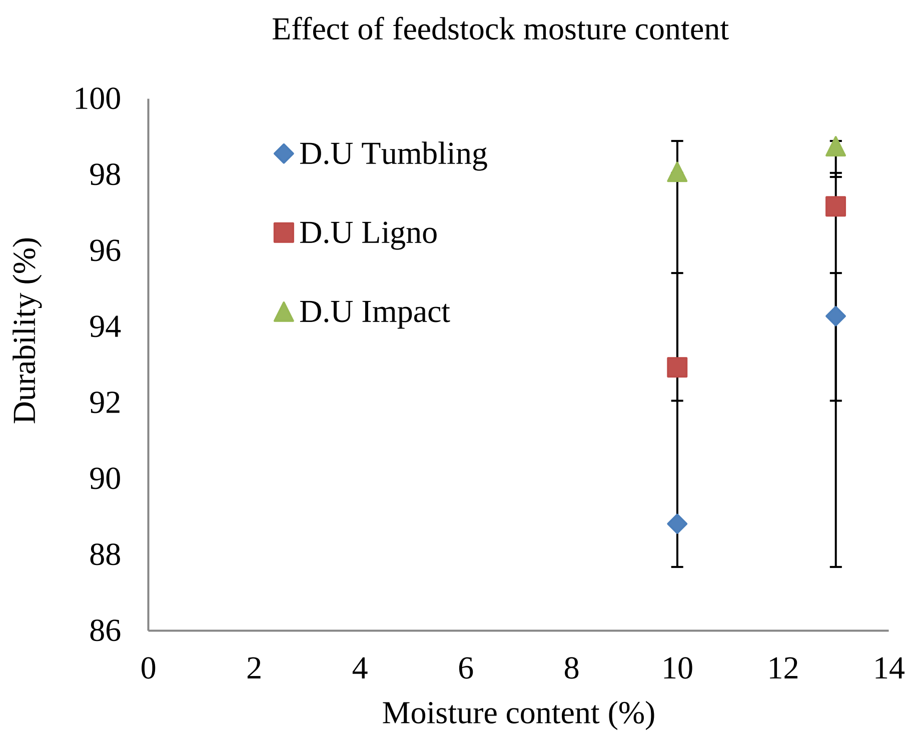

Figure B.2

Another batch of pellets were produced at 10 % and 13 % initial feedstock moisture content but containing 20 % alder to pine wood content at 20°C temperature.

13 Appendix C Additional Results of Steam Conditioning Temperature effect on pellets durability

Further results of steam conditioning effect on pure pine wood pellets produced at (20°C without steam conditioning) and steamed conditioned at (70 °C) with both feedstock at 10 % initial feedstocks moisture content. The comparative durability test results are shown in fig. C1. The standard tumbling box and Ligno testers appear to be more sensitive to the increase in steam conditioning temperature compare to rotary impact tester.

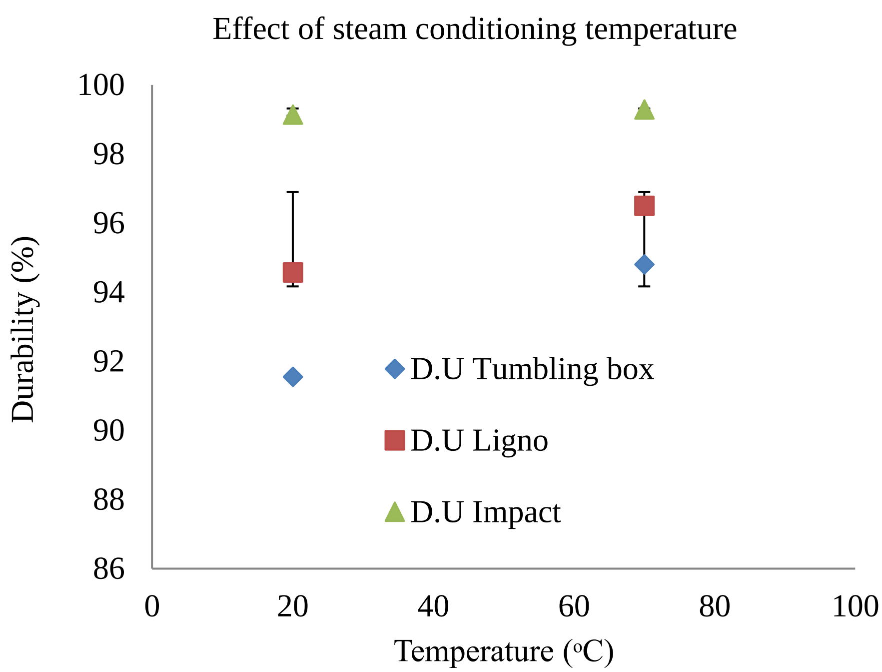

Figure C.1

C.1 Additional results on steam conditioning temperature effect

The strength and durability of another set pure Pine pellets produced at 20°C & 70°C steam condition temperature but different initial feedstock moisture content (13 %) were compared. The calculated pellets durability index values from both standards tumbling box, Ligno tester and the rotary impact tester as shown in fig. C2.

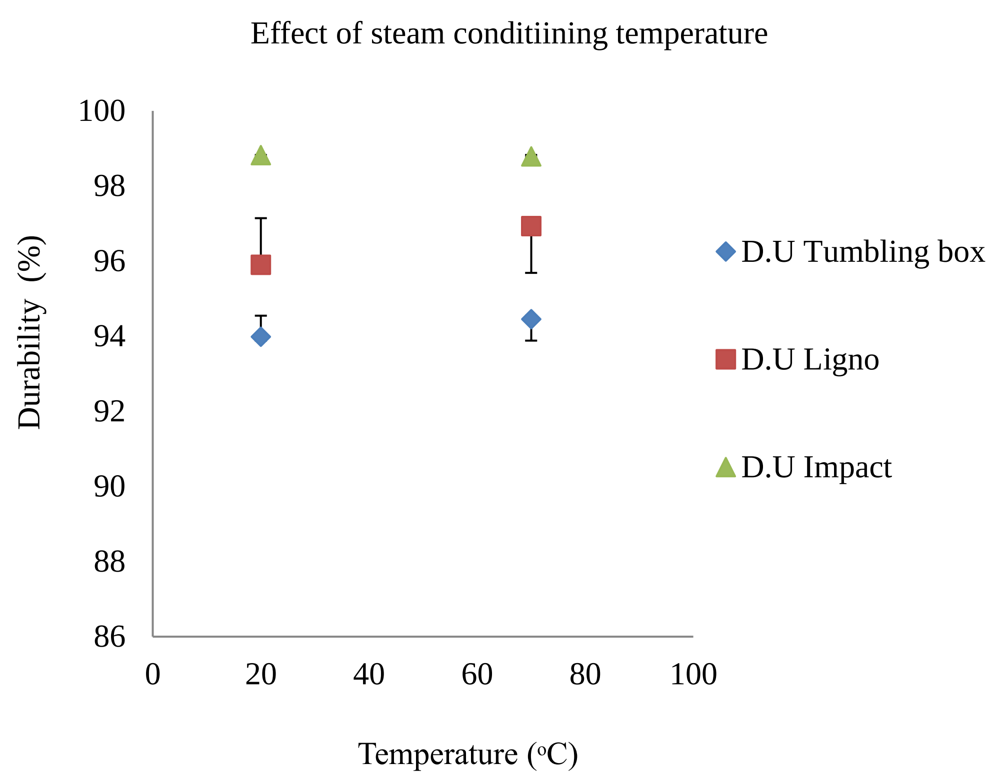

Figure C 1.1

No indication of differences between strength and durability of the pellets produced at 70°C steamed conditioning temperature and that of un-steamed conditioned pellets produced at 20°C both at initial 13 % feedstock moisture content. The similarity in the strength and durability of the pellets was attributed moisture ingress from 13 % to 16.3 % of steamed feedstock conditioned at 70°C which may have results to poor compaction in the die channel due to low friction between the compressed feedstock and channel wall.

