

Measuring the flow properties of consolidated, conditioned and aerated powders — A comparative study using a powder rheometer and a rotational shear cell

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Available online 24 October 2006

Abstract

This paper compares powder flowability measurements using the two methodologies available from a Freeman FT4 Powder Rheometer. The twisted blade method is empirical and measures the energy needed to establish dynamic or three dimensional flow patterns at specific packing conditions. The other is an automated shear cell in which the powder sample is sheared across a single plane to determine its shear strength properties. Six different powders were evaluated to determine their flow performance when consolidated, conditioned and aerated or fluidised. Objectives were to correlate the data from the two methods and assess the sensitivity to some of the key variables that affect powder flow properties.

The results showed that dynamic testing that produces shear without compacting the powder sample (upwards testing), provides data that correlates well with shear cell data. However the standard downward dynamic test that does compact, correlates less well but was highly differentiating. It is apparent that shear strength is only one component relating to flowability and that the measured flow energy is also dependent on the compressibility of the powder and the flow rate. Shear testing of conditioned powders at near zero normal stress used the position control mode rather than force control used for the standard shear tests. Aerated powders could not be evaluated with the shear cell, but were assessed using the dynamic methodology and showed very significant differences of flow energy.

In conclusion, both methodologies provide useful insights into flow behaviour with good repeatability of measurement, but dynamic data provides better differentiation between powders with similar rheological properties in all packing states.

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Keywords: Powder; Flowability; Shear; Rheometer; Flow zone; Permeability

1. Introduction

Predicting flow performance of powders through a given process is of great importance in industry where intentionally or otherwise, the flow properties of powders change, often resulting in stoppages or poor quality product. The need is for reliable prediction of flow performance and this in turn requires reliable information on the bulk, flowability and processability characteristics of the powders concerned.

No definition or units exist to describe the dynamic flow of powders and no ideal way of measuring these complex materials exists. Development of shear cells continues and some are now automated and suitable for providing material characterisation

data, in addition to the traditional focus of silo design. Powder rheometers can provide fast, repeatable, sensitive measurements with a high degree of automation. To make a comparison of these methods, a range of six different materials were selected (Table 1) and the primary variable was chosen to be packing condition, since the presence or absence of air is arguably the most important of the many factors affecting powder flow properties.

2. Instrumentation and methodologies used

The instrument used was an FT4 Powder Rheometer (Freeman Technology Ltd) that is described elsewhere in the literature [1]. Briefly, accessories such as blades, pistons and shear heads can be rotated and simultaneously moved axially into a powder sample whilst axial force and rotational force are measured. A number of control modes are available on both axes including velocity, force and torque. The standard dynamic

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Table 1
Particle and bulk properties data for all 6 powders

Measurements	Units	Materials					
		Spray dried lactose	Sieved lactose	Coarsely milled lactose	Talcum	Limestone CRM116	Finely milled lactose
D_{50} particle size	μm	130	120	100	20	4	20
Particle shape		Spherical	Angular	Angular	Platelets	Angular	Angular
Conditioned bulk density	g/ml	0.64	0.76	0.75	0.74	0.74	0.46
Bulk density — consolidated by 11 kPa DP	g/ml	0.67	0.81	0.83	0.94	0.99	0.65
Bulk density — consolidated by 100 taps	g/ml	0.74	0.87	0.90	0.97	0.95	0.66
Volume change — 18 kPa direct pressure	%	4.6	6.1	8.5	22.5	27.1	29.2
Volume change — 100 taps	%	13.5	12.6	16.7	23.7	22.1	30.3
Adhesion in volume lift off	mm^3	0.46	0.75	0.69	2.0	5.1	6.0
Pressure drop at 11 kPa normal pressure and 2 mm/s air velocity	mbar	0.7	1.2	1.5	22.0	43.2	16.7

tests, aeration testing and shear testing are automated with no operator involvement apart from sample preparation. Dynamic testing used a 48 mm dia blade and a 160 ml powder sample contained in a 50 mm bore, borosilicate test vessel. An automated, 18 segment, 48 mm diameter rotational shear cell accessory was used for all shear testing using a 30 ml sample. All samples for dynamic and shear tests were pre-conditioned using the instrument's 'conditioning' methodology. The 'conditioning' blade action gently disturbs the powder bed and creates a uniform, lightly packed test sample that can be readily reproduced (Figs. 1, 2 and 3).

3. Bulk properties — results and review

Bulk density, compressibility, adhesion and permeability assessments were made for all materials (Table 1).

Bulk density was measured for three packing conditions during the dynamic tests on 160 ml samples. Compressibility tests used a porous piston to apply levels of normal stress to 85 ml samples whilst measuring the volume change. Adhesion tests involved measuring the amount of material adhering to the blade after removal from the powder following dynamic testing. Permeability testing measured the pressure drop across the powder bed whilst the applied normal pressure was varied and

the air velocity through the bed was maintained constant at 2 mm/s (Figs. 4 and 5).

