Effects of Relative Humidity and Temperature on Particle Adhesion Measurements Using Mechanical Surface Energy Tester and Prediction of Powder Flow

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Accurate quantification of particle adhesion is essential for predicting the flow behaviour of cohesive powders, as interparticle forces strongly influence bulk powder performance. Adhesion is known to depend on environmental conditions, particularly relative humidity (RH) and temperature. This study systematically investigates the combined effects of RH and temperature on particle adhesion using a Mechanical Surface Energy Tester. The experiments enable precise control of environmental conditions, allowing adhesion forces to be evaluated under well-defined RH–temperature combinations and expressed as Bond numbers to account for particle size, shape and density effects. Fifteen pharmaceutical powders were selected to represent a broad range of particle size, morphology, and true density. Three controlled RH–temperature conditions were applied for the measurements of corresponding adhesions.

The study results show a complex, material-dependent relationship between environmental conditions and adhesion behaviour. At a low RH of 20%, adhesion generally increased, attributed to enhanced solid–solid intermolecular interactions in the absence of significant surface moisture. At an elevated RH of 80%, it found that in some cases reducing effective adhesion through lubrication effects and promoting improved flowability because of the formation of adsorbed moisture layers altered interfacial mechanics. Temperature further modulated adhesion by influencing material viscoelasticity and surface energy characteristics, leading to measurable changes of adhesions. These findings highlight the coupled influence of environmental conditions and intrinsic particle properties on adhesion behaviour. The outcomes provide valuable insights for predicting powder flow performance and for developing environmental control strategies in pharmaceutical manufacturing and other powder-handling applications.

Keywords: *Particle Adhesion, Relative Humidity, Temperature, Mechanical Surface Energy, Pharmaceutical powders, Flow Properties*

1 Introduction

The transition from batch processing to continuous manufacturing (CM) in the pharmaceutical industry has heightened the need for robust, predictable powder flow behaviour [1]. In continuous processes such as loss-in-weight feeding, continuous blending, twin-screw granulation, and tablet compression, powder flow instability can rapidly propagate through the process, leading to fluctuations in mass flow rate, blend uniformity, residence time distribution, and ultimately product quality [2]. Unlike batch systems, where disturbances can be isolated, continuous systems require steady, reproducible powder performance under dynamically varying operating conditions. Therefore, control of powder flow behaviour under the influences of environmental conditions can be critical to ensure a successful continuous manufacturing.

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Powder flow behaviour is governed by particle size, shape, density, and surface characteristics, as well as interparticle forces that determine bulk cohesiveness [3]. Among these factors, cohesiveness is particularly sensitive to environmental conditions. In continuous manufacturing environments, powders may experience variable relative humidity (RH) and temperature during storage in intermediate bulk containers, transfer through feeding systems, and prolonged exposure in hoppers. Even modest environmental fluctuations can alter interparticle forces, leading to changes in flow regime, feeder refill behaviour, arching propensity, or inconsistent discharge rates [4,5].

Conventional bulk characterisation techniques, such as shear cell testing [6,7], are widely used to assess powder flowability during formulation and process development. However, their application in studying environmental effects presents significant practical challenges. Shear testing requires relatively large material quantities and extensive preconditioning, making systematic RH–temperature mapping time-consuming and resource-intensive. Furthermore, bulk tests provide limited insight into the particle-scale mechanisms responsible for environmentally induced changes in cohesiveness. In continuous manufacturing, where small variations in material properties can significantly influence process control strategies, a more sensitive, material-efficient approach is desirable.

To address these limitations, a particle-scale methodology based on adhesion measurement has been developed at the Wolfson Centre using a Mechanical Surface Energy Tester (MSET) [8]. In this framework, powder cohesiveness is quantified via the Bond number, defined as the ratio of particle adhesion force to particle gravitational force. Adhesion is measured directly by detaching individual particles or small agglomerates from a flat substrate, and the Bond number is calculated from the measured deceleration relative to gravitational acceleration [9]. By incorporating particle size and density, this approach enables the prediction of flow behaviour using small sample quantities, making it particularly suitable for early-stage formulation screening and continuous process development.

At the particle level, adhesion arises from van der Waals interactions, electrostatic forces, and capillary forces. Environmental conditions can significantly alter these interactions. Increasing RH may promote moisture adsorption or liquid-bridge formation at particle contacts, thereby increasing capillary forces and thus cohesiveness. Temperature variations may further influence adhesion by modifying surface energy, viscoelastic behaviour, and moisture distribution at interfaces. In continuous manufacturing systems, where feeders operate under near-static consolidation conditions and low confining stresses, such environmentally induced changes in interparticle forces can strongly influence mass flow consistency.

Previous studies have demonstrated that elevated RH can significantly influence laboratory measurements of powder flowability and powder bed formation [5]. Notably, measurable changes in cohesive behaviour have been observed even at low levels of moisture uptake. Similar humidity-dependent effects have been reported in shear cell testing at 40–80% RH [10]. Earlier work at the Wolfson Centre identified threshold environmental conditions beyond which materials such as mannitol exhibit deterioration in flow properties [11]. These findings suggest the existence of critical humidity–temperature regimes that may

compromise process stability in continuous operations, particularly during prolonged material residence times [12,13].

Importantly, environmentally driven changes in cohesiveness are not always readily detected by conventional bulk testing but can be captured sensitively through particle adhesion measurements [14,15]. Since adhesion directly reflects the cohesive interactions governing bulk flow, it provides a mechanistically grounded indicator of environmental susceptibility. With precise control of RH and temperature, the MSET enables rapid, systematic quantification of adhesion under controlled conditions, supporting risk assessment and the design of environmentally robust continuous processes.

The present study investigates the influence of controlled RH and temperature on particle adhesion and powder cohesiveness for pharmaceutical materials particularly relevant to continuous manufacturing, where the industry currently faces practical challenges and cost issues in controlling environmental conditions in handling process [16-17]. In the study, fifteen pharmaceutical powders including two active pharmaceutical ingredients (APIs), seven excipients, and six co-processed excipients, were selected to represent a range of particle sizes, morphologies, and densities. Particular emphasis is placed on demonstrating how environmentally controlled particle-scale measurements can support predictive assessment of flow performance using small sample quantities and save evaluation costs. The findings aim to improve feeder reliability, process stability, and environmental risk mitigation in continuous pharmaceutical manufacturing.

2 Particle adhesion and Bond number

2.1 Particle adhesion and influential factors

Particle adhesion is defined as a force between particles or a solid surface to stop particle separation, which consists of three primary components: Van der Waals forces, electrostatic forces, and capillary forces, as shown in Eq. (1) [18].

$$F_{ad} = F_{vw} + F_e + F_{cf} \quad (1)$$

where F_{vw} is the Van der Waals force, F_e is the electrostatic force, and F_{cf} is the capillary force.

The magnitude of each component depends on the physicochemical properties of the contact surfaces, the contact orientation, and the separation distance between particles or between particles and the surface [19]. Characterising each adhesion force can be challenging; however, theoretical estimates have been reported in the literature, typically based on the assumption of perfectly rigid spherical particles in contact [20]. This study focuses on the influence of environmental conditions, such as humidity and temperature, on particle adhesion, which may affect particle surface properties or alter capillary forces. Although these factors may influence the electrostatic force, their effects are beyond the scope of this study and have been investigated in a previous study [21].

2.2 Bond number of powders

Bond number (*Bo*) has been used for the description of powder cohesiveness [9], which is defined as a ratio of particle adhesion force, F_{ad}, to the gravity force of the particle or particles, F_g, as shown in Eq. 2.

$$Bo = F_{ad}/F_g = F_{ad}/(mg) \quad (2)$$

where the particle adhesion (F_{ad}) of particles is measured using a mechanical surface energy tester [7], which can determine particle adhesion only using milligrams of sample that contain a sufficient number of particles (typically hundreds of particles, subject to the particle density). With a *Bo* number, powder cohesiveness can be identified at a given size, typically the D50, across a range of particle sizes.