The characteristic of the broken-down fines size distribution was also analysed in the following figures Fig. C.2.1 to C.2.3 below.

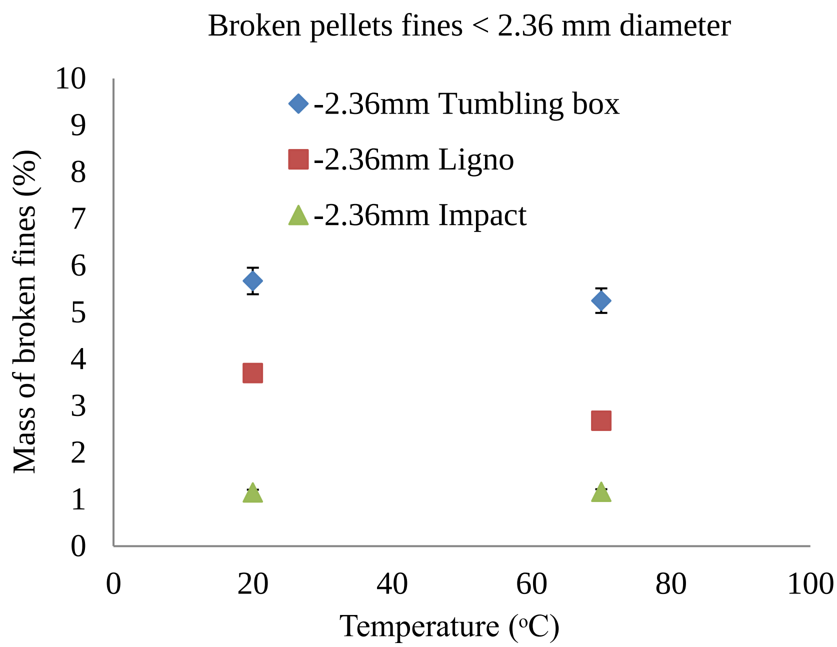

Figure C 1.2

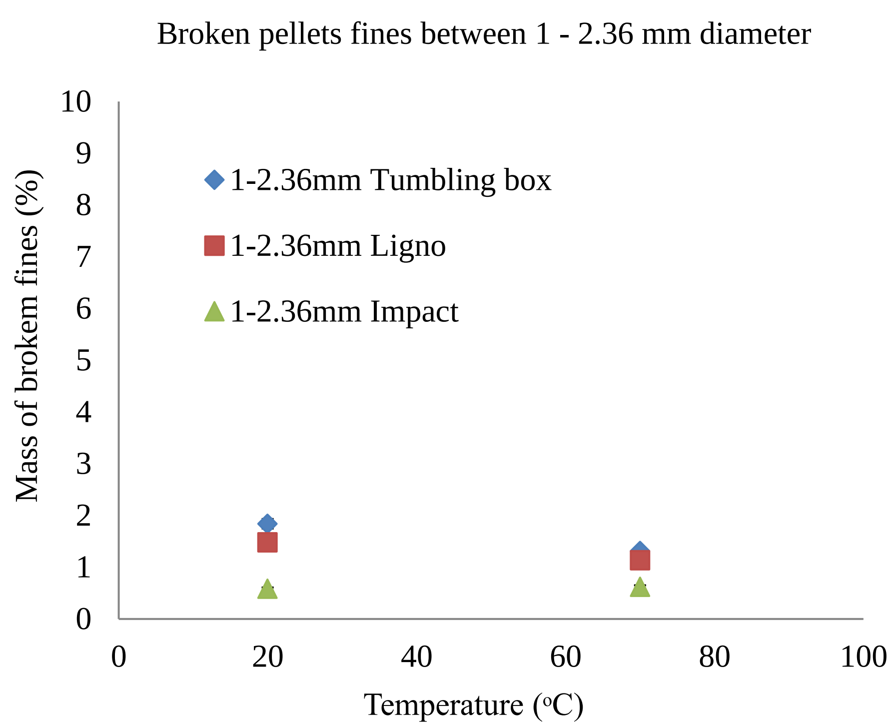

Figure C 1.2

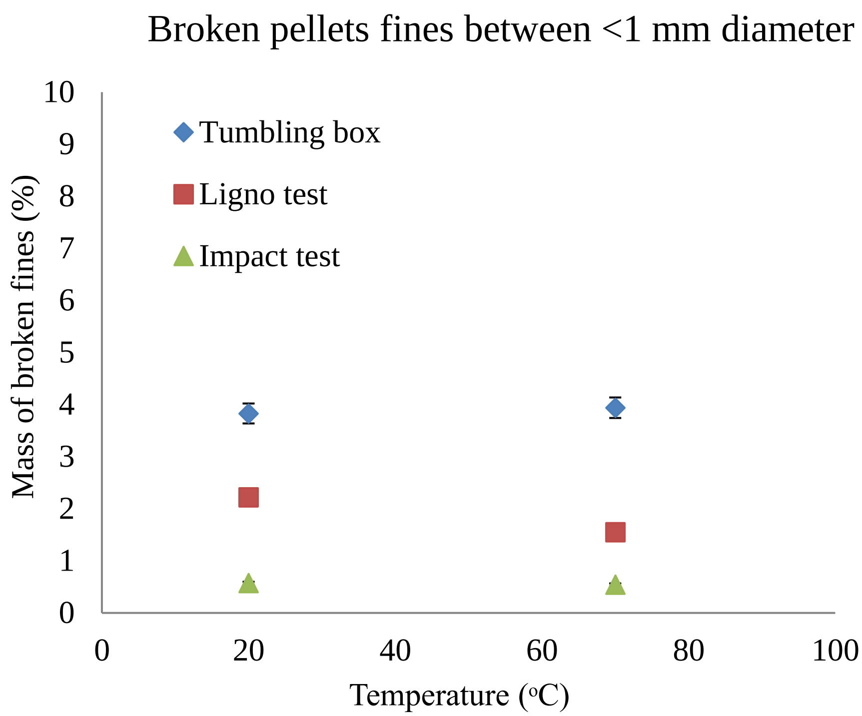

Figure C 1.3

In all condition, the broken pellets fines generated from tumbling box was higher because it takes the longest period of testing the pellets compared to other two bench-scale testers.

14 Appendix D Corrections between the Three Bench Scale Testers Pellet Durability Index

The result in fig. D 1 - D 3 compares the correlation of PDIs derived from the measurement of durability using the three bench testers (i.e. Tumbling box, Ligno and Rotary impact testers).