4. Shear cell tests — results and review

4.1. Shear cell data — results and review

Fig. 6 shows the yield locus for each of the 6 powders, following preshearing at a pre-shear normal stress of 9 kPa. The lowest levels of normal stress applied were consistent with the self-generated normal stress during shearing, being less than the applied normal stress (these minimum levels of normal stress were derived from preliminary tests). Each yield locus was repeatable to within 0.5% for non-cohesive powders and 1% for cohesive powders. Normal stresses were automatically maintained by operating the instrument in the force control mode.

As expected the data (Table 2) shows the cohesive powders having higher shear strength than the larger particle, free flowing powders, with the spray dried lactose with spherical particles having the lowest of all. This set of yield loci are quite similar, showing a differentiation of 1.4 at the 7 kPa data level and 2.1 at 3 kPa normal stress. The yield locus for Limestone CRM116 is in agreement with the certification bulletin [2]. The internal angle of friction varied from 26.5° to 35.8° over the range of powders.

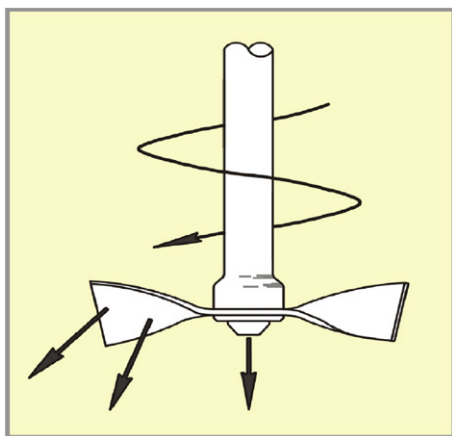


Fig. 1. Downwards testing mode showing bulldozing action along the entire blade length.

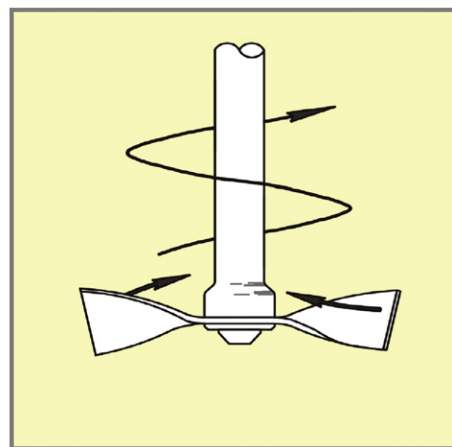


Fig. 2. Upwards testing — shearing with minimal consolidation.

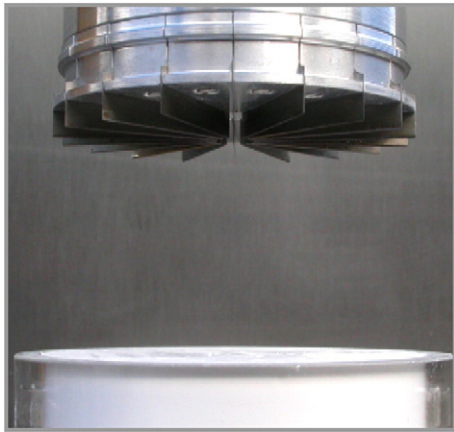


Fig. 3. Shear cell above sample vessel.

For the cohesive powders it was possible to extrapolate the yield loci and use a Mohr circle analysis (ASTM standards [3]) to derive the unconfined yield strength (2.1 to 5.6 kPa), maximum principal stress, cohesion and flowability values. Such an analysis was not viable for the non-cohesive group because their yield loci were equal to the effective yield locus meaning that the derived value of unconfined yield strength would be zero.

4.2. Shear cell tests at zero pre-shear normal stress and near zero normal stress — results and review

A major challenge when trying to measure cohesion or the shear strength at zero normal stress is that the shearing action results in a generated pressure normal to the shear plane. In these tests therefore, the measurement was made by initially

shearing at zero normal stress whilst holding the shear head at fixed height rather than operating in the usual force control mode, and recording the rise in normal stress as the shearing progressed. In this way the shear strength of conditioned or non-stressed powder was measured at normal stress levels that varied from 123 Pa to 219 Pa. The results are listed in Table 2 and show ‘cohesion’ values ranging from 159 Pa to 247 Pa for the least and most cohesive powders. It is interesting that for the non-cohesive powders the generated normal pressure is greater than the corresponding shear strength, whilst for the cohesive group it is substantially less. Possibly this is attributable to the more hydrostatic like behaviour of a powder with large spherical particles (spray dried lactose), in contrast to the fine particle, agglomerated cohesive powders.

4.3. Wall friction measurements — results and review

The frictional resistance of all powders shearing against a 48 mm diameter disc, (grade 304 SS, 120 grit surface finish) was measured during rotation at various normal stresses from 2.75 to 22 kPa, to determine the wall coefficient of friction. Table 2 lists the results alongside the internal angle of friction data derived from the measured yield loci (Fig. 6).