2.3 Prediction of powder flow using Bo numbers

The flow property of powders is mainly driven by particle size distribution, particle shape, solid density, and internal friction [3]. Characterising the flow properties of powders typically requires substantial sample material for reliable measurements [9,22]. A common characteristic for assessing powder flow is the Flow Function (FF), introduced by Jenike in 1967 [23], which is defined as a ratio of the major principal consolidation stress to the unconfined yield strength under compact and shear conditions, as shown in Eq. (3):

$$\text{Flow Function } (ff) = \frac{\text{major principal stress, } \sigma_1}{\text{unconfined yield strength, } \sigma_c} \quad (3)$$

Flow function measurements require determining the failure strengths of a compacted powder bed under a series of controlled consolidation loads. Because the powder bed cannot be too small, a common flow function testing needs a significant amount of test samples, often tens of grams per test, which limits some special applications, such as powder flow assessments at the early formulation development stage for pharmaceuticals [22].

A prediction method of powder flow was developed at the Wolfson Centre based on correlations between powder flowability and powder cohesiveness represented by a Bond number [8]. The prediction model is shown in Eq. 4, in which the flowability of powders is a function of consolidation stress (σ_1) levels.

$$1/ffc = m(Bo) + c \quad (4)$$

where $m=a_1 ln(\sigma_1)+b_1$ and $c=a_2(\sigma_1)^{b_2}$, and a_1, a_2, b_1 and b_2 are constants as -0.020, -0.442, 0.117 and -0.073, respectively, from a previous study [9, 15], the prediction model can be:

$$1/ffc = [-0.020 \ln(\sigma_1) + 0.117](Bo) - 0.442(\sigma_1)^{-0.073} \quad (5)$$

In this method, powder flow properties are predicted using the Bond number and consolidation stress (σ_1). This method offers significant advantages for determining powder flow properties using milligrams of sample material [9]; however, it is sensitive to Bond number measurements, which are influenced by particle adhesion and many environmental factors. It is essential to examine the environmental factors that influence particle adhesion measurements.

3 Materials and methods

3.1 Test Materials

In this study, 43 sample powders were investigated, covering a wide range of particle size, shape, and solid density, and 15 pharmaceutical powders (2 APIs, 7 excipients, and 6 co-

processed excipients) are presented. The characteristics of the materials, including particle size, size span, and particle solid density, are shown in Table 1.

Table 1: MATERIALS STUDIED AND MATERIAL PHYSICAL PROPERTIES

Materials	Name	Short name	*Particle Size* (μm)			Size Span	Solid density (kg/m^3)	Sphericity (at 20°C, 50%RH)
			D_{10}	D_{50}	D_{90}			
API	**Caffeine (virgin)**	Caf.v	7	70	326	4.56	1454	0.724
API	**Caffeine (roller-compacted)**	Caf.c	7	76	348	4.49	1475	0.764
Excipient	**MCC Avicel PH-101**	MCC101	18	61	133	1.89	1675	0.648
Excipient	**MCC Avicel PH-102**	MCC102	34	116	243	1.80	1657	0.724
Excipient	**MCC Avicel PH-105**	MCC105	5	19	44	2.05	1675	0.712
Excipient	**MCC Avicel PH-200**	MCC200	59	180	337	1.54	1689	0.821
Excipient	**Isomalt 801**	Iso801	6	24	58	2.17	1580	0.698
Excipient	**Isomalt 721**	Iso721	45	161	331	1.78	1589	0.764
Excipient	**Parteck M100**	PM100	45	102	215	1.67	1544	0.789
Co-p Ex.	**Pharmaburst™ 500**	PB500	7	71	178	2.41	1768	0.658
Co-p Ex.	**Ludipress®**	Ludip	25	115	389	3.17	1753	0.822
Co-p Ex.	**StarTab®**	STab	23	74	156	1.80	1645	0.785
Co-p Ex.	**Microcelac® 100**	MC100	19	70	224	2.93	1815	0.787
Co-p Ex.	**Prosolv® SMCC 50**	ProS50	22	60	130	1.80	1686	0.821
Co-p Ex.	**CombiLac®**	Combi	14	45	122	2.40	1873	0.824

3.2 Experimental methods

3.2.1 Particle size and density measurements

The particle sizes of the powders were measured using laser diffraction (Mastersizer 3000, Malvern Panalytical Ltd, UK) with a dry feeding method. For example, about 5-7g of powder was used for 5 measurements, which were taken at an air pressure of 2 bar and a 50% feed rate. The averaged result of all measurements was used for the study. The size span (S_{span}) was calculated as defined in Eq. (6) using the measured sizes, representing the particle size range that may significantly influence powder adhesion measurements.

$$S_{\text{span}} = (D_{90} - D_{10})/D_{50} \quad (6)$$

where D_{50} is the median size in diameter, where 50% of the powder in volume is smaller than the size. D_{10} and D_{90} are the sizes where 10% and 90% of the powder are below the size, respectively.

Particle density was measured using a gas pycnometer (Ultrapyc 1200e, Quantachrome Instruments, USA) with nitrogen gas. Five repeats were taken, with a standard deviation of approximately 0.05% of the mean.

3.2.2 Mechanical surface energy tester

A mechanical surface energy tester was used to measure particle adhesion in cohesive powders and to calculate the Bond number (*Bo*). The details of the tester and the operating

method have been provided in the previous study [9]. A brief description of the tester is given here.

Approximately 50 mg of sample powder was deposited on a 40 mm-diameter glass substrate disc using an air-expansion disperser at 1.5 bar. After deposition, the sample weight was measured using a digital balance (accuracy: 0.1 mg). The prepared sample discs (4 substrate discs per test) were placed in a sample holder and discharged under gravity through a guide rod, where the particles decelerated upon hitting a metal buffer. The deceleration and the mass of the detached particles were measured. The detached particles were collected and then analysed under a Malvern G3 microscope (Malvern Panalytical Ltd, UK) to determine the median particle size (D_{50}). The Bond number (*Bo*) was calculated using the deceleration value and adhesion force, as shown in Eq. (2).

3.2.3 Procedure and test conditions

In this study, two major factors affecting particle adhesion were examined: air humidity and environmental temperature. First, the powder sample was deposited onto the substrate disc using an air-expansion disperser. The substrate discs with the deposited samples were stored in an environment-controlled chamber for 2 hours of conditioning. After conditioning, the sample discs were installed in the MSET, which had been previously located in the chamber for the same environmental conditions. The detachment tests were conducted, and the sample holders were collected for detached-particle analysis. With the mass measured of the detached particles and the acceleration recorded, the Bo number was calculated, and the particle adhesion of the sample was determined.

For the study, the temperatures were 20 °C, 30 °C, and 40 °C, while the relative humidity was maintained at 50% at 20 °C. 3 levels of relative humidity were studied: 30%, 50%, and 70%. It covers common environmental conditions but not the extreme conditions.

3.2.4 Powder flow properties and shear tester

The powder flow properties were measured using a commercial shear cell powder flow tester (PFT, Brookfield Engineering Laboratories Inc., Middleboro, MA, USA), which is typically used for determining flow functions under varied consolidation stresses [23]. The tester consists of an annular shear cell (263 cm^3 for the standard cell, or 43 cm^3 for a small cell) and a knifed lid. A weighed powder sample (accuracy: 1 mg) was loaded into the cell evenly, and the sample was tested under a sequence of consolidation stresses. In this study, 1.58, 3.20 and 6.50 kPa consolidation stresses were used. Once a desired consolidation stress level was achieved, shear forces were then applied to the powder bed. The torque generated was recorded to calculate Mohr's circle and the unconfined yield strength at each consolidation stress level. The tests were conducted under the same designed environmental conditions as the MSET used for adhesion measurements to predict powder flow properties.

4 Results and discussion

4.1 Environmental temperature

With a constant environmental humidity of 50%, the Bond numbers of the powders used in this study were measured at three environmental temperatures: 20, 30, and 40 °C. The Bo numbers for the materials studied are given in Table 2 and shown in Figure 1.