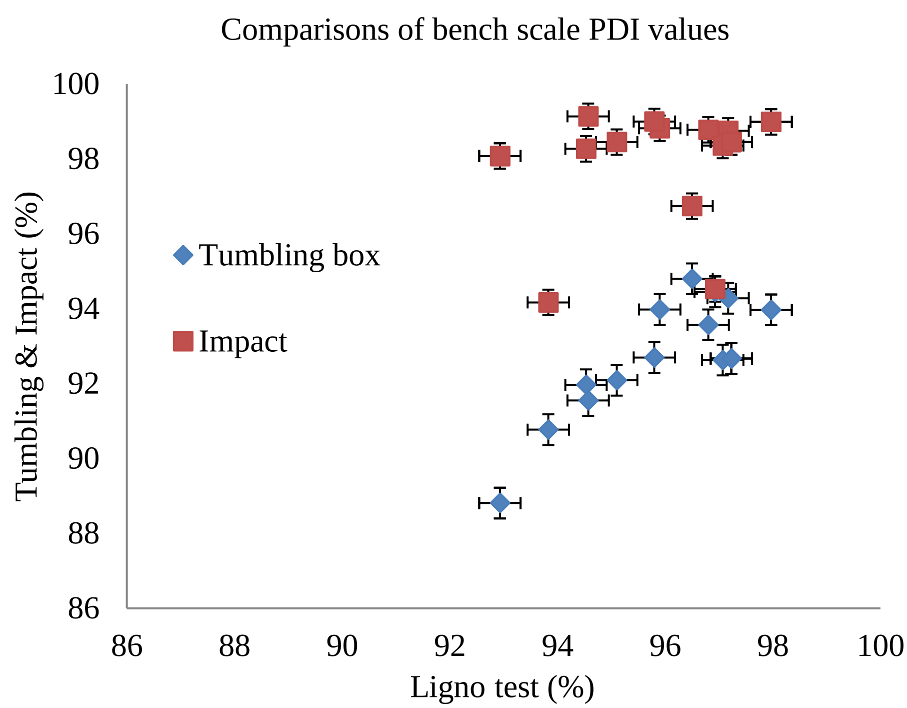

Figure D 1 Correlation between tumbling and impact vs Ligno durability test

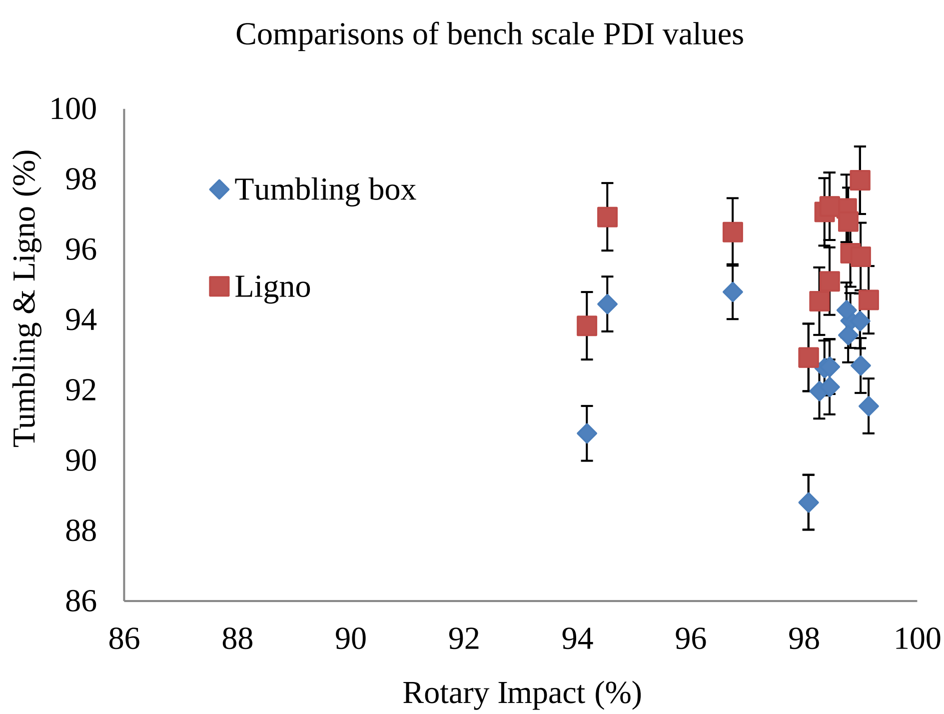

Figure D 2 Correlation between tumbling box and impact vs Ligno test

No correlation appears to exist in figure D 2.

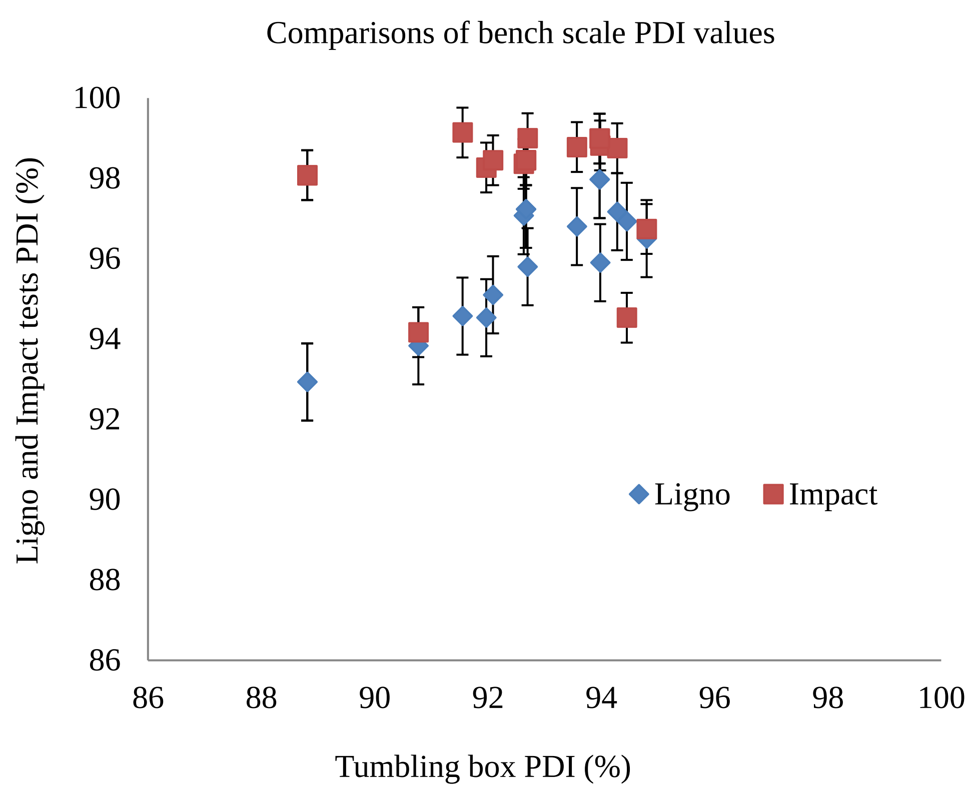

Figure D3 Correlation between Ligno and impact vs tumbling box test.

No positive correlation exists between the two standard PDI devices and rotary attrition impact tester.

D 1.1 Compares the correlation of percentage mass of broken pellets fine (< 2.36 mm diameter) derived during tumbling box, rotary impact and Ligno testing's.