5. Dynamic testing – results and review

5.1. Dynamic downwards testing to determine BFE, SI and FRI parameters (Fig. 7) — results and review

In these conventional dynamic tests, a previously conditioned powder (see 2 above), was consolidated by a bull-dozing blade action (Fig. 1) that forced the powder downwards towards

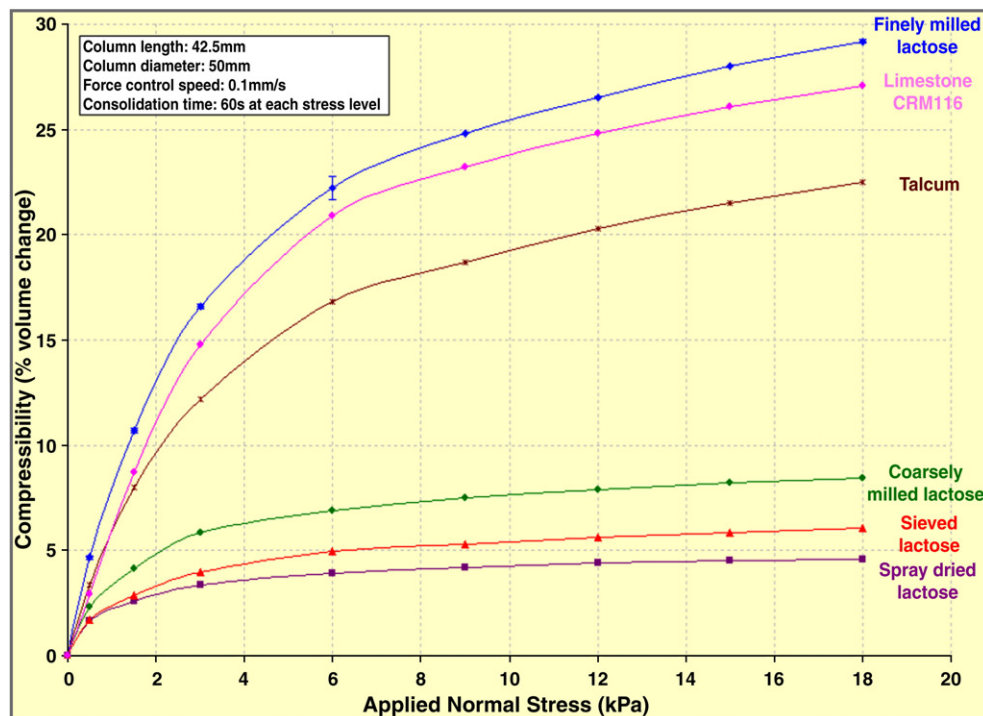


Fig. 4. Bulk compression of initially conditioned samples as a function of applied normal stress.

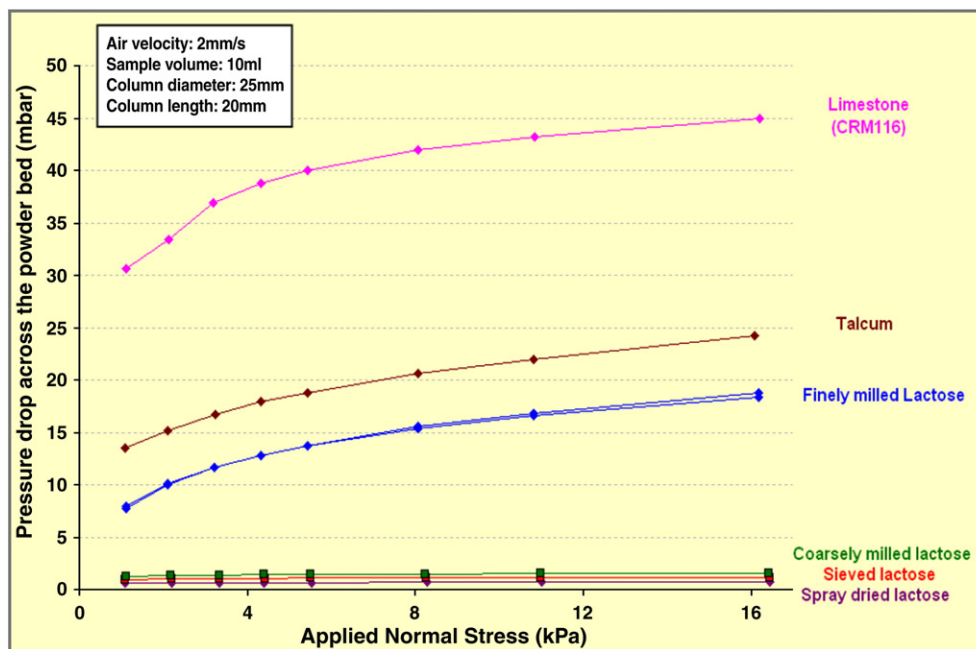


Fig. 5. Pressure drop through powder bed at constant 2 mm/s air velocity as a function of applied normal stress.

the bottom of the containing vessel. Fig. 7 shows the flow energy measurements for seven identical repeat tests on each powder, with conditioning between each, followed by the variable flow rate tests at reducing blade speeds.

The stabilised flow energy level (test 7), is the Basic Flowability Energy (BFE) value and is a key flowability parameter. These profiles show a BFE differentiation factor of about 5, reflecting their different resistances to forced flow. The high levels of repeatability of the initial 7 tests show that all powders have a stable rheology.