Table 2: *Bo* measured at 20, 30 and 40 ˚C at the 50% relative humidity

Materials	*Name*	*D50* (μm)	*Bo* numbers at the temperature		
			20°C	30°C	40°C
API	Caf.v	70	6.6	6.6	7.2
API	Caf.c	76	5.8	5.8	6.2
Excipient	MCC101	61	6.2	6.5	6.8
Excipient	MCC102	116	5.4	5.5	5.6
Excipient	MCC105	19	8.7	8.9	8.9
Excipient	MCC200	180	5.0	5.2	5.3
Excipient	Iso801	24	8.4	8.7	8.8
Excipient	Iso721	161	4.4	4.4	4.4
Excipient	PM100	102	4.6	4.7	4.8
Co-p Excipient	PB500	71	4.4	4.5	5.2
Co-p Excipient	Ludip	115	4.5	4.8	5.0
Co-p Excipient	STab	74	4.3	4.3	4.6
Co-p Excipient	MC100	70	4.8	4.9	5.3
Co-p Excipient	ProS50	60	6.1	6.1	6.5
Co-p Excipient	Combi	45	4.5	4.6	4.7

With the measured Bond numbers shown in Table 2 and the material properties (size and density) shown in Table 1, the particle adhesions are calculated by the Eq. (2) and the results are shown in Fig. 2. For the results in Fig. 1 and 2, it can be found that the particle adhesion generally increases with the environmental temperatures at a constant level of relative humidity. For this phenomenon, a theoretical explanation is that the level of surface moisture on the particles decreases as temperature increases, while the RH remains constant. It is observed that the increment gradient is not linear.

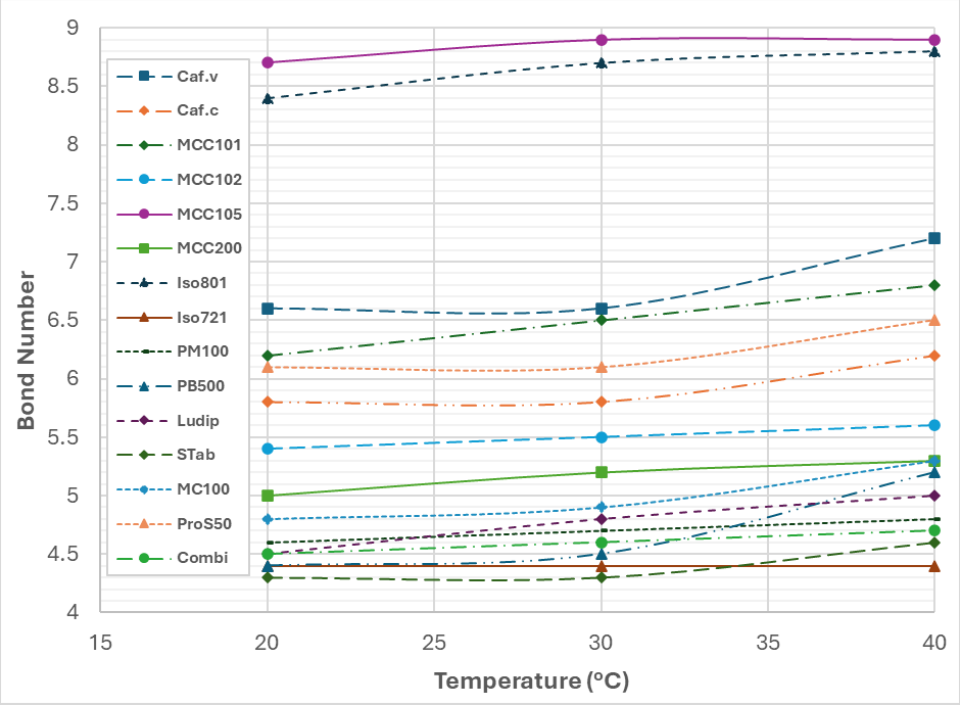

Figure 1: Bond numbers of the materials measured at the temperatures of 20, 30 and 40 ˚C and the relative humidity of 50%.

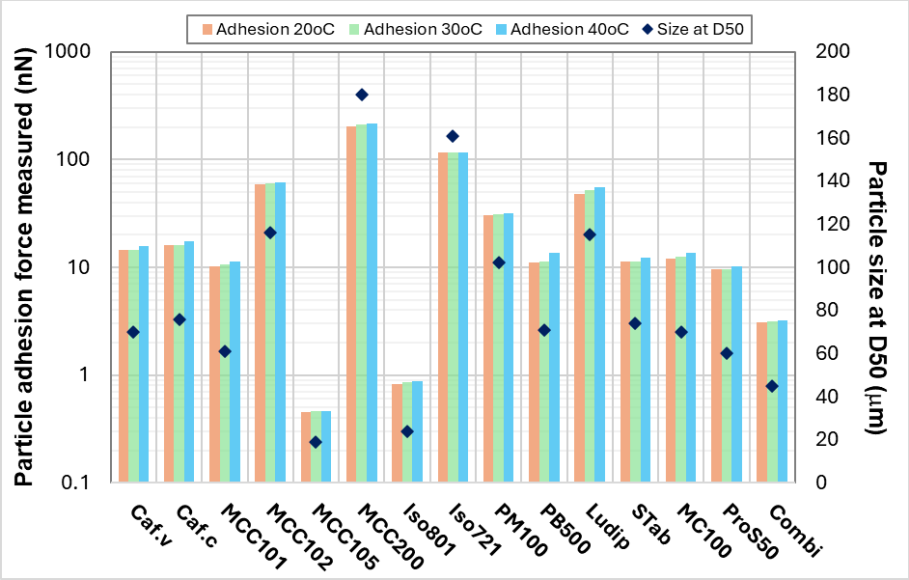

Figure 2: Particle adhesions measured with corresponding particle size (D50) for the temperatures of 20, 30 and 40 ˚C at a constant level of relative humidity of 50%.

In Fig. 2, it can be seen that variations in particle adhesion due to changes in environmental temperature are generally small. All materials show a slight increase in temperature, except Iso721, which has not shown a change in particle adhesion. Commonly, it is thought that particle adhesion is influenced by the surface texture of particles and the contact distance between the particles. With the same materials, surface moisture may change the capillary force if it forms liquid bridges. If it is not the case, the temperature may alter the surface energy level and, in turn, change particle adhesion. In average of gradients, the particle adhesion will increase about 1.2±2.0 nN for every 10˚C, which is about 0.3% nN/°C. The influence of temperature seems small, but it can be significant if the temperature difference exceeds 100 °C. Proportionally, adhesion can increase by more than 30% when the temperature increases by 100 °C.

4.2 Environmental humidity

The influence of air relative humidity on particle adhesion has been studied. With a constant environmental temperature of 30 °C, the Bo numbers of the sample materials used in this study were measured at three different environmental humidities: 30%, 50%, and 70% RH. The results of the Bo numbers are presented in Table 3 and Figure 3.

In Fig. 3, the Bond numbers decrease with increasing environmental humidity at 30 ˚C. Compared to the results in Fig. 1, the Bond number level changes significantly at a constant environmental temperature, indicating that surface moisture on particles can significantly influence particle adhesion. For this phenomenon, the theoretical explanation is that the level of surface moisture on the particles increases as environmental RH increases, which may increase capillary forces but significantly decrease electrostatic forces. With the Bond numbers shown in Table 3 and the material properties (size and density) shown in Table 1, the particle adhesions calculated by Eq. (2) are shown in Fig. 4.

Fig. 4 shows that particle adhesion decreases with increasing environmental humidity. All materials exhibit a reducing trend as relative humidity increases at a given temperature. It

can be due to the influence of surface moisture on the particles and the reduction of electrostatic forces between them. However, surface moisture may alter capillary forces if liquid bridges form. In this case, surface moisture may reduce surface energy and, in turn, particle adhesion. This study shows that increased surface moisture reduces particle adhesion, indicating that capillary force has a limited effect on particle adhesion unless the surface moisture is saturated. In average of gradients, the particle adhesion will reduce about 1.6±2.1 nN for every 10% RH increase, which is about 0.46% nN/%RH. The influence of humidity is more significant than that of environmental temperature. However, the humidity's influence on particle adhesion will be limited by the surface moisture's saturation point.

