

An Introduction to Powders

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Foreword

Powders are used to produce many of the products we value most in daily life. Here at Freeman Technology we focus exclusively on powders, most especially how to characterise and understand them so as to enhance product development and improve manufacturing processes. This booklet, the first in a series, is a distillation of what we've learned about powder behaviour, from more than a decade of working with these challenging but fascinating materials.

An Introduction to Powders

Whether as raw materials, intermediates or final products, powders are integral to a huge range of industrial processes, contributing to some 80% of all manufactured goods.

However, despite their ubiquity they continue to present challenges during product development, manufacturing, and in quality assurance.

Often powders are labelled as 'bad', when actually it would be more accurate to say we simply don't understand how they are behaving. A good understanding of powder behaviour is an essential foundation for optimising production processes, developing a high quality product and for selecting suitable powder characterisation methods.

This booklet provides a straightforward, practical introduction to powders. Written for those new to the field, or for those more experienced with powder handling looking for new insight, it addresses the following questions:

- Powders or particles? What are the differences and why are those differences important?
- What aspects of powder behaviour are interesting from an industrial perspective?
- Why do powders flow, or stop flowing?
- What factors influence how powders behave – in a process, or as a product?

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Section 1

What is a powder?

Powders are bulk assemblies, containing particles, but they are more than just the particles alone. It is often the case that the terms 'particle' and 'powder' are used interchangeably, but this can be misleading. Powders also consist of gases, normally in the form of air, and liquid, usually water, on the surface of the particle or within its structure.

It is the properties of each phase of a powder, and the interactions between them, that define bulk powder behaviour. This means that behaviour is influenced by a large number of variables and an array of potential interactions.

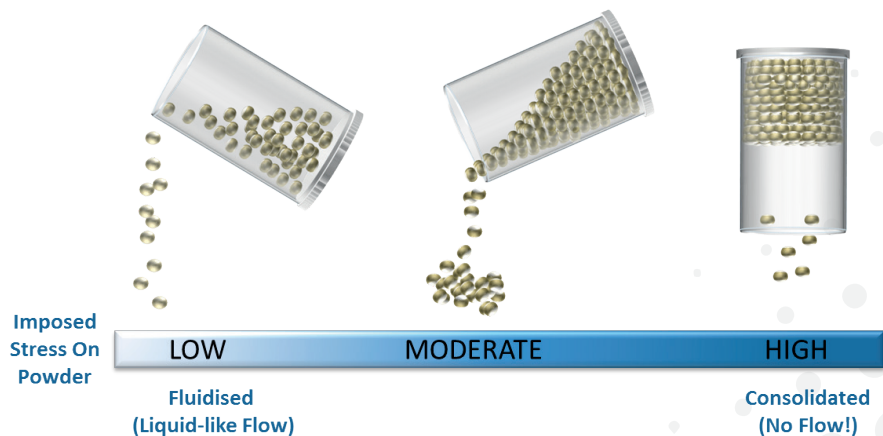
Many of these variables relate to the physical properties of the particles, including particle:

- Size
- Shape
- Surface Texture
- Surface Area
- Density
- Cohesion
- Adhesion
- Elasticity
- Plasticity
- Porosity
- Potential for Electrostatic Charge
- Hygroscopicity
- Hardness / Friability
- Amorphous Content



'Powders are bulk assemblies consisting of solids, liquids and gases. Interactions between all three of these phases determine the bulk powder behaviour.'

(Note that many properties are also distributions, rather than a single value.)



'Particle properties are important when it comes to powder behaviour but so too are external variables such as the extent of aeration or consolidation.'

Other variables relate to the process or 'external' influences, such as the amount of air present, flow rate and the degree of consolidation.

Powder behaviour is dependent on both the particle and external variables, which is why it is complex and why we cannot accurately predict powder performance from measurements of physical properties alone. From a practical perspective, too many variables impact powder behaviour to make accurate mathematical modelling viable. Moreover, it is reasonable to say that we do not yet fully understand all of the possible interactions, nor do we have the capability to directly measure many of the influencing parameters.

Current understanding is limited to recognising that:

Powder Behaviour = $\text{fn}(\text{Particle Size}) + \text{fn}(\text{Particle Shape}) + \text{fn}(\text{Particle Stiffness})$
+ $\text{fn}(\text{Particle Porosity}) + \text{fn}(\text{Particle Surface Texture})$
+ $\text{fn}(\text{Particle Density}) + \text{fn}(\text{Cohesion}) + \text{fn}(\text{Adhesion}) + \text{etc}$

and also external variables, such as:

- Consolidation
- Aeration
- Humidity Level
- Extent of Shear / Strain
- Equipment Surface Properties

A common problem: changing raw material supplier

A powder processor is considering a change of raw material supplier, in order to reduce costs. A grade is identified with the same specification in terms of composition, purity level, particle size, bulk density and moisture content. The new material arrives with a specification that matches what was agreed but when introduced into the plant the process performs poorly. Blockages become more frequent, flow rates are compromised, and the final product fails to meet quality standards. Why are such problems occurring when the specification was matched?