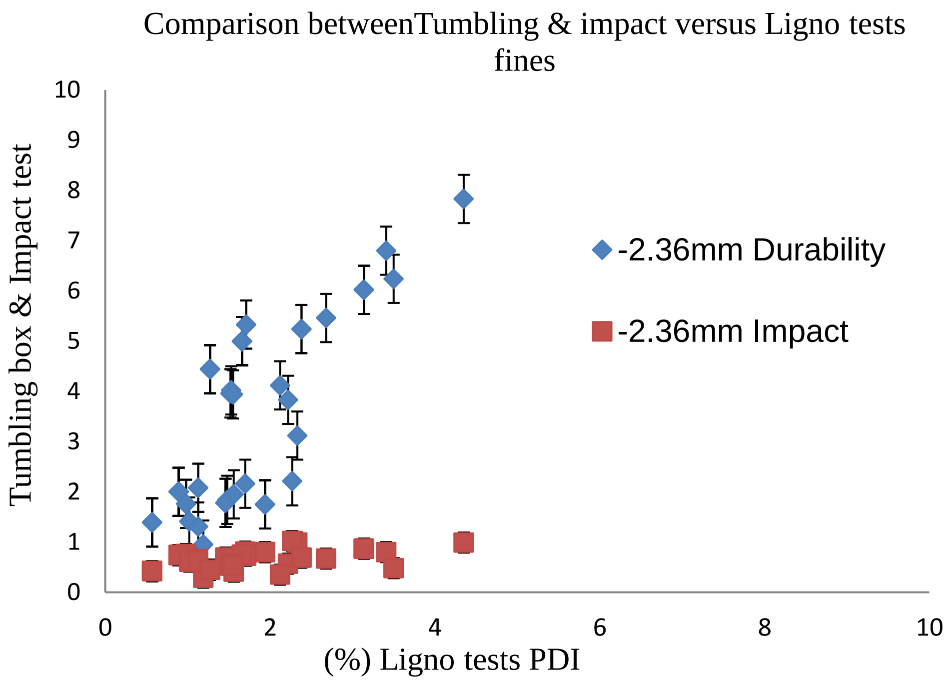

Figure D.1.1 Correlation between fines (< 2.36mm) of tumbling box / impact vs Ligno test PDI value

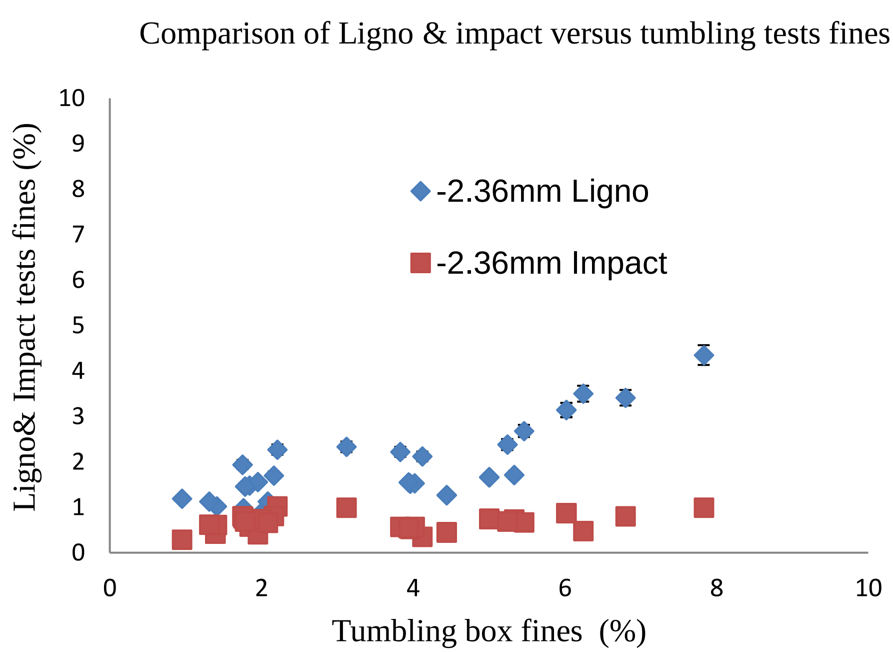

Figure D 1.2 Correlation between the percentage mass of fines (< 2.36mm) sizes

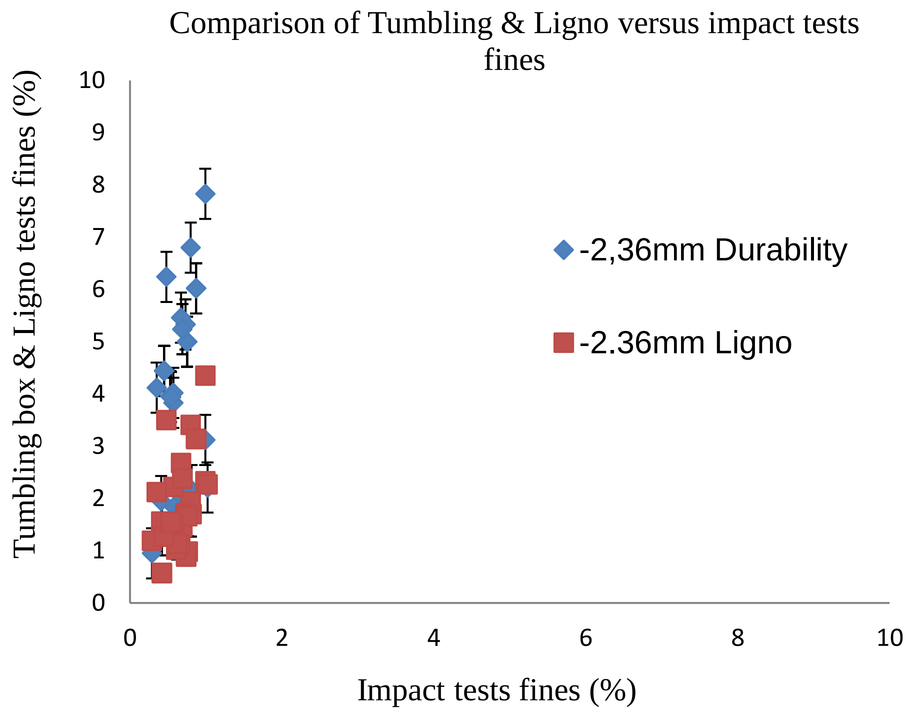

Figure D 1.3 Correlation between the percentage mass of fines (< 2.36mm) sizes derived from tumbling / Ligno vs rotary impact pellets durability tests.

No correlation appears to exist between fines (< 2.36 mm) PDIs produced from the two standard tumbling box and lingo vs rotary impact tester.