Table 3: *Bo* measured at 30%, 50% and 70% RH at the temperature of 30 ˚C

Materials	*Name*	*D50* (μm)	*Bo* numbers at the relative humidity		
			30%	50%	70%
API	Caf.v	70	6.9	6.6	6.5
API	Caf.c	76	6.4	5.8	5.7
Excipient	MCC101	61	7.2	6.5	6.1
Excipient	MCC102	116	5.9	5.5	5.2
Excipient	MCC105	19	9.2	8.9	8.4
Excipient	MCC200	180	5.5	5.2	5
Excipient	Iso801	24	8.9	8.7	8
Excipient	Iso721	161	4.9	4.4	4.2
Excipient	PM100	102	5.1	4.7	4.4
Co-p Excipient	PB500	71	4.7	4.5	4.1
Co-p Excipient	Ludip	115	5.3	4.8	4.1
Co-p Excipient	STab	74	4.5	4.3	4
Co-p Excipient	MC100	70	5.6	4.9	4.4
Co-p Excipient	ProS50	60	6.6	6.1	5.8
Co-p Excipient	Combi	45	5.1	4.6	4.2

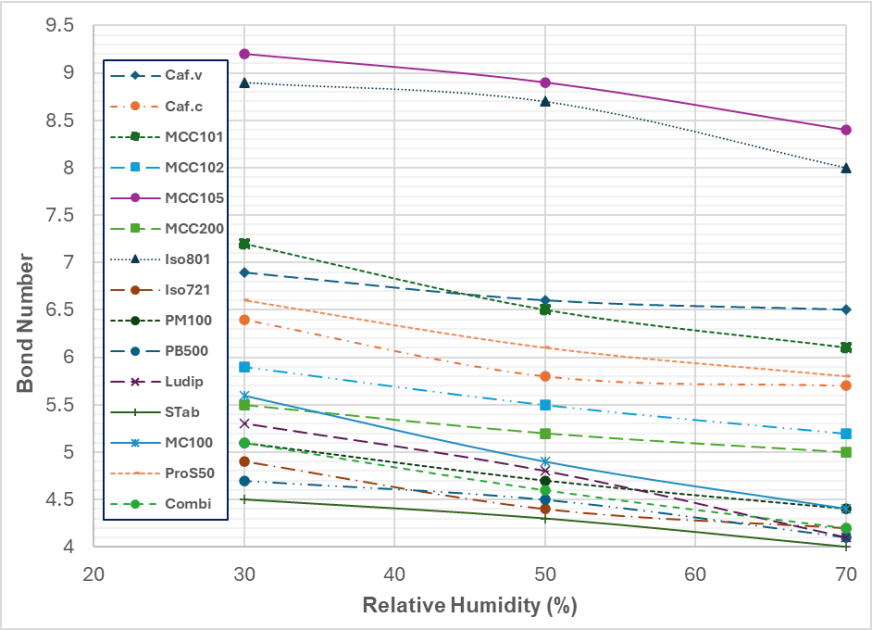

Figure 3: Bond numbers change at the relative humidity of 30%, 50% and 70% of the powder materials measured at a temperature of 30 °C.

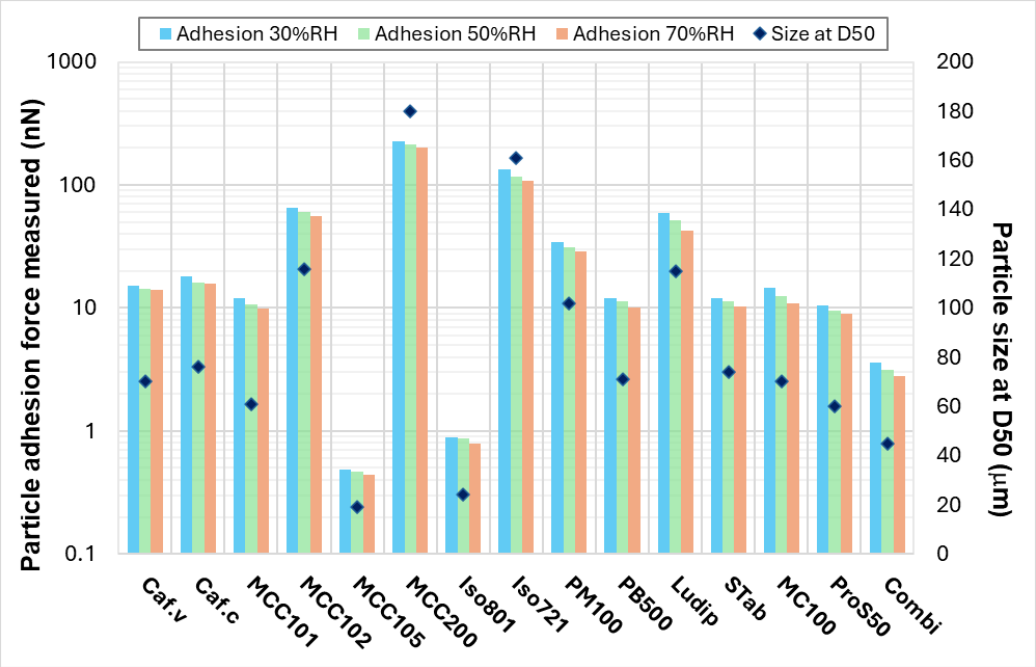

Figure 4: Particle adhesions measured with corresponding particle size (D50) for the relative humidity of 30%, 50% and 70% at a temperature of 30 °C.

4.3 The influence of particle shape

In measurements using MSET, results can be influenced by particle orientation when particles are deposited on the substrate, depending on particle shape. In theory, the contact area between particles and the surface can differ [24], depending on how the particles attach to the surface. With more irregular shapes, the particle may be more likely to deposit in a certain orientation, resulting in a higher contact area and, by extension, a higher particle adhesion compared to spherical particles. Scanning electron microscope (SEM) images of the tested materials show the shape differences in Fig. 5.

In the measurements of particle Bo numbers, the measurement of particle adhesion is not influenced only by the particle shape, but also by the contact area and how the particles were deposited on the substrate surface. To examine the influence of particle shape and particle deposition, particle sphericity and particle size at D50 were measured. The results are shown in Fig. 6.

For the results in Fig. 6, it can be seen that the particles detached during the measurements have higher sphericity and larger particle size. The increase in particle sphericity and particle size means spherical or larger particles tend to have a smaller contact area and, alternatively, a smaller particle adhesion force for the same projected particle size. The results show that the average sphericity of the materials increases from 0.756 before detachment to 0.897 after detachment. The increase in particle sphericity is about 19.3%, for irregular particles such as MCC101, the sphericity of detached particles shows the largest increase among all particles. For rounded particles such as Ludipress, the increase in sphericity is much smaller. The interesting thing is that the variation of the sphericity of the detached particles is smaller compared to the variation in the virgin materials, which is 0.897±0.044 for detached particles compared to 0.756±0.059 for virgin materials.