Maximum flow energy is demanded by the non-cohesive powders which interestingly have the lowest shear strength. With the exception of spray dried lactose the BFE figures correlate inversely with the compressibility measurements shown in Fig. 4 indicating that compressibility is a key factor in these measurements. A possible explanation is that for non-cohesive powders, the flowing zone ahead of and around the blade in which shearing is occurring, is extensive due to the low compressibility of the powder and the high transmissibility of forces from particle to particle. A high proportion of the sample

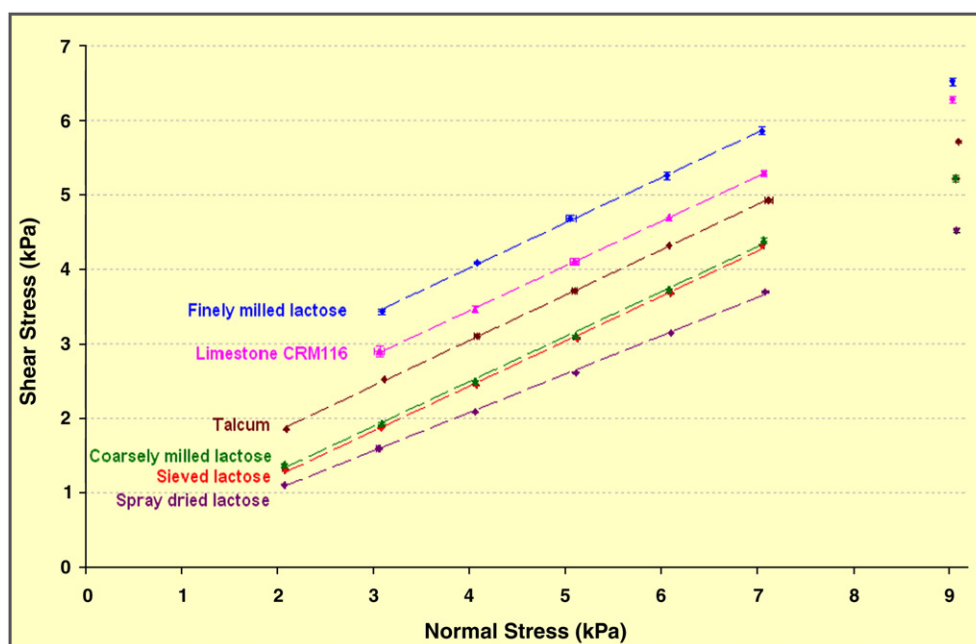


Fig. 6. Shear test yield loci for 6 materials following preshear at 9 kPa normal stress.

Table 2
Summary of shear testing parameters

Measurements	Units	Materials					
		Spray dried lactose	Sieved lactose	Coarsely milled lactose	Talcum	Limestone CRM116	Finely milled lactose
Shear stress at 9 kPa preshear, τ_p (RSD)	kPa	4.5 (± 0.6)	5.2 (± 0.4)	5.2 (± 0.8)	5.7 (± 0.3)	6.3 (± 0.7)	6.5 (± 0.7)
Shear stress at 7 kPa normal stress, τ_7 (9 kPa preshear) (RSD)	kPa	3.7 (± 0.5)	4.3 (± 0.2)	4.4 (± 0.5)	4.9 (± 0.5)	5.3 (± 0.5)	5.9 (± 0.8)
Shear stress at 3 kPa normal stress, τ_3 (9 kPa preshear) (RSD)	kPa	1.6 (± 0.3)	1.9 (± 0.1)	1.9 (± 0.6)	2.5 (± 0.03)	2.9 (± 2.0)	3.4 (± 1.2)
Major principal stress, σ_1	kPa	14.7	15.8	15.5	16	17.7	16.7
Unconfined yield strength, σ_c	kPa	–	–	–	2.1	3.7	5.6
Cohesion, τ_0	kPa	–	–	–	0.6	1.05	1.58
Flowability, ff_c	–	>10	>10	>10	7.6	4.8	3.0
Angle of internal friction at steady state flow (at 9 kPa), Φ_i	degrees	26.5	30	30	32.1	34.7	35.8
Angle of wall friction relative to grade 304 stainless steel — 120 grit finish, Φ_w	degrees	22.8	28	28	30.5	35	33
Shear stress at near zero normal stress, τ_z	Pa	159	200	223	188	243	247
Normal stress generated by the above shear test at zero initial normal stress, σ_z	Pa	193	203	219	123	113	150
τ_z/σ_z	–	0.82	0.99	1.02	1.53	2.15	1.65

volume is required to move, as a kind of chain reaction, as the blade penetrates the powder and more work is done than would be the case for a cohesive powder which contains considerable air and is therefore more compressible. The flow zone of material ahead of and around the blade as it moves, is much smaller so that the number of particles that shear or move relative to their neighbours is smaller, as is the work done. The spray dried lactose requires a flow energy in the middle range because the spherically shaped particles can move with less frictional resistance (than the angular ones of similar size) and it has the lowest shear strength of all six powders (Fig. 6).