It is clear that the specification is simply not capable of differentiating between feeds that will perform poorly and those that will perform well in the process.

There must be other properties of the material that influence in-process behaviour that are not included in the specification. Therefore, when selecting a powder on the basis of its ability to process in a certain way, it is essential to define measurable parameters that relate to in-process performance and that can be used to effectively eliminate poor performers. Particle and chemical data alone are often unable to achieve this.

'Many variables impact powder behaviour - predicting it from a knowledge of particle properties and external variables is not yet feasible.'

'A powder flows through a process as a 'bulk assembly' and therefore should be quantified in terms of its bulk properties, if the intention is to predict and understand processing performance.'

Section 2

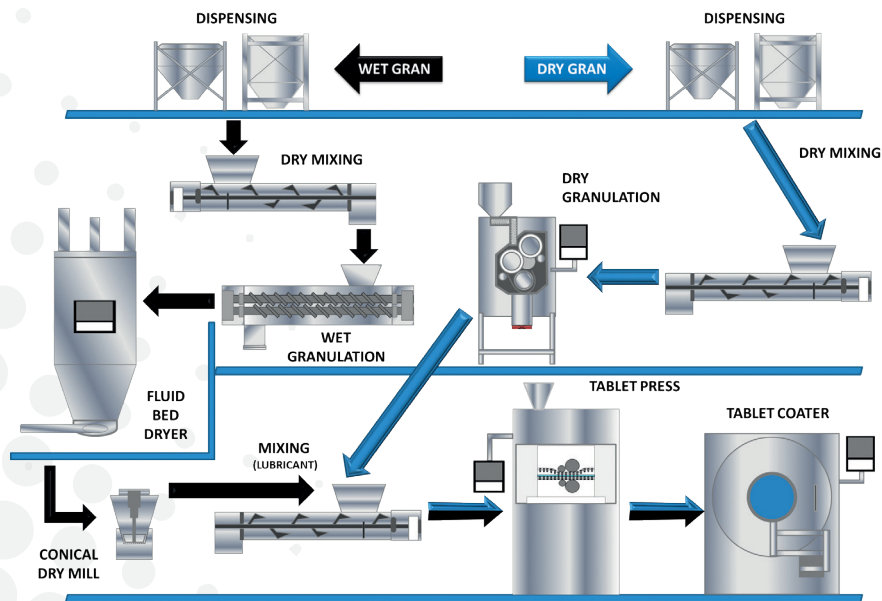
Interesting aspects of powder behaviour

'Powder behaviour does not just mean flow from a hopper! Powder processors are also interested in feeding, mixing/blending, granulation, drying, filling, tableting, aerosolisation, pneumatic conveying, dosing, storage, transportation and so on...'

Powders are bulk assemblies of particles, gas and liquid, and this fact certainly explains why they are so complex, but it also underpins their industrial value. Powders perform in many different ways, depending on how they are formulated and manufactured, as well as the environment to which they are subjected. This is why we find them so useful. Just think of a powder flowing through a press but then exiting as a hard stable tablet, or a powder coating adhering to a metal panel dipped in a fluidised bed.

For many people, discussions about powders and especially powder testing are all about flow from a hopper and hopper design but powder behaviour, and industrial interest in it, extends far beyond this narrow definition.

Let us take a closer look at those aspects of powder behaviour that are particularly interesting.



Schematic of a Continuous Manufacturing Process for Tablet Production.

Flowability

Imagine two samples of powder sitting in jars, one is granulated sugar and the other is flour. Swirling the jar containing sugar will produce fluid-like movement in the powder and if the jar is rolled on its side the sugar will smoothly tumble, maintaining a steady flow pattern.

Rotating the flour sample in either plane induces very different, intermittent movement, mostly of agglomerates. It is possible to move the jar a small way and find that nothing happens, and then an avalanching event occurs as the powder collapses to a new position. This powder is flowing too but in a very different way that makes it intuitively less appealing for those whose primary concern is steady process flow.

In this loose packing state, these two powders lie at opposite ends of the flowability spectrum. In simple powder characterisation terms, sugar would be described as 'free-flowing' and flour as 'cohesive', but it is vital to recognise that many powders lie at finely differentiated points between these two extremes.

Moreover, when each powder is consolidated or aerated, this will have an influence on their flow properties and the relative differences in their behaviour may change. If the sugar particles are subjected to vibration then they may lock together very efficiently, resulting in a material that is very poorly flowing, perhaps even worse than the flour after it has also been consolidated through vibration.

The impact of the external variables of aeration and consolidation can be dramatic, turning a once moderate flowing powder into a fluid-like material if aerated (talc), or indeed, a once free flowing material into a solid entity after consolidation (toner). Therefore, in order to fully understand the range of flow characteristics that powders can exhibit, it is essential to assess their behaviour across all stress states, from aerated to consolidated.