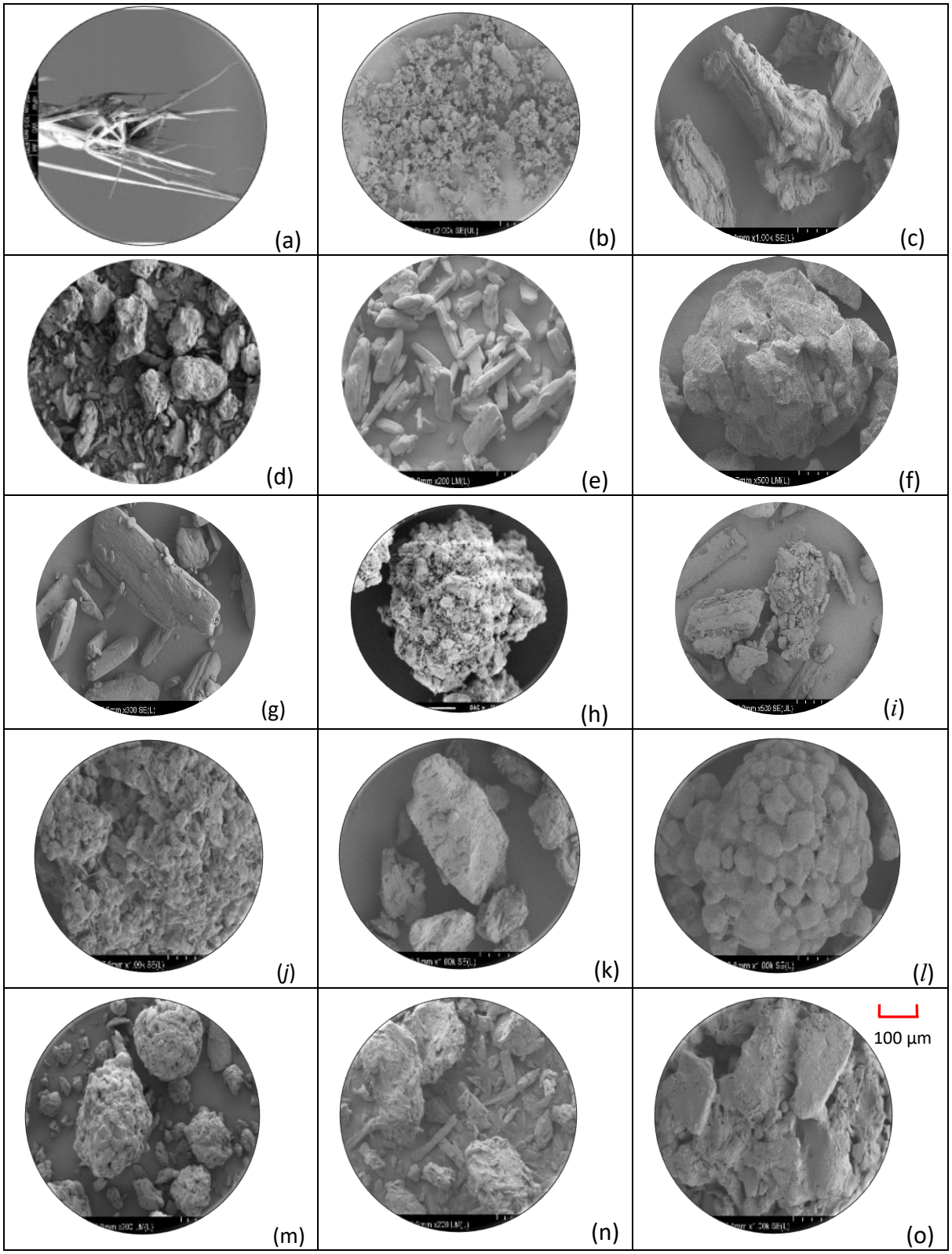

Figure 5: SEM images of the sample materials tested: (a) Caf.v, (b) Caf.c, (c) MCC101, (d) MCC102, (e) MCC105, (f) MCC200, (g) Iso801, (h) Iso721, (i) PM100, (j) PB500, (k) Ludip, (l) STab, (m) MC100, (n) ProS50, and (o) Combi.

For the particle size, the D50 of the detached particles increased by about 20.2% in average compared to the D50 of the particles deposited. For some materials, especially those with a large D50 such as Iso721, the increase in particle size is not significant, ranging from 5.6% to

11.3%. However, some material, such as MCC105, is quite significant, accounting for about 89.5%. An explanation is particle agglomeration and the influence of particle shape, which determines the status of particle attachment onto the substrate surface. For example, Caf.v and Caf.c have similar particle sizes (70 µm and 76 µm). Still, in the Bo number measurements, they are quite different (see Fig. 7). For MCC101 and MCC102, particle size clearly influences particle adhesion, as large particles (MCC102) have a lower Bo number.

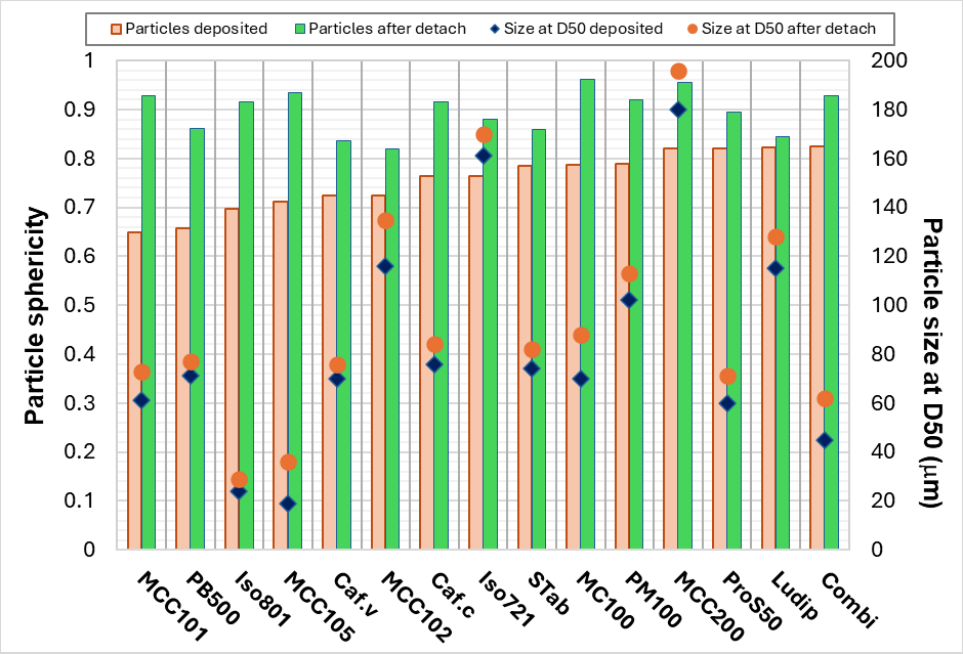

Figure 6: Particle sphericity with corresponding particle size (D50) of deposited and detached particles before and after the tests using MSET at a temperature of 20 ˚C and 50%RH.

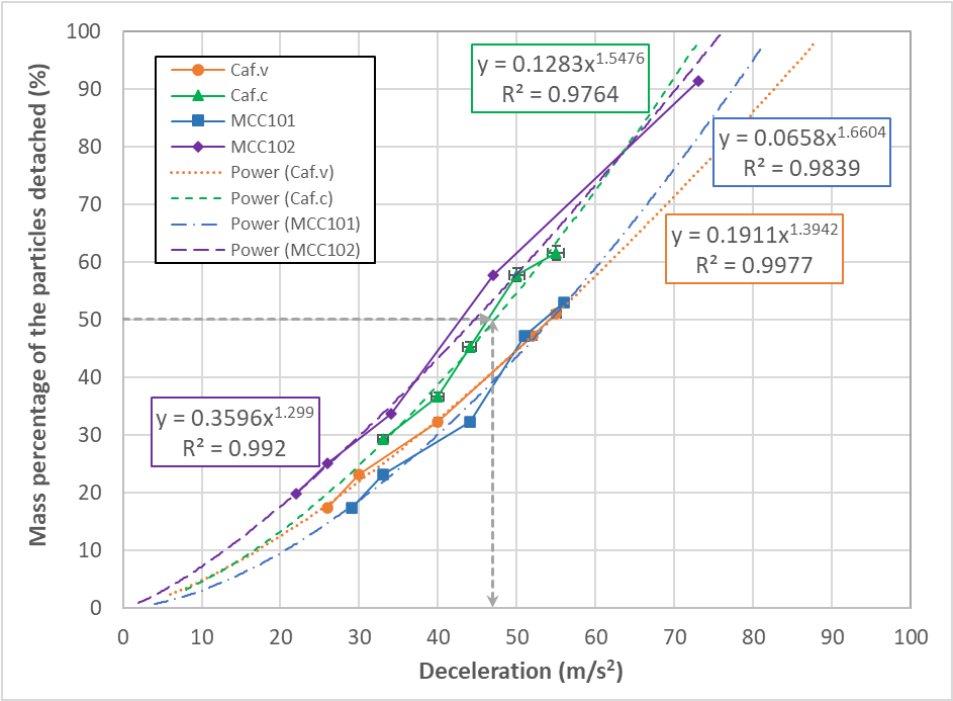

Figure 7: The mass proportions detached from the powders in the MSET measurements at different decelerations of Caf.v, Caf.c, MCC101 and MCC102.

The results in Fig. 7 also show that the materials have similar Bo numbers, such as Caf.v and MCC101, but particle adhesion for different-sized particles can exhibit quite different behaviours. For fine particles, Caf.v shows more cohesion compared to MCC101, although MCC101 has a smaller D50. This may be due to the influence of particle surface texture and conditions (see Fig. 5).