The sensitivity to blade speed or flow rate during these compactive tests is shown by tests 8 to 11 of Fig. 7 and is called the flow rate index (FRI=test11/test8). The measured values are listed in Table 3. The cohesive powders require greater flow

energy at lower flow rates because the entrained air is able to escape, leaving a stiffer material, more resistant to flow. The non-cohesive powders are much less sensitive to flow rate, especially the spray dried lactose with spherical particles and high permeability (Fig. 5). Probably, in this case, the void space and the contact between particles remains more or less unaffected by the shear rate and the bulk density remains unchanged. Even so, the resistance to flow increases with decreasing testing speed, as shown by the energy measurements, but not to the same extent as the cohesive powders.

Adhesion tests were made as part of the above by measuring the amount of material adhering to the blade after removal from the powder. These figures, (Table 1) range from 0.46 mm³ to 6 mm³ indicating that the finely milled lactose and the limestone were by far the most adhesive materials as expected.

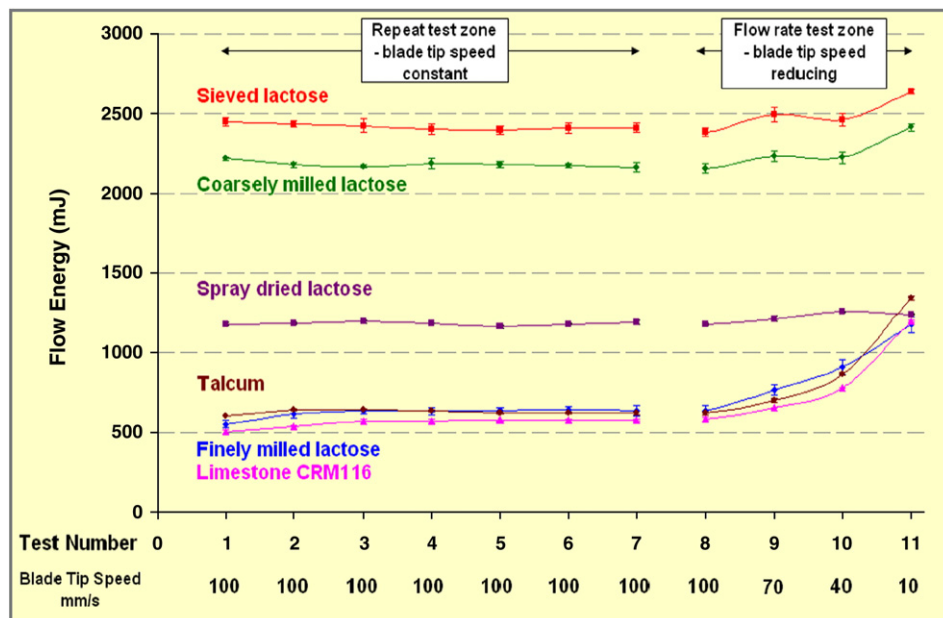


Fig. 7. Flow energy measurements at fixed and variable blade speeds.

Table 3
Dynamic flowability data

Measurements	Units	Materials					
		Spray dried lactose	Sieved lactose	Coarsely milled lactose	Talcum	Limestone CRM116	Finely milled lactose
Basic Flow Energy, BFE	mJ	1191	2413	2164	623	576	635
Flow Rate Index (FRI)	–	1.05	1.11	1.12	2.17	2.06	1.86
Consolidation Index, $CI_{100 \text{ Taps}}$	–	3.4	2.9	4.0	7.6	3.3	7.9
Consolidation Index, $CI_{11 \text{ kPa DP}}$	–	1.4	1.6	1.7	5.6	4.6	5.8
Specific Energy per g	mJ/g	4.8	6.4	7.1	6.4	7.9	9.6
Aerated Energy at 14 mm/s	mJ	7.6	9.7	14.5	6.9	360	181
Aeration Ratio (BFE/energy at 14 mm/s)	–	156	248	149	90	1.6	3.5

5.2. Dynamic downwards testing of already consolidated powders to determine CI parameters — results and review

The previous dynamic tests measured the flow energies of conditioned powders when being bulldozed by the action of the blade. These further tests imposed flow on powder samples already pre-consolidated either by tapping or by applying direct pressure. The results (graphical data not included), are summarised in Table 3 in terms of a Consolidation index (CI) — the factor by which the flow energy increased relative to the BFE value.

Following 100 taps, the powders with small particle size have a $CI_{100 \text{ TAPS}}$ of about 8 except for the limestone from which air was less easily removed even though the bulk density increased by 28% (Table 1). This correlates with the exceptionally poor permeability of limestone (Fig. 5). As expected, the non-cohesive powders are less affected when consolidated by tapping, having $CI_{100 \text{ taps}}$ values of 2.9 to 4. For these powders, the energy increase results from the realignment and interlocking of particles as well as air removal.