D 2 Compares the percentage mass of dust (fines < 1 mm diameter) generated from the three bench-scale pellets durability testing equipment's

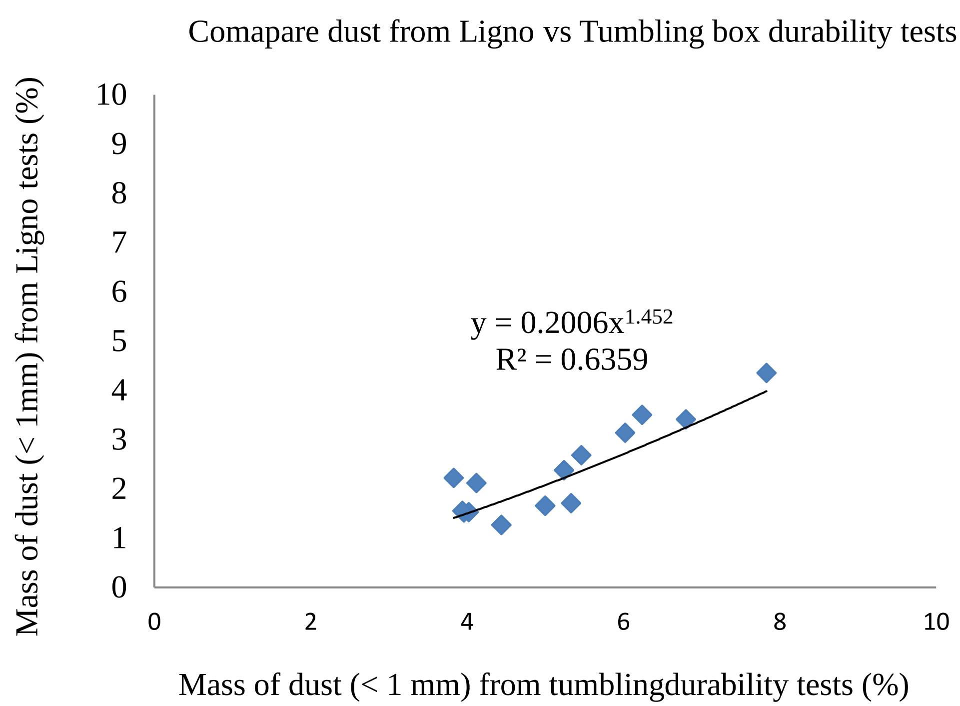

Figure D.1 Comparisons between fines (< 1mm) of Ligno vs tumbling box tests

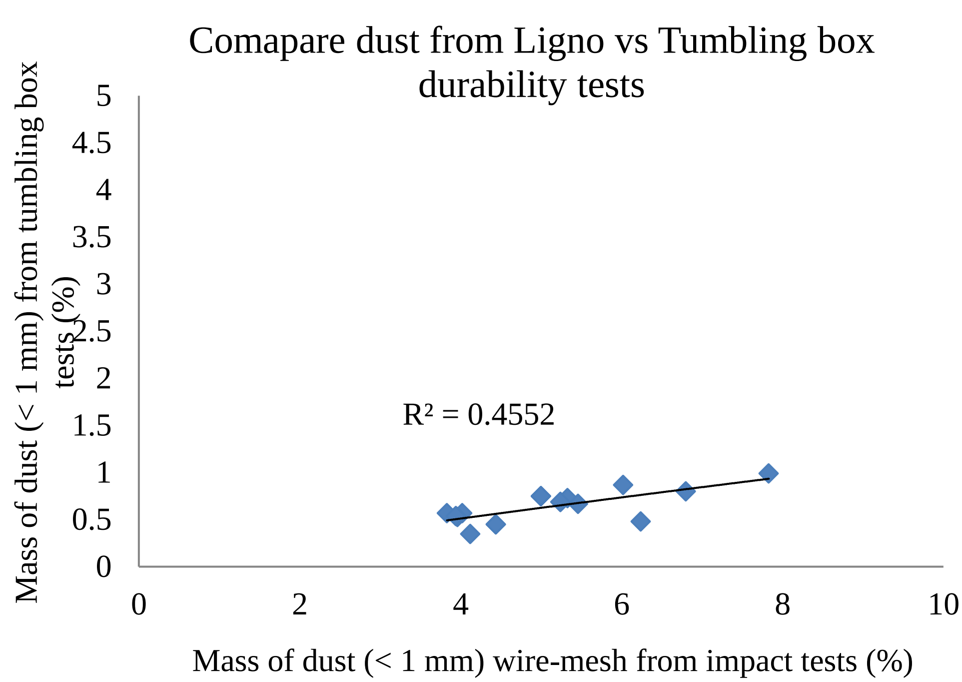

Figure D.2. Comparisons between fines (< 1 mm) of tumbling box vs rotary impact tests

The correlation between the three degradation testers (tumbling box, Ligno and rotary attrition impact tester) indicates the percentage broken fines (< 1 mm) diameter are produced from tumbling and Ligno testers has slight degree of correlation but none of the standard testers results seem to correlate with the rotary attrition impact test result.

D.3 Additional result on repeated bench-scale pellet durability tests

Repeated tumbling box, Ligno and rotary impact durability testing of different pellets samples, one sample per each tester, for ten consecutive times are shown in fig. D 3.1 – D 3. 6.