4.4 Comparison between the measured and the predicted flow functions

The results in Figs. 1 and 3 demonstrate the influences of environmental temperature and humidity on the measured Bond numbers. With the measured Bo numbers, the predicted flow functions of the sample powders, derived using the Bo numbers in Tables 1 and 3 and the model shown in Eq. 5, were compared with the measured flow functions using the PFT shear tester. For the predicted flow functions of the test materials, 4 principal consolidating stresses were used: 1.25, 2.25, 4.5, and 9 kPa. For the measured flow functions obtained using the PFT shear tester, 3 intermediate major principal consolidating stresses were used: 1.58, 3.35, and 6.98 kPa. Because of the total of 15 test materials, including API, excipients, and co-processed excipients, selected comparison results for some typical samples are shown in Figs. 8-13, including Caf.v and Caf.c (APIs), MCC101 (excipients), and Ludip (co-processed excipients). The comparison results for other materials can be found in the appendix.

The comparison in Fig. 8 shows the flow functions of Caf.v and Caf.c at 20 °C- 40 °C and 50% RH. It shows a good match between the predicted and measured flow functions. The prediction errors are mostly within 10%. The predictions also picked up the influence of the temperatures, which the powders of Caf.v and Caf.c become more cohesive at the temperature of 40 ˚C. However, over the range of 20 °C to 30 °C, the temperature did not show a significant effect, and the Bo number measurements also showed a similar result.

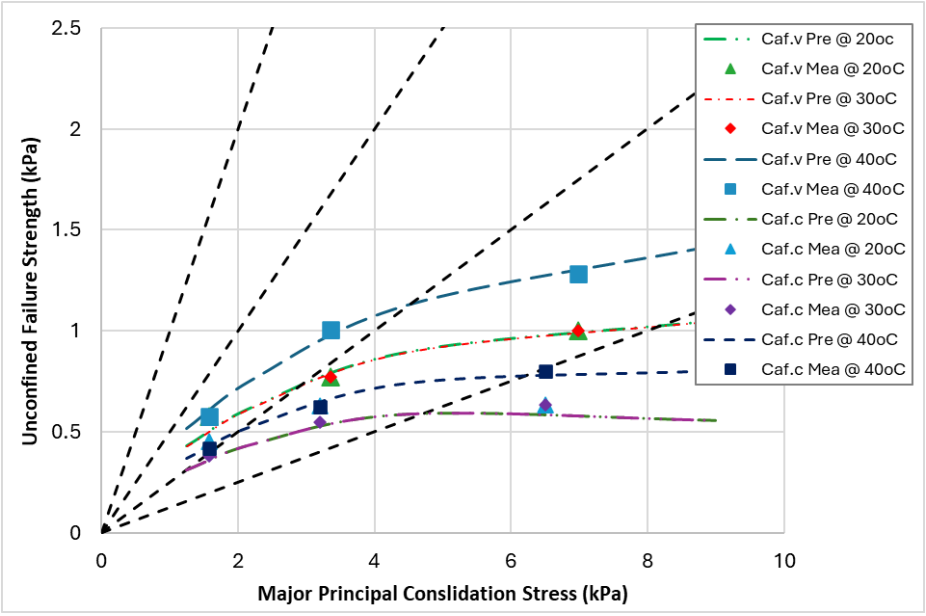

Figure 8: Predicted flow functions by the model compared to the measured flow functions for Caf.v and Caf.c at the temperatures of 20, 30 and 40 ˚C and the same humidity of 50% RH.

The comparison in Fig. 9 shows the flow functions of the Caf.v and Caf.c for different humidity levels of 30%, 50% and 70% RH at a temperature of 20 ˚C. It also shows a good match

between the predicted and measured flow functions. The prediction errors are slightly higher than the predictions at different temperatures, especially at the low consolidation stresses. However, the predictions did capture the influence of environmental humidity, showing a decrease in powder cohesiveness as humidity increased.

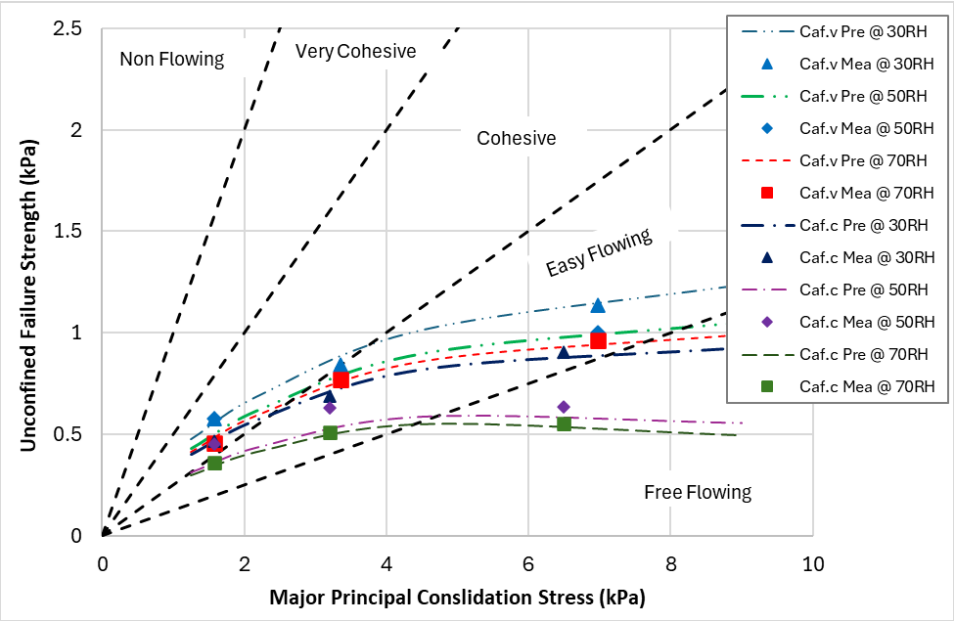

Figure 9: Predicted flow functions by the model compared to the measured flow functions for Caf.v and Caf.c at the humidity of 30%, 50% and 70%RH and the same temperature of 20 ˚C.

As shown in Fig. 6, excipient MCC101 has the lowest sphericity but is not likely to be the Caf.v, which has a needle shape (see Fig. 5). Therefore, comparisons of flow functions for MCC101 are shown in Figs. 10 and 11 for the environmental temperature and humidity influences, because of its irregular particle shape.

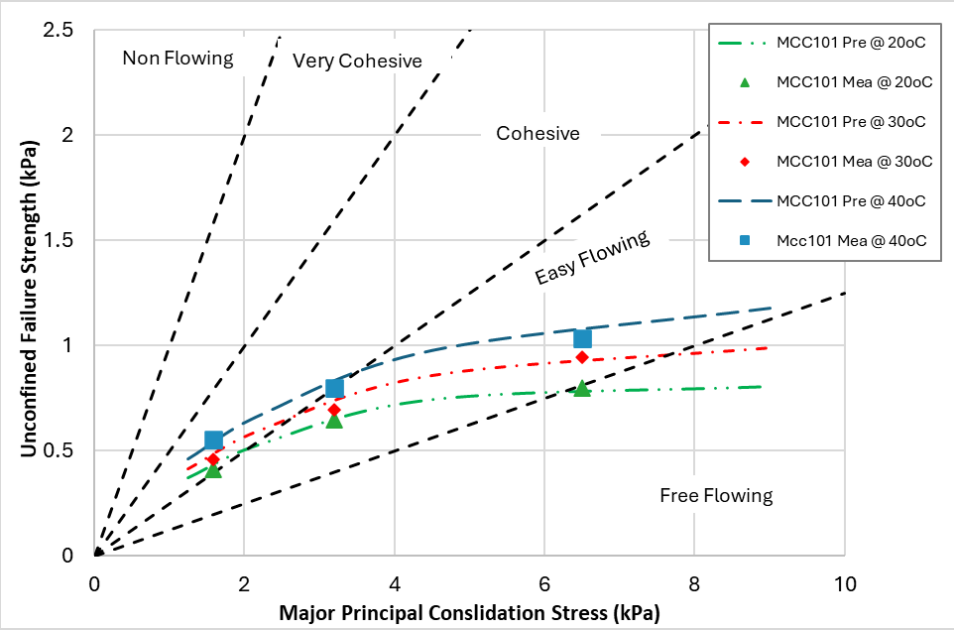

Figure 10: Predicted flow functions by the model compared to the measured flow functions for MCC101 at the temperatures of 20, 30 and 40 ˚C and the same humidity of 50% RH.