Furthermore, powders frequently exhibit flow rate sensitivity, meaning that the ease with which they flow is dependent on the rate of shear applied to them. A practical example that illustrates this point is a mixing process.

Some powders with high flow rate sensitivity will require a high shear mixing process in order to achieve blend uniformity. Powders that are less flow rate sensitive can be blended to uniformity at low shear rates, providing the opportunity to utilise low energy mixing processes, as opposed to high shear operations that may also damage particles and induce electrostatic charging.

Understanding how powders flow is critical for the efficient operation of many processes. Flow properties influence how easily powders will mix or blend, how they behave in a feeder, or how they flow into and fill a capsule or die. Understanding the factors that influence flow is also important for establishing optimal storage conditions. However, even

when two powders have relatively similar flow properties, they can still exhibit quite different process behaviour due to differences in their bulk or shear properties. Being able to accurately quantify minor differences in every property relevant to behaviour is vital if a thorough and robust characterisation is to be achieved.

There are many unit operations employed in powder processing, and each will subject the powder to a specific set of conditions. There is no such thing as a universally 'good' powder – it is more a question of “are this powder's properties compatible with the process conditions experienced in this unit operation?”

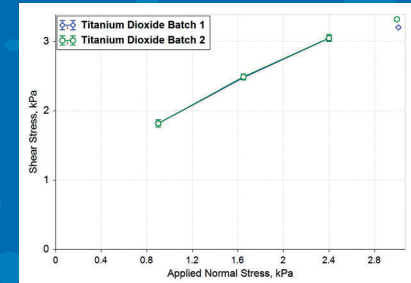
A common problem: measuring the wrong property!

A powder processor collects data for two titanium dioxide samples, one set using a shear tester, the other using a dynamic flow testing technique which produces a direct measure of flowability – Basic Flowability Energy (BFE). The shear data suggest that the two samples have identical properties but the dynamic flowability results indicate that they do not. Which is right?

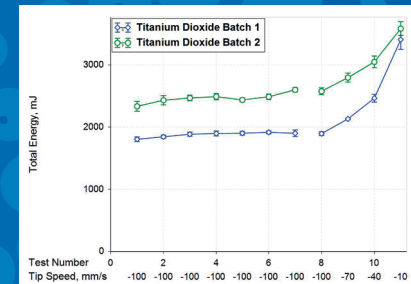
Both sets of data are correct. After all, these techniques measure different characteristics of powder behaviour. What we can say from these results is that while the two samples are likely to behave in the same way when

in a consolidated environment, during the initiation of flow, such as in a hopper (shear testing data), they have significantly different flow properties when moving dynamically in a process, as quantified by the measurement of their dynamic flowability.

If the reason for this analysis is to assess whether these powders will process identically, then the answer is that it depends on what part of the process is being considered. Both powders are likely to behave in a similar way in a hopper, but when assessed for performance in more dynamic, moderate or low stress environments, such as mixing and filling processes, these powders are likely to exhibit different performance.



Shear Data



Dynamic Flow Data

Cohesion

The term cohesion is commonly associated with a powder's flowability and indeed it is often the most influential property in regard to bulk powder behaviour. Cohesion is a mechanism that acts between particles and has the tendency to 'bond' one particle to its neighbour. These tensile forces are a combination of electrostatic charges, or surface energies, and Van der Waals forces.

The magnitude of the cohesive force between two adjacent particles is typically small and often insignificant when powders are in a consolidated state, where the forces of friction and mechanical interlocking are most dominant. However, when a powder is in a loose packing state, the cohesive forces can be

large relative to the other forces acting on the particle and may dominate bulk powder behaviour. As powders are often processed in a low stress packing state, the strength of the cohesive forces can make the difference between good process performance and a powder that behaves poorly.

This topic is covered in more detail later but it is worth emphasising here that, particularly in any process or application where the powder is loosely packed, cohesive properties will be important.