Consolidation by direct pressurisation (applied to 25% incremental volumes), to 11 kPa shows a small effect on the

non-cohesive powders, but greatly affects the three cohesive powders from which air is readily excluded as shown by the bulk density increase of 27% (talc) to 41% (finely milled lactose). The flow energy requirement of the cohesive powders increased by a factor of about 5 due to the closer packing producing increasing levels of cohesion and friction and reduced compressibility (Table 3). The stiffer non-cohesive powders are marginally affected with CI_{DP} values between 1.4 and 1.7.

5.3. Dynamic upwards testing of conditioned powder — results and review

The objective of these tests was to measure the resistance to flow of the six powders when close to a non-consolidated or stress free state and to do this without imposing compression stresses. Samples were prepared using the standard ‘conditioning’ blade action to gently disturb the powder bed and create a uniform, lightly packed sample that could be readily reproduced.

160 ml powder samples were tested with the rheometer blade moving along an upward helical path to cause shear but little

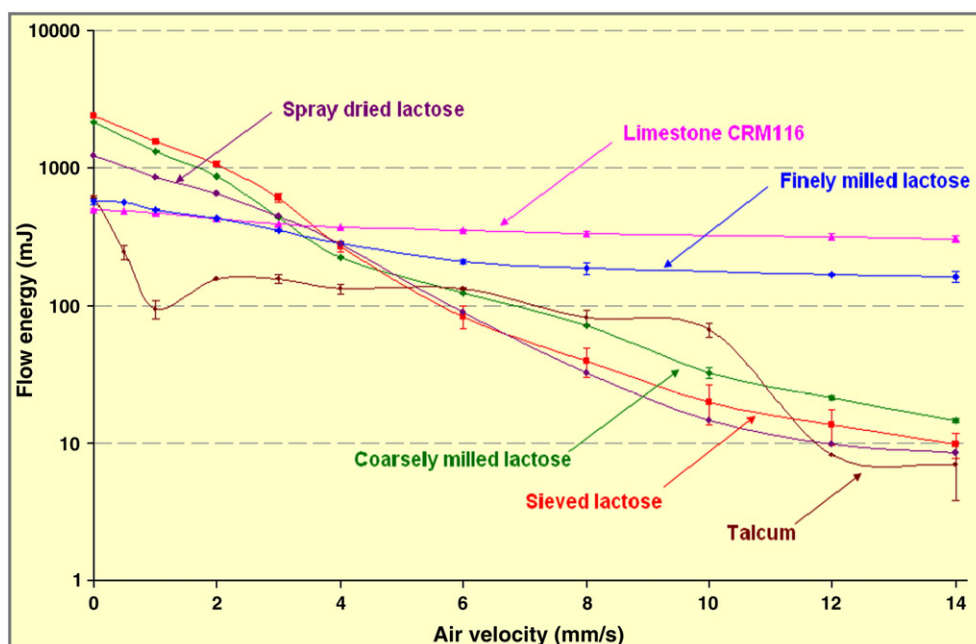


Fig. 8. Flow energy (log scale) as a function of air velocity.

consolidation (Fig. 2). Torque and force on the blade were measured in the usual way to determine the energy expended in establishing the flow pattern. Because of the dominance of gravity in this test, the flow energy is expressed as Specific Energy, mJ/g in order to compensate for varying bulk densities. The results (Table 3 and Fig. 9), range from 4.8 mJ/g to 9.6 mJ/g and again show the cohesive group requiring greater energy to establish flow.

5.4. Dynamic downwards testing of aerated powders (Fig. 8) — results and review

160 ml samples were prepared and evaluated using the automated aeration programme that runs a sequence of tests at increasing levels of air velocity through the powder sample, with a conditioning cycle before each test cycle. The flow energies measured during each test cycle are shown in Fig. 8 which indicates the minimal affect that aeration had on the 2 most cohesive powders in contrast to the 4 other powders which readily aerated.

Three of these 4 powders have a high sensitivity to even small amounts of air, showing a rapid rate of flow energy reduction. The 4th powder, the spherical spray dried lactose initially aerates at a slower rate, probably due to its higher permeability (Fig. 5). All 4 powders fluidise at air velocities above 12 mm/s. The reduction of flow energy is quantified by the Aeration Ratio (AR). When aerated at 14 mm/s air velocity, AR varied from 1.6 for limestone to 248 for the sieved lactose.

6. Review and comparison of dynamic and shear results

6.1. Pre-consolidated powders — results comparison and review

The yield loci for pre-consolidated (9 kPa) powders were repeatable (0.5% non-cohesive, 1% cohesive) and gave the expected ranking, with differentiation between the most and

least cohesive powders of <1.5 (yield at 7 kPa), 2.1 (yield at 3 kPa) and 1.2 (major principal stress). The Unconfined Yield Strength (UYS), varied from 2.1 to 5.6 kPa for the cohesive powders but could not be reliably determined for the non-cohesive group because of the significant error on extrapolating the yield locus towards zero.