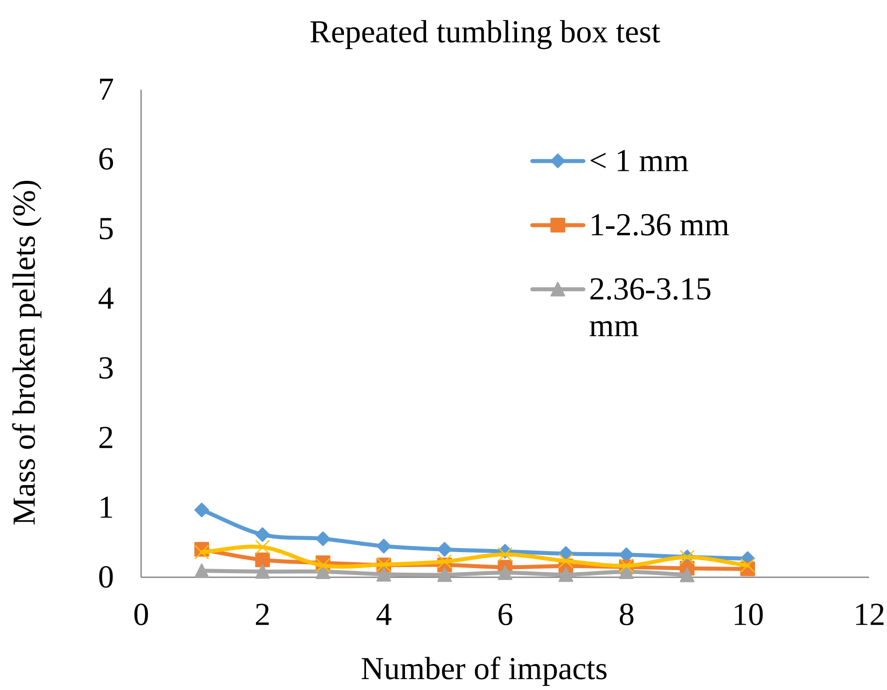

Figure D 3. 1

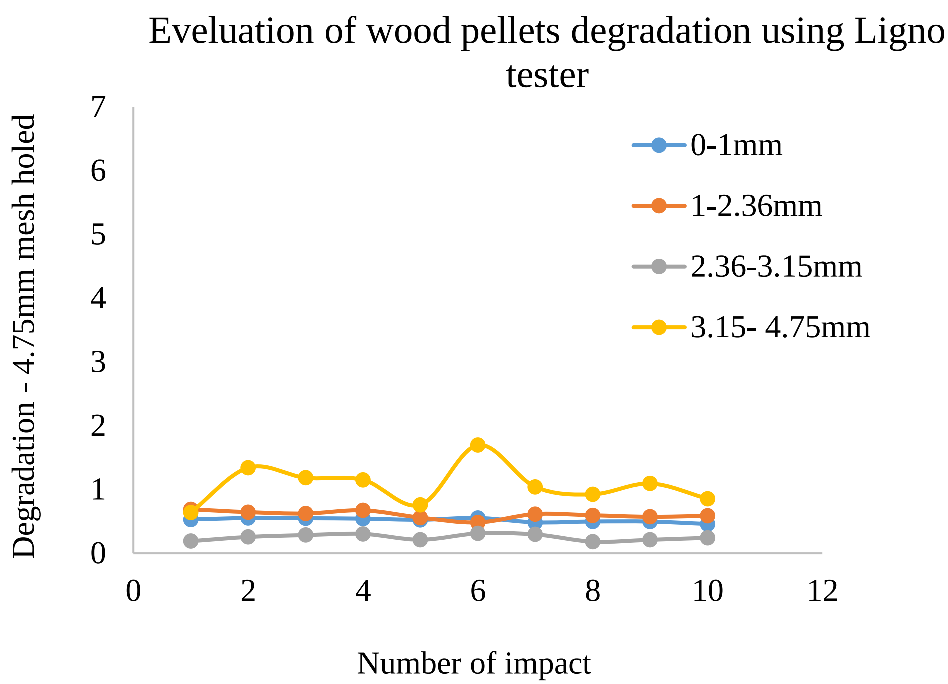

Figure D 3.2

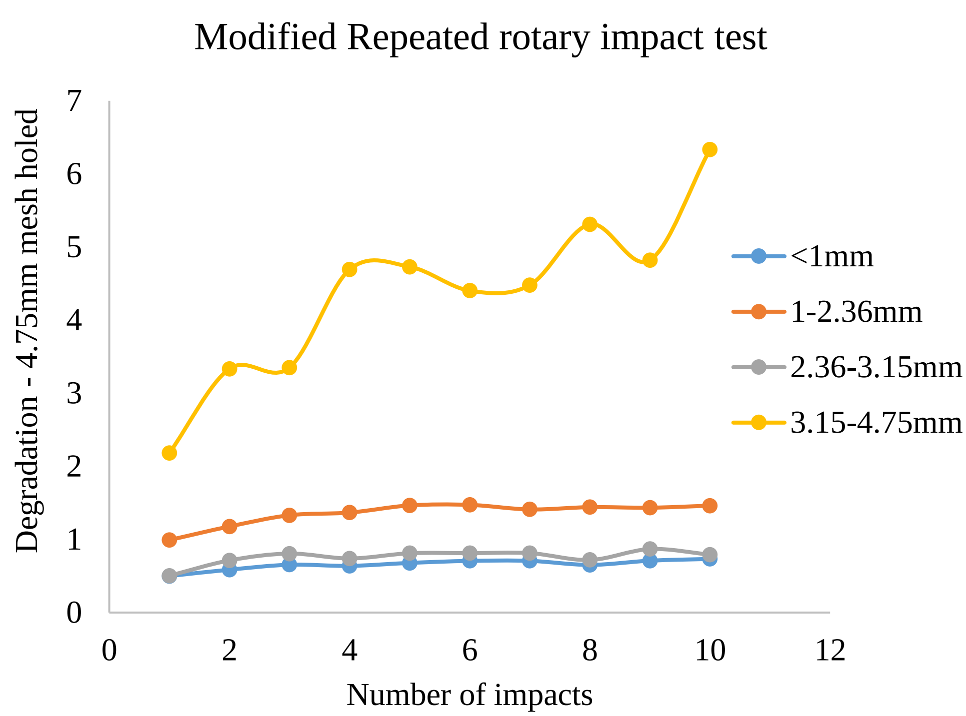

Figure D 3.3

The figures D 3.1 – D 3.3 present the breakage pattern of one wood pellets sample into different size fractions tested in tumbling box, Ligno and rotary impact testers. The mass of fines < 4.75 mm diameter were screened into different particle sizes to understand the actual breakage matrices of the pellets in the three bench-scale testers.

15 Appendix E presents the actual experiments and predict breakage matrix data of repeated bench-scale pellets durability tests and full-scale pneumatic pellets degradation tests

Repeated Rotary impact test real matrix results

> 4.75 mm	3.15-4.75mm	2.36-3.15mm	1-2,36mm	0-1mm	Test run
0.9574	0.0233	0.0044	0.0092	0.0044	1
0.9484	0.0280	0.0065	0.0115	0.0055	2
0.9313	0.0428	0.0069	0.0130	0.0059	3
0.9298	0.0428	0.0075	0.0135	0.0064	4
0.9211	0.0509	0.0075	0.0140	0.0063	5
0.9309	0.0405	0.0076	0.0145	0.0065	6
0.9105	0.0602	0.0082	0.0143	0.0067	7
0.9146	0.0558	0.0078	0.0141	0.0070	8
0.9169	0.0556	0.0072	0.0139	0.0068	9
0.9108	0.0599	0.0081	0.0142	0.0068	10

Matrix for first pneumatic blow degradation test					
	Wire	Wire+Round .Hole			No of run
Durability > 4.75mm	3.15-4.75mm	2.36-3.15mm	1-2.36mm	< 1mm	
					Test runs
0.9496	0.0328	0.0046	0.0080	0.0051	1
0.9513	0.0336	0.0042	0.0065	0.0043	2
0.9593	0.0286	0.0032	0.0053	0.0036	3
0.9639	0.0254	0.0040	0.0044	0.0024	4
0.9646	0.0255	0.0027	0.0043	0.0029	5
0.9521	0.0296	0.0049	0.0078	0.0056	6
0.9470	0.0324	0.0054	0.0092	0.0059	7
0.9470	0.0300	0.0058	0.0106	0.0065	8
0.9734	0.0179	0.0022	0.0039	0.0025	9
0.9689	0.0207	0.0025	0.0047	0.0026	10
0.9578	0.0256	0.0043	0.0079	0.0050	11
0.9655	0.0231	0.0032	0.0050	0.0031	12
0.9821	0.0121	0.0014	0.0026	0.0018	13
0.9890	0.0058	0.0012	0.0023	0.0017	14
0.9698	0.0129	0.0038	0.0068	0.0043	15
0.9297	0.0417	0.0087	0.0120	0.0071	16
0.9607	0.0249	0.0039	0.0063	0.0040	

Tumbling box matrix variables					
	Wire	Wire+R.Hole			
Durability >4.75mm	3.15-4.75mm	2.36-3.15mm	1-2.36mm	0-1mm	
					Test runs
0.9812	0.0036	0.0009	0.0040	0.0097	1
0.9853	0.0043	0.0008	0.0025	0.0061	2
0.9901	0.0017	0.0008	0.0021	0.0055	3
0.9912	0.0018	0.0004	0.0018	0.0045	4
0.9933	0.0023	0.0004	0.0018	0.0040	5
0.9907	0.0033	0.0007	0.0014	0.0037	6
0.9919	0.0023	0.0004	0.0016	0.0034	7
0.9927	0.0017	0.0008	0.0015	0.0032	8
0.9917	0.0029	0.0003	0.0013	0.0029	9
0.9936	0.0017	0.0003	0.0012	0.0027	10

Ligno pellets durability test matrix variables					
	Wire	Wire+R.Hole			
Durability >4.75mm	3.15-4.75mm	2.36-3.15mm	1-2.36mm	0-1mm	
					Test runs
0.9710	0.0092	0.0028	0.0082	0.0066	1
0.9712	0.0088	0.0030	0.0072	0.0065	2
0.9661	0.0161	0.0028	0.0076	0.0070	3
0.9704	0.0136	0.0033	0.0061	0.0054	4
0.9729	0.0122	0.0018	0.0059	0.0054	5
0.9686	0.0149	0.0024	0.0064	0.0055	6
0.9736	0.0119	0.0024	0.0055	0.0048	7