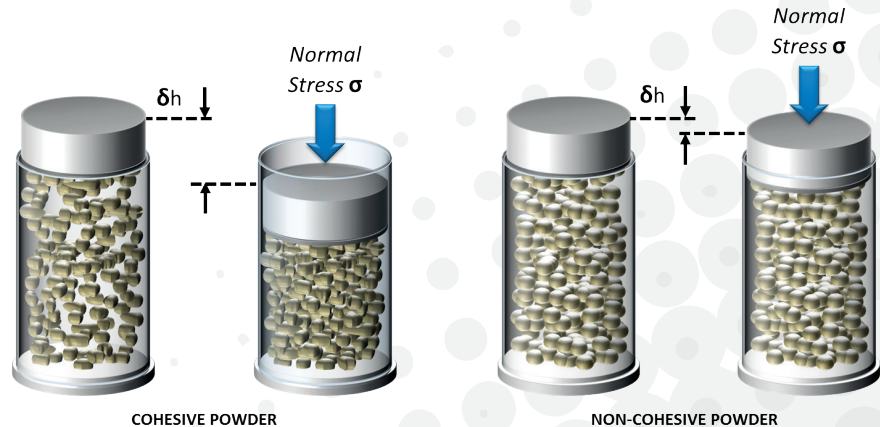
Adhesion

Whilst cohesion quantifies the strength of particle-particle interactions, adhesion is a measure of the propensity of particles to stick to a different surface or material – often the surface of the processing equipment. This is an important issue when it comes to processing, since powder residues can result in blend heterogeneity, require more thorough cleaning, increase the risk of cross-contamination between batches, and be a major initiator of blockages.

Compressibility

Compressibility is a measure of the volume change in a powder sample as a consequence of an applied consolidating stress. This stress forces particles closer together, packing the same number of particles into a smaller volume, and thereby increasing bulk density. Compressibility should not be confused with consolidation induced by vibration, an entirely different mechanism, dependent on particle reorganisation as the bulk powder is jostled.

There are times when compression is intended, during tableting, for example, and others when it just happens in a relatively uncontrolled way, such as when a powder sits in storage under the pressure of its own weight.



'Generally speaking cohesive powders, which tend to be inefficiently packed and therefore contain more air, are more compressible than less cohesive powders.'

Some powders are fairly incompressible while others are readily reduced in volume. Returning to our two examples, granulated sugar is relatively incompressible. In contrast, applying a consolidating stress to a sample of flour will cause a significant change in bed height, at the same time producing a plug with increased structural strength. Flour is relatively compressible.

There are links between compressibility and flow behaviour, although they are not as definitive as some traditional testing methods would suggest. Powders exhibiting high compressibility tend to be characterised by an inefficient packing structure when in a low stress state, and this is mostly symptomatic of relatively cohesive

powders. Non-cohesive powders, in contrast, tend to be far less compressible.

It is this principle that underpins traditional bulk density methods, and their use for flowability measurement, however it should be noted that these methods rely on uni-axial deceleration (or tapping) to induce volume change. Whilst they are traditionally referred to as 'compressibility' tests, this term should not be confused with compressibility induced by the application of an external force. Inferring flow from density measurements in this way can be misleading and is far less sensitive than direct flow measurement.

Permeability

The ease with which air can be transmitted through a powder bed is a function of the powder's bulk permeability (not to be confused with aeration, as introduced previously). Generally speaking, powders with a large particle size tend to have high permeability due to the large channels that exist between particles, through which air can easily pass. Powders containing small particles may have a higher relative air content, or lower solids fraction or bulk density, however due to the smaller interstitial spaces and poorly connected 'pockets' of air, the resistance of the bulk powder to air flow is higher.

Permeability is also influenced by other powder properties, such as the amount of fine particles present, the shape of the particles, and their

surface properties. In addition, the bulk powder's permeability is dependent on the extent of compression that the powder is exposed to. Powders that are highly compressible tend to exhibit larger changes in their permeability as a result of consolidation. In contrast, powders whose packing structure changes to a lesser extent when subjected to a consolidating load exhibit more constant permeability. Quantifying permeability across a range of consolidating stresses is therefore advisable.

Permeability measurements help to quantify how easily a powder becomes aerated or de-aerated, identifying materials that have the potential to transition from liquid-like to solid-like behaviour (or vice-versa) very rapidly and become problematic in the process.

If a relatively free-flowing powder becomes aerated then it may retain this state such that it 'floods' through the process in a completely uncontrolled manner. On the other hand a powder that easily loses air may rapidly transform into an immobile material that flows poorly.

Filling and compression processes are particularly sensitive to permeability, as the air inside the die or mould needs to be excluded rapidly and replaced by particles. Low permeability of the powder restricts air back-flow between particles, as the particles fill the die and will strongly influence fill rate.

During tablet compression, the ability of the air to escape from the loose powder contained in the die during the compression step is strongly linked to the mechanical properties of the tablet, and undesirable characteristics such as lamination and capping.

It is relatively easy to see the relevance of permeability when it comes to fluidisation processes and other unit operations such as pneumatic conveying, where air (or another gas) plays a prominent role. However, the amount of air in a powder is typically uncontrolled and may change significantly during routine processing. Powders can easily pick up and lose air, during discharge from a vessel, for example, or when left to settle under their own weight. With some powders this results in a dramatic change in behaviour.



Image courtesy of
Solids Handling Technologies

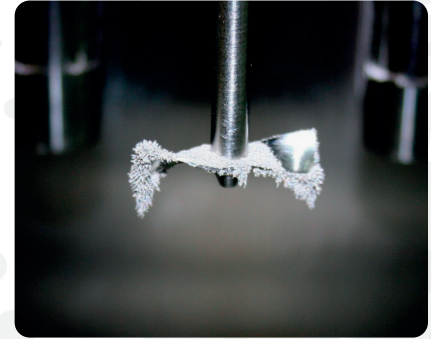
'Powders can be intentionally aerated or simply pick up or release air during routine processing. When flooding occurs, loss of process control can cause costly problems.'