In comparison, the dynamic methodology when downwards testing, Fig. 1, produced similar ranking of the six powders with results for pre-consolidated powders giving a differentiation of 4 (flow energy) and 4 (CI values) and having some correlation with the shear data ($R^2=0.74$ to 0.82). Greater differentiation was achieved by the dynamic methodology — for example the coarsely milled lactose and the sieved lactose have very similar yield loci but significantly different BFE and CI values. Also, whilst there is a level of correlation between the shear and dynamic data, the latter measures three dimensional flow and takes into account the size of the flow zone in which shearing occurs. It appears likely that flow energy measurements reflect the combined affect of the key variables such as shear strength, cohesion, compressibility and physical properties. Certainly the dynamic methodology is simple, quick, and reproducible and is highly differentiating, especially for non-cohesive powders.

6.2. Conditioned powders — results comparison and review

Shear measurements of conditioned powder at zero pre-shear normal stress and zero normal stress were not possible but were obtained for close to zero normal stress values of 123 to 219 Pa. The differentiation between the least and most cohesive was 159 to 247 Pa.

In comparison (Fig. 9), the dynamic measurements when upwards testing a conditioned powder to measure the Specific Energy, showed differences between the least and most

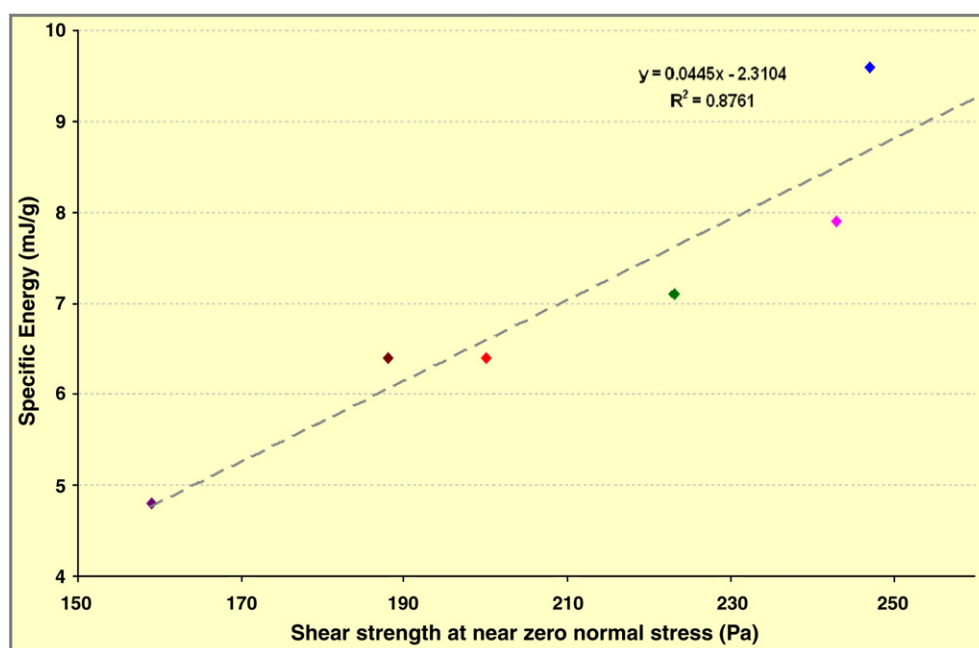


Fig. 9. Correlation of dynamic measurements (upwards testing) with shear data (cohesion).

cohesive of 4.8 mJ/g and 9.6 mJ/g with an identical ranking. Both methods provide similarly differentiating data, even for the similar coarse milled and sieved lactose.

6.3. Aerated powders — results comparison and review

Shear cell tests on aerated powders were not possible but the dynamic methodology was very suitable and showed high differentiation between the powders. The aeration assessment showed small reductions of flow energy for the most cohesive powders, but the attenuation level for talcum was 90 and as high as 248 for the sieved lactose showing how dramatically aeration can change flow properties as is well known in flooding from hoppers.

7. Conclusions

1. Dynamic upwards testing using a negative helix that produces shear without consolidation, provides data that correlates well with shear cell data, Fig. 9. In the case of the ‘cohesion’ shear data, $R^2=0.88$ and in relation to the measured internal angle of friction $R^2=0.84$. In both methodologies, shearing occurs without inducing further consolidation. Dynamic upwards testing provides reasonably differentiating data (factor of 2) across the range of six powders.
2. Dynamic downwards testing that produces consolidation (the BFE test using a negative helix), is highly differentiating (factor of 4.2), especially for non-cohesive powders, but shows little correlation with shear data. The reason for this is that the dynamic methodology measures a combination of factors including shear strength and the extent of the shear or flow zone and this varies greatly in size depending on the compressibility of the sample. The non-cohesive powders that are not very compressible have a large flow zone (ahead of and around the blade) and therefore the highest flow energy requirement.
3. The shear data provides yield loci with a reproducibility of around 1% or 0.5% for the non-cohesive powders and differentiation across the range of six powders of 2 or less. Accuracy of the yield locus, internal angle of friction and cohesion (at zero normal stress), is about 1%. The unconfined yield strength and to a lesser extent the cohesion or Y axis intercept, can be determined with reasonable accuracy for the cohesive powders but not for the non-cohesive powders due to errors from extrapolating the yield loci close to zero.
4. The shear measurements at zero pre-shear normal stress and near to zero normal stress produced results that were differentiating and that correlated well with the dynamic data obtained from upwards testing (Fig. 9). This shearing methodology is new and worthy of further development and the relationship between generated pressure and shear strength also warrants further study.
5. The non-cohesive powders were well differentiated by the dynamic flowability measurements in direct contrast to the shear measurements which have similar yield loci that are close to intersecting at zero, meaning that cohesion and UYS could not be derived for this group of powders.