0.9655	0.0192	0.0035	0.0070	0.0057	8
0.9693	0.0120	0.0040	0.0066	0.0060	9
0.9697	0.0146	0.0026	0.0055	0.0051	10

E 1 present the format of the predicted breakage matrices of repeated pellets degradation for the three bench-scale testers

Modified Repeated Rotary Impact Durability test matrix results

	Input size class					Rotary impact test output
In put size class	8.0 - 4.75 (mm) (%)	3.15-4.75 (mm)	2.36-3.15 (mm)	1-2.36 (mm)	0-1 (mm)	
						0.9574
8.- 4.75	0.9574	0	0	0	0	0.0233
3.15- 4.75	0.0233	1	0	0	0	0.0044
2.36- 3.15	0.0044	0	1	0	0	0.0092
1- 2.36	0.0092	0	0	1	0	0.0044
< 1	0.0044	0	0	0	1	
0.9574	0.9574	0	0	0	0	0.9166
0.0233	0.0233	1	0	0	0	0.0456
0.0044	0.0044	0	1	0	0	0.0086
0.0092	0.0092	0	0	1	0	0.0180
0.0044	0.0044	0	0	0	1	0.0086
0.9166	0.9574	0	0	0	0	0.8776
0.0456	0.0233	1	0	0	0	0.0670
0.0086	0.0044	0	1	0	0	0.0126

0.0180	0.0092	0	0	1	0	0.0264
0.0086	0.0044	0	0	0	1	0.0126
0.8776	0.9574	0	0	0	0	0.8402
0.0670	0.0233	1	0	0	0	0.0874
0.0126	0.0044	0	1	0	0	0.0165
0.0264	0.0092	0	0	1	0	0.0345
0.0126	0.0044	0	0	0	1	0.0165
0.8402	0.9574	0	0	0	0	0.8044
0.0874	0.0233	1	0	0	0	0.1070
0.0165	0.0044	0	1	0	0	0.0202
0.0345	0.0092	0	0	1	0	0.0422
0.0165	0.0044	0	0	0	1	0.0202
0.80439	0.9574	0	0	0	0	0.7701
0.10699	0.0233	1	0	0	0	0.1257
0.02020	0.0044	0	1	0	0	0.0237
0.04224	0.0092	0	0	1	0	0.0496
0.02020	0.0044	0	0	0	1	0.0237
0.7701	0.9574	0	0	0	0	0.7373
0.1257	0.0233	1	0	0	0	0.1437
0.0237	0.0044	0	1	0	0	0.0271
0.0496	0.0092	0	0	1	0	0.0567
0.0237	0.0044	0	0	0	1	0.0271
0.7373	0.9574	0	0	0	0	0.7059
0.1437	0.0233	1	0	0	0	0.1609
0.0271	0.0044	0	1	0	0	0.0304
0.0567	0.0092	0	0	1	0	0.0635
0.0271	0.0044	0	0	0	1	0.0304

0.7059	0.9574	0	0	0	0	0.6758
0.1609	0.0233	1	0	0	0	0.1773
0.0304	0.0044	0	1	0	0	0.0335
0.0635	0.0092	0	0	1	0	0.0700
0.0304	0.0044	0	0	0	1	0.0335
0.6758	0.9574	0	0	0	0	0.6470
0.1773	0.0233	1	0	0	0	0.1930
0.0335	0.0044	0	1	0	0	0.0365
0.0700	0.0092	0	0	1	0	0.0762
0.0335	0.0044	0	0	0	1	0.0365

Input size class

		8.-4.75	3.15-4.75	2.36-3.15	1-2.36	0-1	Our put
	Output size class	(%)					
0.8bar	8.0 -4.75	0.9496	0	0	0	0	0.9496
1st	3.15-4.75	0.0328	1	0	0	0	0.0328
	2.36-3.15	0.0046	0	1	0	0	0.0046
	1-2.36	0.008	0	0	1	0	0.008
	< 1	0.0051	0	0	0	1	0.0051
	0.9496	0.9496	0	0	0	0	0.9017
1 bar	0.0328	0.0328	1	0	0	0	0.0639
2nd	0.0046	0.0046	0	1	0	0	0.0090
	0.008	0.008	0	0	1	0	0.0156
	0.0051	0.0051	0	0	0	1	0.0099

	0.9017	0.9496	0	0	0	0	0.856
0.5 bar	0.0639	0.0328	1	0	0	0	0.094
3rd	0.0090	0.0046	0	1	0	0	0.013
	0.0156	0.008	0	0	1	0	0.023
	0.0099	0.0051	0	0	0	1	0.015
	0.8563	0.9496	0	0	0	0	0.813
0.3bar	0.0935	0.0328	1	0	0	0	0.122
4th	0.0131	0.0046	0	1	0	0	0.017
	0.0228	0.008	0	0	1	0	0.030
	0.0145	0.0051	0	0	0	1	0.019
	0.8131	0.9496	0	0	0	0	0.772
0.8 bar	0.1216	0.0328	1	0	0	0	0.148
5th	0.0171	0.0046	0	1	0	0	0.021
	0.0297	0.008	0	0	1	0	0.036
	0.0189	0.0051	0	0	0	1	0.023
	0.7722	0.9496	0	0	0	0	0.733
0.8 bar	0.1483	0.0328	1	0	0	0	0.174
6th	0.0208	0.0046	0	1	0	0	0.024
	0.0362	0.008	0	0	1	0	0.042
	0.0231	0.0051	0	0	0	1	0.027
	0.7332	0.9496	0	0	0	0	0.696
0.8 bar	0.1736	0.0328	1	0	0	0	0.198
7th	0.0243	0.0046	0	1	0	0	0.028
	0.0423	0.008	0	0	1	0	0.048
	0.0270	0.0051	0	0	0	1	0.031

	0.6963	0.9496	0	0	0	0	0.661
0.8 bar	0.1977	0.0328	1	0	0	0	0.220
8th	0.0277	0.0046	0	1	0	0	0.031
	0.0482	0.008	0	0	1	0	0.054
	0.0307	0.0051	0	0	0	1	0.034
	0.6612	0.9496	0	0	0	0	0.628
0.3 bar	0.2205	0.0328	1	0	0	0	0.242
9th	0.0309	0.0046	0	1	0	0	0.034
	0.0538	0.008	0	0	1	0	0.059
	0.0343	0.0051	0	0	0	1	0.038
	0.6279	0.9496	0	0	0	0	0.596
0.5 bar	0.2422	0.0328	1	0	0	0	0.263
10th	0.0340	0.0046	0	1	0	0	0.037
	0.0591	0.008	0	0	1	0	0.064
	0.0377	0.0051	0	0	0	1	0.041
	0.5962	0.9496	0	0	0	0	0.566
	0.2628	0.0328	1	0	0	0	0.282
1 bar	0.0369	0.0046	0	1	0	0	0.040
11th	0.0641	0.008	0	0	1	0	0.069
	0.0409	0.0051	0	0	0	1	0.044
	0.5662	0.9496	0	0	0	0	0.538
0.8 bar	0.2823	0.0328	1	0	0	0	0.301
12th	0.0396	0.0046	0	1	0	0	0.042
	0.0689	0.008	0	0	1	0	0.073
	0.0439	0.0051	0	0	0	1	0.047