Electrostatic charging

The particles sticking to a computer monitor are a prime example of the influence of electrostatic charge. Some particles are easily charged, changing the balance of forces within the powder and impacting behaviour. However, powders are generally electrical insulators, so simply earthing a charged powder does little to change its behaviour. It is routine practice to 'ground' processing equipment for safety reasons but this action should not be assumed to eliminate charge evolution in the bulk powder. A far more 'effective' method is to optimise the water content in the powder. Water is usually considered detrimental when it comes to powder flow, but in an electrostatically charged powder, water will act as a more conductive medium.

In this way water can provide an effective route to ground, discharging the system and potentially enabling the particles to flow more freely.

In applications such as powder coating (automotive) or toners (laser printing), the electrostatic properties of powders are fundamental to the success of the application. Here surface modification of toner particles allows the electrical characteristics of the bulk toner to be engineered such that they have optimal performance for the intended process and application.



'Electrostatic charge build-up in powders can transform behaviour.'

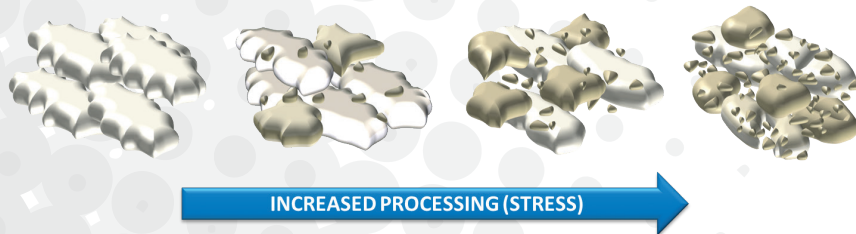
Physical changes

When processing powders, it is possible that some of the properties of the particles will change, either intentionally or otherwise. For example, particles vary substantially in terms of their affinity for water. The impact of processing in a humid atmosphere will therefore vary depending on a powder's tendency to take on water, as will performance in certain unit operations such as wet granulation. Furthermore, particles that are not mechanically robust may undergo attrition if

subject to stress. Attrition can result in a reduction of particle size, changes in particle shape, increases in surface area and modification of surface properties, all of which will impact powder behaviour.

In many cases, a process step designed to produce one outcome may at the same time, inadvertently and irreversibly, change particle and powder properties. A common example of such changes is the

agglomeration and densification phenomena that occur when feeding a cohesive powder. Screw feeders are utilised to control the flow rate of a feed material into the next step of a process, but they subject a powder to high levels of shear and compaction. As a result, certain powders will possess very different properties after being passed through the feeder, even though this is not the intention.



'Particles may undergo attrition if subjected to stress, resulting in a reduction in particle size and a change in shape and surface area.'

'The diversity of powder behaviour cannot be captured with just one measurement method and certainly not with just a single number. Using a multi-faceted approach in powder testing is now recognised as being the most productive strategy.'

The myth of the single number

Powders are tested to answer a variety of questions. These may include:

- Will this blend result in high quality tablets if manufactured using a direct compression process?
- Can I be sure that this powder coating will fluidise well in my customer's plant?
- Is this new raw material going to achieve good blend uniformity in my existing blender?
- How closely do I need to control storage conditions for this raw material?

- What is the optimum water content required during granulation to ensure ideal final product attributes?

These represent just a few of the many hundreds of questions that may be asked by the powder processing community.

Powder behaviour is complex and multi-faceted and there is a need to understand this behaviour within the context of many different processing environments. It is therefore impossible to holistically describe powders with just a single number, or even a single technique. It is like trying to describe a person with a single adjective. A simple measurement such as Hausner Ratio will give

some insight into behaviour, however limited, but trying to develop the in-depth knowledge necessary for efficient processing from just a single analysis is unrealistic.

Section 3

Spotlight on powder flowability

The way in which powders flow is arguably their most defining characteristic. Flowability is relevant in many processes and is often the problem at the heart of processing efficiency issues. In this section we are going to look in more detail at the mechanisms of interaction between particles and how these translate to bulk powder flow characteristics.