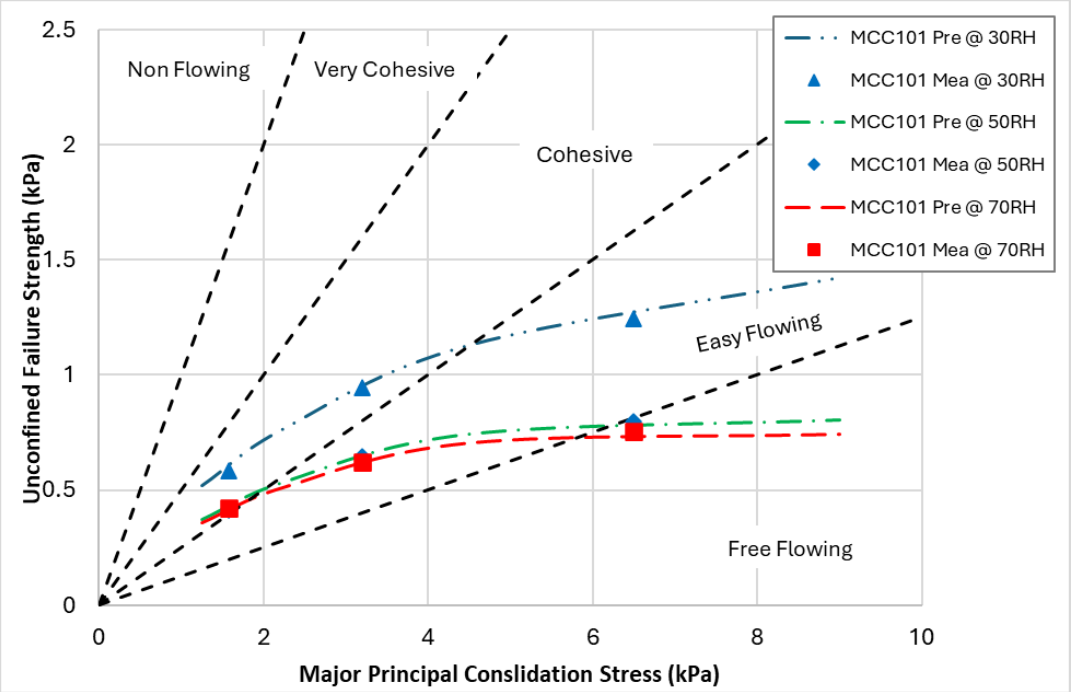

Figure 11: Predicted flow functions by the model compared to the measured flow functions for MCC101 at the humidity of 30%, 50% and 70% RH and the same temperature of 20 ˚C.

For the co-processed excipient, the comparison results of flow functions for Ludip are shown in Fig. 12 and 13, because in the analysis of particle shape effects, Ludip shows the smallest change in particle sphericity. The images in Fig. 5 show that Ludip has a regular particle shape and less agglomeration, which is better for showing the environmental influences.

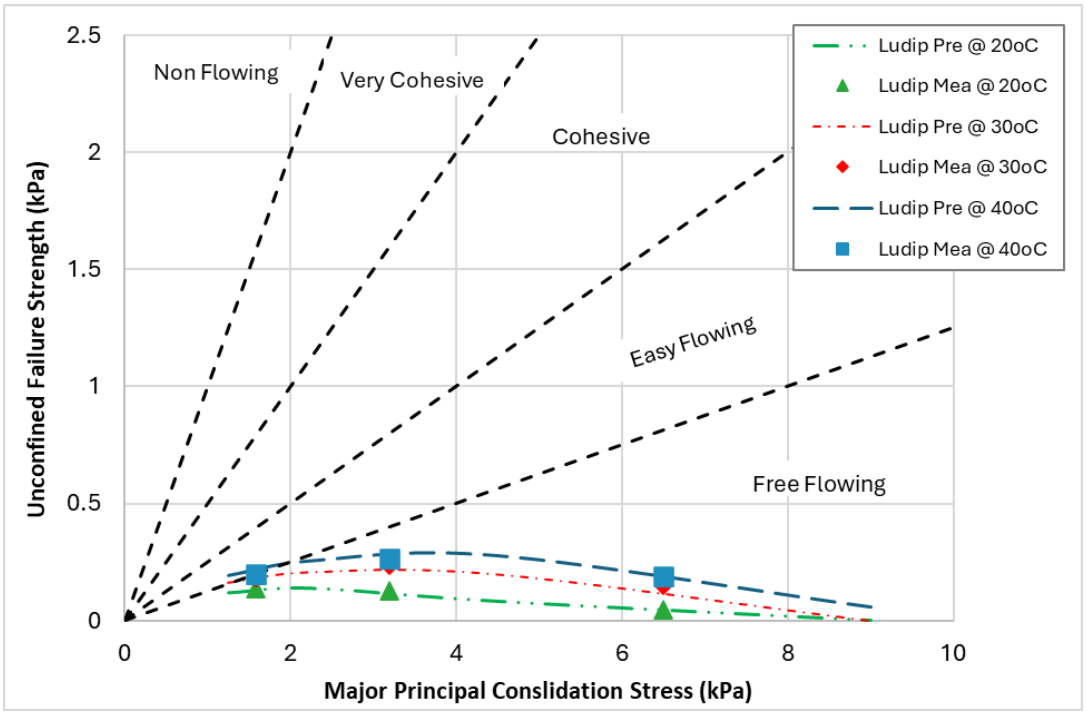

Figure 12: Predicted flow functions by the model compared to the measured flow functions for Ludipress® at the temperatures of 20, 30 and 40 ˚C and the same humidity of 50% RH.

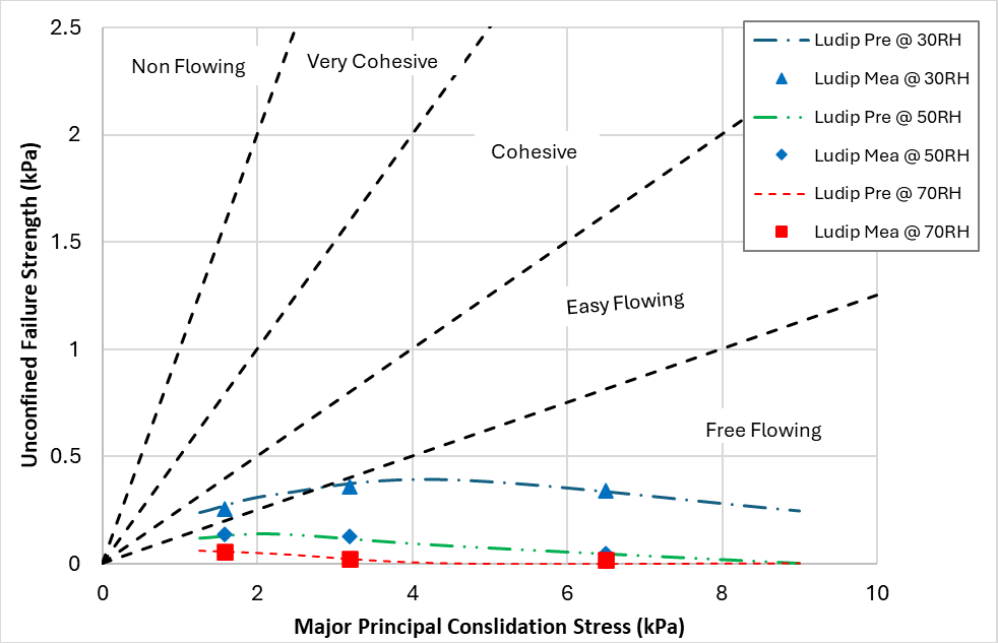

Figure 13: Predicted flow functions by the model compared to the measured flow functions for Ludipress® at the humidity of 30%, 50% and 70% RH and the same temperature of 20 ˚C.