6. Bulk density, compressibility, permeability and adhesion measurements are useful for helping to interpret flow behaviour (Table 1).
7. Whilst the flow performance of aerated or fluidised powders could not be evaluated using the shear cell, the dynamic methodology was very suitable and showed high differentiation between the powders. Aeration always improves flowability and in the case of non-cohesive powders that eventually fluidise, the transformation is shown to be dramatic.
8. Shear strength is a complex function of many physical and environmental properties. Flowability is even more complex being dependant upon shear strength, compressibility, air content, the rate of flow and other factors. In particular the high transmissibility of flow forces in consolidated, non-cohesive powders, resulted in high flow energy, even though these materials have relatively low shear strength and are free flowing when not confined.
9. Powder flowability is still a very long way from being an exact science and yet the need for industry to be able to predict flow performance is more important than ever. Although this comparative study has used six very different powders, the typical industrial challenge is to identify differences between very similar powders. Therefore the highest achievable levels of sensitivity and repeatability of measurement are required over the widest range of test methods, including both shear and dynamic flow techniques.

Nomenclature

Dynamic testing — symbols and definition of terms

Term	Units	Symbol	Definition or description
Flow energy	mJ		Work done derived from measurements of all forces acting on the rheometer blade when displacing powder
Helical path angle or helix	degrees	α	Angle from horizontal along which the blade moves
Negative helix	degrees		Compacting action as in Fig. 1
Positive helix	degrees		Slicing action
Tip speed	(mm/s)	V_{tip}	Velocity of blade tip along helical path
Upwards testing			Recording test data when moving upwards along helical path from bottom to top of the testing vessel (Fig. 2)
Downwards testing			Recording test data when moving downwards along helical path from top to bottom of the testing vessel (Fig. 1)

Conditioning			Gentle disturbance of the powder sample to prepare for testing using a slicing helix downwards and a lifting helix upwards	Conditioned Bulk Density	g/ml	CBD	powder sample whilst being aerated at X mm/s Bulk density of a conditioned powder sample (see definition of conditioning above)
Basic Flowability Energy	mJ	BFE	The energy needed to displace a conditioned powder sample during downwards testing at specific consolidating conditions (Fig. 1)	Tapped Bulk Density	g/ml	$BD_{X \text{ taps}}$	Bulk density of a powder sample after tapping X times
				Consolidated Bulk Density	g/ml	$BD_{X \text{ kPa DP}}$	Bulk density of a powder sample after incremental consolidation to a normal stress of X kPa
Specific Energy	mJ/g	SE	The energy per gram needed to displace conditioned powder during upwards testing using a negative 5° helix (lifting to produce shear and no consolidation)	Shear Testing — symbols and definition of terms			
Flow Rate Index		FRI	The factor by which the flow energy is changed when the flow rate (tip speed) is reduced by a factor of 10	Term	Symbol	Definition or description	
				Pre-shear normal stress	σ_p	Normal stress maintained during preshear	
				Normal stress	σ_s	Normal stress applied to powder at shear	
Stability Index		SI	The factor by which the measured flow energy changes during repeated testing or processing	Pre-shear shear stress	τ_p	Shear stress measured during preshear	
				Shear stress	τ_s	Shear stress measured at failure	
Consolidation Index — tapped		$CI_{X \text{ taps}}$	The factor by which the BFE is increased when the powder sample is retested following consolidation by tapping to X taps (X =typically 100)	Major principal stress	σ_1	Major consolidation stress given by Mohr stress circle of steady state flow	
				Unconfined yield strength (compressive strength)	σ_c	The major principal stress of the Mohr stress circle being tangential to the yield locus with the minor principal stress being zero	
Consolidation Index — direct pressure		$CI_{X \text{ kPa DP}}$	The factor by which the BFE is increased when the powder sample is retested following consolidation by incrementally applied direct pressure to X kPa	Cohesion	τ_o	Shear strength at zero normal stress	
				Angle of internal friction	Φ_i	The angle between the axis of normal stress (abscissa) and the tangent to the yield locus	
				Angle of wall friction	Φ_w	The arctan of the ratio of the wall shear stress to the wall normal stress	
				Flowability	ff_c	Flowability defined by Jenike as σ_1/σ_c	
Aeration Ratio		AR_X	The factor by which the BFE is reduced when the sample is retested whilst being aerated at X mm/s of air velocity	Shear stress zero	τ_z	Shear stress at near zero normal stress, of a conditioned powder	
				Generated normal stress	σ_z	Normal stress generated by the above shear test at zero initial normal stress	
Aerated Energy	mJ	AE_X	The energy needed to displace an aerated	References			
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