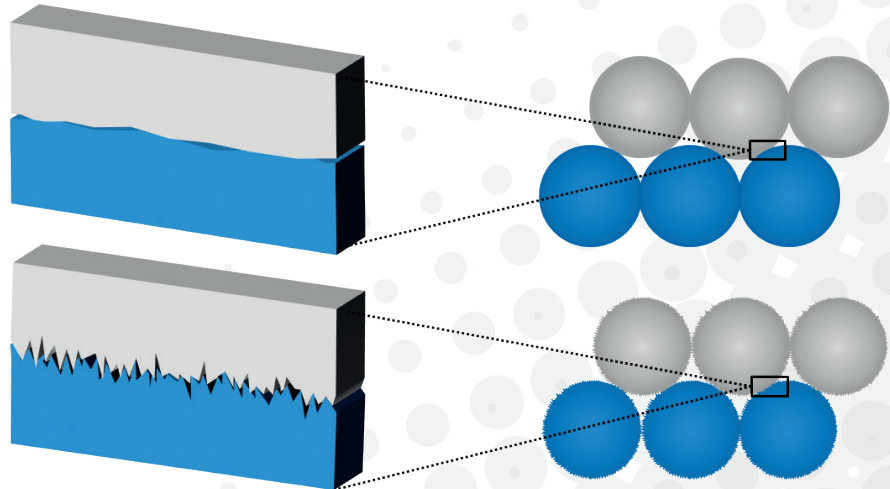
When powders flow, the particles within them move relative to one another. The mechanisms that define the ease of that movement are:

- Friction – between particles and between particles and equipment surfaces
- Mechanical interlocking – relating to the shape of the particles
- Liquid bridging – resulting in capillary forces
- Cohesion - inter-particulate interactions due to electrostatics and Van der Waals
- Gravitational effects – directly related to the density and size of the particles

Friction

Smooth particles tend to slide more easily, relative to each other, as a consequence of the lower friction acting at the contact points. Likewise, the level of friction between particles and the process equipment wall will be influenced by the surface properties of both the particle and the material of construction.

Surface roughness and also the chemical properties of the material can influence frictional interactions.

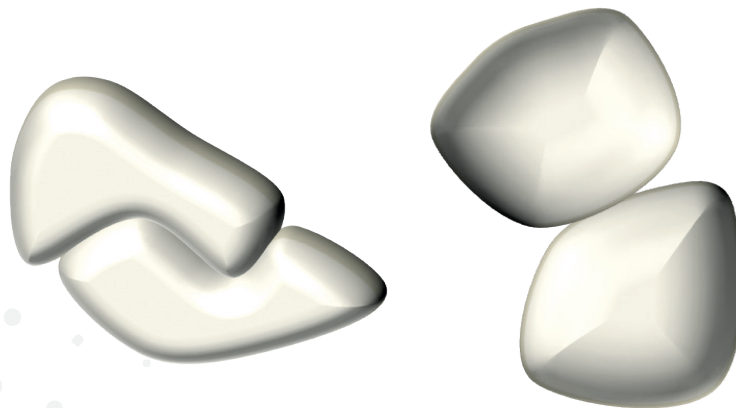


'Particles with a smoother surface will generally have a lower frictional interaction and flow more easily than those that are rougher, assuming all other features are identical.'

Mechanical interlocking

Particles with a complementary shape have the potential to result in substantial mechanical interlocking. As this occurs, the particles will strongly resist further movement, even if their surface friction is low. However, when particle morphology is more spherical, mechanical interlocking is less influential due to the more rounded nature of the particles.

In this case the particles are more likely to glance past one another, although their net interactions will still be influenced by other mechanisms, such as friction. It is generally the case that powders comprising particles of irregular shape will tend to possess poorer flow properties.



'Particles of a certain shape can mechanically interlock and resist flow.'

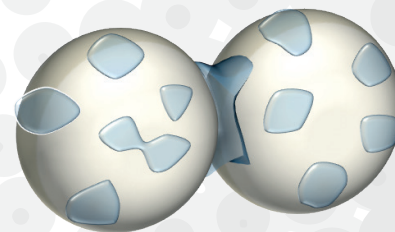
Liquid bridging

When it comes to powder flowability, adsorbed moisture is widely perceived to have a negative impact. This is not always the case, but liquid bridging can certainly be a detriment to flow. Liquids introduced into a powder have a tendency to coat the surface of the particles, forming liquid bridges that inhibit the free movement of one particle relative to another.

This effect is exploited in wet granulation where water is used to bind individual powder particles to form more easily handled granules, with better compression properties. Elsewhere the uncontrolled ingress of water can significantly degrade material quality, compromising processability, promoting caking

and reducing productivity. Liquid bridging can also occur between powder particles and the walls of the processing equipment, creating further processing challenges.

However, as previously noted, water can help to dissipate electrostatic charges, improving flow properties. The challenge is to ensure the bulk powder contains sufficient water to minimise the effect of electrostatics, but not so much that capillary bonds become established between particles, reducing flowability.



'Liquid has the ability to bridge between particles, reducing particle independence.'