	0.5376	0.9496	0	0	0	0	0.511
	0.3009	0.0328	1	0	0	0	0.319
0.3 bar	0.0422	0.0046	0	1	0	0	0.045
13th	0.0734	0.008	0	0	1	0	0.078
	0.0468	0.0051	0	0	0	1	0.050
	0.5105	0.9496	0	0	0	0	0.485
	0.3185	0.0328	1	0	0	0	0.335
0.5 bar	0.0447	0.0046	0	1	0	0	0.047
14th	0.0777	0.008	0	0	1	0	0.082
	0.0495	0.0051	0	0	0	1	0.052
	0.4848	0.9496	0	0	0	0	0.460
1 bar	0.3353	0.0328	1	0	0	0	0.351
15th	0.0470	0.0046	0	1	0	0	0.049
	0.0818	0.008	0	0	1	0	0.086
	0.0521	0.0051	0	0	0	1	0.055
	0.4604	0.9496	0	0	0	0	0.437
0.8 bar	0.3512	0.0328	1	0	0	0	0.366
16th	0.0493	0.0046	0	1	0	0	0.051
	0.0857	0.008	0	0	1	0	0.089
	0.0546	0.0051	0	0	0	1	0.057

	Output size class	8 - 4.75	3.15-4.75	2.36-3.15	1-2.36	< 1	Outputs
	8.0 -4.75	0.9812	0	0	0	0	0.9812
	3.15-4.75	0.0036	1	0	0	0	0.0036
1st	2.36-3.15	0.0009	0	1	0	0	0.0009
	1-2.36	0.004	0	0	1	0	0.004
	< 1	0.0097	0	0	0	1	0.0097
	0.9812	0.9853	0	0	0	0	0.9668
	0.0036	0.0043	1	0	0	0	0.0078
2nd	0.0009	0.008	0	1	0	0	0.0087
	0.004	0.0025	0	0	1	0	0.0065
	0.0097	0.0061	0	0	0	1	0.0157
	0.9668	0.9901	0	0	0	0	0.9572
	0.0078	0.0017	1	0	0	0	0.0095
3rd	0.0087	0.0008	0	1	0	0	0.0095
	0.0065	0.0021	0	0	1	0	0.0085
	0.0157	0.0055	0	0	0	1	0.0210
	0.9572	0.9912	0	0	0	0	0.9488
	0.0095	0.0018	1	0	0	0	0.0112
4th	0.0095	0.0004	0	1	0	0	0.0099
	0.0085	0.0018	0	0	1	0	0.0102
	0.0210	0.0045	0	0	0	1	0.0253
	0.9488	0.9933	0	0	0	0	0.9424
	0.0112	0.0023	1	0	0	0	0.0134
5th	0.0099	0.004	0	1	0	0	0.0137
	0.0102	0.0018	0	0	1	0	0.0119
	0.0253	0.004	0	0	0	1	0.0291

	0.9424	0.9907	0	0	0	0	0.9337
	0.0134	0.0033	1	0	0	0	0.0165
6th	0.0137	0.0007	0	1	0	0	0.0144
	0.0119	0.0014	0	0	1	0	0.0132
	0.0291	0.0037	0	0	0	1	0.0326
	0.9337	0.9919	0	0	0	0	0.9261
	0.0165	0.0023	1	0	0	0	0.0186
7th	0.0144	0.0004	0	1	0	0	0.0147
	0.0132	0.0016	0	0	1	0	0.0147
	0.0326	0.0034	0	0	0	1	0.0358
	0.9261	0.9927	0	0	0	0	0.9193
	0.0186	0.0017	1	0	0	0	0.0202
8th	0.0147	0.0008	0	1	0	0	0.0155
	0.0147	0.0015	0	0	1	0	0.0161
	0.0358	0.0032	0	0	0	1	0.0387
	0.9193	0.9917	0	0	0	0	0.9117
	0.0202	0.0029	1	0	0	0	0.0229
9th	0.0155	0.0003	0	1	0	0	0.0158
	0.0161	0.0013	0	0	1	0	0.0173
	0.0387	0.0029	0	0	0	1	0.0414
	0.9117	0.9936	0	0	0	0	0.9059
	0.0229	0.0017	1	0	0	0	0.0244
10th	0.0158	0.0003	0	1	0	0	0.0160
	0.0173	0.0012	0	0	1	0	0.0184
	0.0414	0.0027	0	0	0	1	0.0439

	Output size class	8 - 4.75	3.15 - 4.75	2.36 - 3.15	1 - 2.36	< 1	Out put
	8 - 4.75	0.971	0	0	0	0	0.971
1st	3.15 - 4.75	0.0092	1	0	0	0	0.0092
	2.36 -3.15	0.0028	0	1	0	0	0.0028
	1 - 2.36	0.0082	0	0	1	0	0.0082
	< 1	0.0066	0	0	0	1	0.0066
	0.971	0.971	0	0	0	0	0.9428
	0.0092	0.0092	1	0	0	0	0.0181
2nd	0.0028	0.0028	0	1	0	0	0.0055
	0.0082	0.0082	0	0	1	0	0.0162
	0.0066	0.0066	0	0	0	1	0.0130
	0.9428	0.971	0	0	0	0	0.9155
	0.0181	0.0092	1	0	0	0	0.0268
3rd	0.0055	0.0028	0	1	0	0	0.0082
	0.0162	0.0082	0	0	1	0	0.0239
	0.0130	0.0066	0	0	0	1	0.0192
	0.9155	0.971	0	0	0	0	0.8889
	0.0268	0.0092	1	0	0	0	0.0352
4th	0.0082	0.0028	0	1	0	0	0.0107
	0.0239	0.0082	0	0	1	0	0.0314
	0.0192	0.0066	0	0	0	1	0.0253
	0.8889	0.971	0	0	0	0	0.8632
	0.0352	0.0092	1	0	0	0	0.0434
5th	0.0107	0.0028	0	1	0	0	0.0132
	0.0314	0.0082	0	0	1	0	0.0387
	0.0253	0.0066	0	0	0	1	0.0311

	0.8632	0.971	0	0	0	0	0.8381
6th	0.0434	0.0092	1	0	0	0	0.0513
	0.0132	0.0028	0	1	0	0	0.0156
	0.0387	0.0082	0	0	1	0	0.0458
	0.0311	0.0066	0	0	0	1	0.0368
	0.8381	0.971	0	0	0	0	0.8138
	0.0513	0.0092	1	0	0	0	0.0591
7th	0.0156	0.0028	0	1	0	0	0.0180
	0.0458	0.0082	0	0	1	0	0.0526
	0.0368	0.0066	0	0	0	1	0.0424
	0.8138	0.971	0	0	0	0	0.7902
	0.0591	0.0092	1	0	0	0	0.0665
8th	0.0180	0.0028	0	1	0	0	0.0203
	0.0526	0.0082	0	0	1	0	0.0593
	0.0424	0.0066	0	0	0	1	0.0477
	0.7902	0.971	0	0	0	0	0.7673
	0.0665	0.0092	1	0	0	0	0.0738
9th	0.0203	0.0028	0	1	0	0	0.0225
	0.0593	0.0082	0	0	1	0	0.0658
	0.0477	0.0066	0	0	0	1	0.0530
	0.7673	0.971	0	0	0	0	0.7451
	0.0738	0.0092	1	0	0	0	0.0809
10th	0.0225	0.0028	0	1	0	0	0.0246
	0.0658	0.0082	0	0	1	0	0.0721
	0.0530	0.0066	0	0	0	1	0.0580