4.5 Influences of environmental humidity and temperature

The detection of Bo measurements shows the influence of environmental humidity and temperature on particle adhesion, although particle deposition may also be influenced by particle shape and deposition orientation. The results of Bo numbers show that environmental temperature generally increases powder cohesiveness, but environmental humidity may reduce it as relative humidity increases. These influences can be detected in the measurements of particle adhesion using the mechanical surface energy tester. Using the model and the measured Bo numbers, the predicted powder flow functions also demonstrate the effects of humidity and temperature. The predictions have been verified by experimental measurements using a PFT shear cell tester.

For the APIs, the results in Fig. 8 show a significant change in powder flow functions when the temperature increased from 30 °C to 40 °C, but the change is insignificant when the temperature increased from 20 °C to 30 °C. For other materials, including excipients and co-processed excipients, the influences can differ and depend on the material. For some fine materials, such as MCC101, and some cohesive materials, such as Iso801, the influence of temperature is clear and significant. In general, for free-flowing materials, temperature has little effect. Still, for some co-processed excipients, such as PB500 (see Fig. G1), the change in powder cohesiveness is quite significant at higher temperatures.

The results in Fig. 9, 10, and 13 show that environmental humidity influences particle adhesion and flow functions, indicating that with increased relative humidity, powder cohesiveness decreases and the powder becomes more free-flowing. In principle, surface moisture may increase particle adhesion due to capillary forces [25]. However, this study of particle adhesion shows a decreasing trend in adhesion as RH in the environment increases. A hypothesis for this may be that a higher RH level promotes the formation of moisture layers on the particle surface, but not the liquid bridges, which could potentially weaken particle

adhesion by lubricating the interface and resulting in the free-flowing nature of the materials [3]. However, this does not explain the decrease in particle adhesion, as more liquid bridges would increase the adhesion force between particles. The wettability or surface textures of the tested powders could provide further explanation on the experimental results. However, this will need to be studied more precisely and a lot of further work involved to be done in future.

Moreover, the results show that environmental variations, including temperature and humidity, influence the viscoelastic properties of the contacting materials, further modulating adhesion behaviour. As a result, environmental conditions significantly impact powder flow behaviour, which will happen in industrial process environment. The results of this study show that the mechanisms underlying particle adhesion are complex, but the use of the MSET provides a robust experimental platform for investigating adhesion phenomena under controlled conditions and for predicting the powder's flowability using a small amount of the material. The insights gained from the study can inform the further development of strategies for controlling powder flow behaviours and mitigating particle adhesion across diverse applications, such as industrial manufacturing processes, air quality management, and surface engineering.

The results presented in Figs. 9-13 demonstrate that environmental humidity and temperature significantly influence particle adhesion and, consequently, powder flow behaviour. While temperature exhibits a relatively modest effect within the investigated range (20-40°C), relative humidity (RH) produces a more pronounced and systematic reduction in both adhesion force and Bond number.

From a classical perspective, increasing RH is expected to enhance particle adhesion due to the formation of liquid bridges at particle contacts, thereby increasing capillary forces [25]. However, the experimental results in this study show the opposite trend, with adhesion decreasing as RH increases from 30% to 70%. This apparent discrepancy suggests that, within the investigated RH range, capillary bridge formation is not the dominant mechanism governing interparticle interactions.

A key consideration is the state of moisture at particle surfaces, which depends on RH, surface roughness, and material wettability [3]. At moderate RH levels, moisture is more likely to exist as adsorbed thin films rather than forming fully developed liquid bridges. Under these conditions, two competing mechanisms may dominate:

1. Reduction of electrostatic forces: Increasing RH enhances surface conductivity, facilitating charge dissipation and thereby reducing electrostatic attraction between particles. This effect has been widely reported in cohesive powder systems and can significantly reduce adhesion, particularly for fine particles.
2. Modification of interfacial mechanics through adsorbed moisture layers: Adsorbed water films can alter the effective surface energy and act as a lubricating layer at the contact interface. This may reduce the real area of solid–solid contact and lower the resistance to particle detachment, resulting in decreased measured adhesion forces.

These mechanisms may outweigh capillary contributions when the moisture content is insufficient to form stable liquid bridges. Therefore, the observed decrease in adhesion with increasing RH can be interpreted as a transition regime, where adsorption-driven effects dominate over capillary condensation.

The dominance of these mechanisms is expected to be strongly material-dependent, as reflected in the experimental results. Factors such as particle morphology, surface roughness, and chemical composition influence moisture adsorption behaviour and the likelihood of capillary bridge formation. For example, irregular particles with rough surfaces may inhibit liquid bridge formation at moderate RH, while smoother or more hydrophilic particles may exhibit different trends under similar conditions.

Temperature further modulates adhesion behaviour by influencing both surface moisture distribution and material properties. At constant RH, increasing temperature reduces relative surface moisture coverage and may enhance solid–solid interactions, leading to a slight increase in adhesion. In addition, temperature may affect viscoelastic properties and surface energy, contributing to the observed material-dependent trends.

It is important to emphasise that the mechanisms proposed here are based on physically plausible interpretations supported by literature, but direct experimental evidence (e.g., moisture adsorption isotherms, surface energy measurements, or electrostatic charge quantification) was not obtained in this study. Therefore, the discussion should be considered as a hypothesis consistent with the observed experimental trends, rather than a definitive mechanistic conclusion.

Overall, the results highlight that particle adhesion under realistic environmental conditions is governed by a complex interplay of van der Waals forces, electrostatic interactions, and moisture-related effects. The findings demonstrate that, even in the absence of strong capillary bridging, environmental humidity can significantly reduce particle adhesion and improve powder flowability. This has important implications for industrial processes, where moderate variations in RH may lead to non-intuitive changes in powder behaviour.

5 Conclusions

This study demonstrates that particle adhesion, quantified using a Mechanical Surface Energy Tester (MSET), provides a highly sensitive, reproducible, and physically grounded indicator of environmentally induced changes in powder cohesiveness. By deriving the Bond number (Bo) from directly measured adhesion forces, a robust dimensionless framework is established that links particle-scale interactions to bulk flow behaviour. The strong agreement observed between adhesion-derived predictions and shear cell measurements confirms that particle-level mechanics can be used to anticipate bulk flow trends with significantly reduced material demand and experimental complexity.

The results clearly show that relative humidity and temperature fundamentally alter interparticle interactions in a material-dependent manner. At low RH, enhanced solid–solid intermolecular forces increased adhesion and cohesiveness. At elevated RH, adsorption-driven interfacial modifications altered contact mechanics, in some cases reducing effective

adhesion through lubrication effects and improving flowability. Temperature effects were modest within typical ambient conditions (20–30 °C) but became pronounced at higher temperatures, where measurable increases in adhesion were observed across most materials. In extreme cases, adhesion forces changed by more than 30% with substantial temperature variation, underscoring the sensitivity of cohesive behaviour to thermal exposure. These findings collectively demonstrate that environmental variables directly modulate the balance of van der Waals, capillary, and surface energy contributions governing particle contact.

Crucially, the study shows that environmentally driven changes in powder flow originate at the particle scale and may not be fully resolved using conventional bulk shear testing alone. Adhesion measurements provide earlier and more mechanistically transparent detection of environmental susceptibility, particularly for fine and inherently cohesive powders. While particle shape influences contact geometry, its contribution to variability is secondary to that of humidity- and temperature-induced interfacial effects.

Beyond its specific experimental findings, this work proposes a shift in the way environmentally sensitive powder behaviour is characterised, although plenty of further works have been left behind on the scientific reasons of the environmental influecnes. Rather than relying solely on bulk empirical measurements, the Bond number framework offers a mechanism-based, environmentally controlled approach that directly quantifies the forces governing cohesiveness. The ability to systematically map adhesion as a function of RH and temperature using small material quantities enables more efficient formulation screening, targeted environmental risk assessment, and rational process design.

Overall, this particle adhesion measurement under controlled environmental conditions provides a powerful and scalable platform for next-generation powder characterisation. By quantitatively bridging adhesion physics and bulk flow performance, the work advances both scientific understanding and industrial assessments of cohesive powders. The methodology has the potential to inform future standards for environmentally conscious powder testing and to support the development of more robust, predictable, and resilient powder-handling systems across the pharmaceutical and related industries.

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