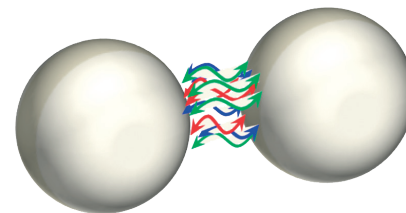
Inter-particulate forces of cohesion

The inherent strength of the inter-particulate forces of attraction (often called cohesive forces) is derived from a combination of Van der Waals forces and electrostatic charge on the surface of the particles. These are typically tensile forces, holding particles close to their neighbours and inhibiting independent particle mobility. They result in the formation of agglomerates, and can be the cause of many processing and quality issues.

The absolute values of interparticulate forces can vary widely, depending on the chemical composition of the particles, their shape and surface texture, bulk water content, and processing history. They may also change with time, where powders can be seen to 'relax' as the

electrostatic charge dissipates (following a high shear blending process, for example).

Cohesive forces are perhaps the most challenging of all particle-particle interactions and are very difficult to measure and model. However, their influence dominates powder behaviour in many processes and applications, particularly where the powder is uncompressed and required to flow. Process operations such as filling, mixing, conveying, and applications such as dry powder inhalers, are all dominated by the cohesive strength of the powder. It is imperative, therefore, that these forces are well understood and accurately quantified.



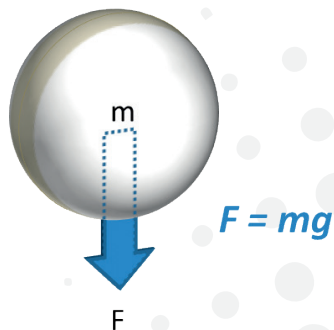
'Interparticulate forces act between contacting particles, and those in close proximity'

Gravity

So far in this section we have considered forces that act to restrict particle-particle independence. Generally speaking, the stronger their influence, the poorer the powder's flow properties. However, flow can be observed in powders with high levels of cohesion, irregular morphology and high surface friction, so there is clearly a significant motivating force that causes particles to move. This force is that imposed by the acceleration due to gravity.

Ignoring for a moment that particles in motion will have inertia, the primary force acting on a loosely packed stationary particle is that due to gravity – its weight. Therefore, the ability of a particle to begin to flow, particularly in powders that are unconsolidated,

is largely dependent on the strength of the gravitational force acting on it. It is for this reason that powders containing particles of large size, or consisting of material that has a high density, tend to flow better when loosely packed, as the particle's individual mass, and therefore the gravitational force acting on it, is high.



'F = mg, where g is acceleration due to gravity. Gravitational forces are often the only motive force acting on the particle.'

The force relationship between all restrictive forces and the motivating force of gravity is what dictates whether particles can move independently or whether they will exist as part of a stronger agglomerate. In the latter case bulk flow is influenced by the mass of the agglomerate and its relationship with surrounding agglomerates. There is a common misconception that powders with small particle size have stronger cohesive forces, but this is not necessarily the case.

In this scenario, the gravitational forces acting on the particle are small because the particle mass is low, and hence the relative size of the cohesive force to the gravitation force is high, even though the absolute value of cohesive force could be low.

A powder consisting of larger particles could have stronger cohesive forces acting between particles, but as particle mass is high, the gravitational force dominates and particles can flow independently.

Generally speaking, for loosely packed powders, if the:

- Gravitational force is greater than all restrictive forces, particles are mobile and the powder flows well

An extreme example would be a powder comprising large, spherical particles, with a low friction surface and good electrical conductivity.

- Gravitational force is weaker than all restrictive forces, particles are immobile and powder agglomerates and flows poorly

An extreme example would be a powder comprising small, irregularly shaped particles, with high surface energy, high surface friction, and some form of binder, such as excess water or fat.

Of course there are an infinite number of relationships between these two extremes, and this is further complicated by the fact that at particle scale, each force is variable and changeable depending on the environment to which the powder is subjected.

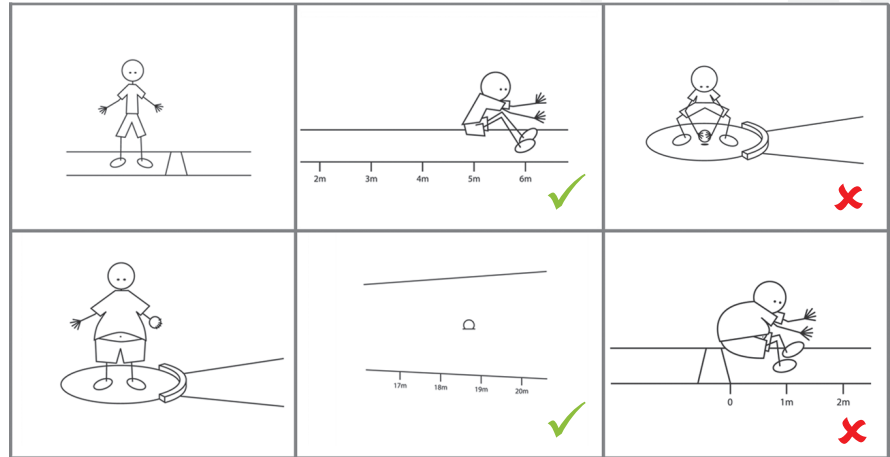
Section 4

The process environment

For most powder processors, powder behaviour is not a subject of academic interest, but more often a daily challenge. When powders are processed they are subjected to different stresses and environmental conditions in a wide variety of unit operations, including:

- Hoppers
- Feeders
- Blenders / mixers
- Granulators
- Dryers
- Conveyors
- Mills
- Extruders
- Fillers
- Compression processes

Powders are neither intrinsically good nor bad but they can be variously suited to different situations.



'Like athletes, powders have different characteristics that make them variously suited to different processes and applications. Selecting and configuring a process operation that is well-suited to a powder's inherent properties ensures success.'

Developing an optimised powder process relies on understanding the intrinsic characteristics of the powder, understanding the demands of the process and making sure that the two are compatible. If not, then one or both need to be modified to achieve efficient processing and high quality product over the long term. In this final section we are going to take a look in more detail at the processing environment and its influence on product properties and quality.

Consider the environment and stresses acting on a powder discharging from a well-filled hopper. Powder flow is induced by gravity and flow rates are, in general, relatively low compared with other processes. The powder is consolidated by the weight of

material above it, potentially over a prolonged period depending on its residence time, and this weight imposes a moderate to high stress environment on the powder just above the outlet. Frictional interaction between the powder and the hopper wall is an important additional consideration. At the time of discharge, a valve at the bottom of the hopper is opened and the same consolidation stress that compacted the powder during storage is now relied upon to force the powder to begin to flow through the valve.

‘To understand how a powder behaves in a process it is best tested under conditions that simulate the processing environment.’

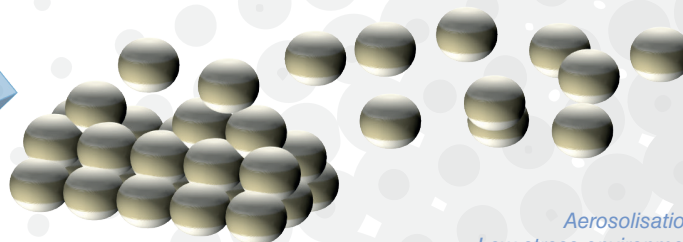
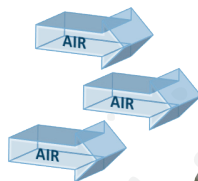


*Flow from a hopper:
Low flow rate, high stress environment*

In this environment, powders that are compressible are more susceptible to changes in their behaviour as a consequence of the imposed weight of the powder bed. A combination of powder and material of construction that results in low friction at the hopper wall will be beneficial in terms of enhancing flow, as will relatively low inter-particulate forces. Under stress, particles are forced closer together, so frictional forces and mechanical interlocking are the mechanisms most likely to dominate flow behaviour. Cohesive forces may exist, but they are negligible in contrast to these other mechanical interactions.

Therefore, the information that is especially relevant when it comes to evaluating or predicting powder behaviour in this environment is:

- Shear properties of the powder under moderate to high stress
- Wall friction acting between the powder and the material from which the hopper is constructed
- Compressibility and density data
- Permeability, particularly if the outlet of the hopper is connected to a transfer chute or other hardware that mitigates backflow of air



*Aerosolisation:
Low stress environment
Powder needs to dilate and fluidise*

Contrast the hopper application with what happens during aerosolisation of a powder, in pneumatic conveying, powder coating, or during drug delivery via a dry powder inhaler for example. In these situations there is little if any external compression stress acting on the powder. Air is being drawn through the sample with the potential for inter-particulate lubrication, aeration, and ultimately dilation of the powder into a stream of discrete particles.

Here, the more relevant questions to ask, and answer, are:

- What is the cohesive strength of the powder (as this will strongly influence its response to aeration)?
- How do the flow characteristics of the powder change when it is aerated?
- Does the powder fluidise?
- If so, what is the minimum fluidisation velocity for this powder?
- Are the particles robust, or are they likely to suffer from attrition?

So, with this application, candidate powders must be judged against very different criteria from those applied for the hopper environment. In this low stress regime, cohesive

forces will tend to define flow behaviour, rather than mechanisms that rely on closer particle proximity. A highly cohesive powder is unlikely to flow easily or to exhibit steady, uniform fluidisation and progressive dispersion. However, cohesive powders often have low permeability and therefore tend to fail catastrophically during an aeration process, giving rise to a high energy dispersion that may be of benefit to the application. Nevertheless, the optimum dispersion mechanism needs to be considered in relation to the specific application.

In fact each process or unit operation brings into focus a different combination of powder properties. Take transport as a further example. Here, consolidation due to vibration as well as imposed normal stress

may cause an issue, while caking can result if the powder is stored in unsuitable conditions. During die filling, performance is defined by the ability of the powder to flow rapidly and uniformly under gravity, often at low stress, and the powder's ability to rapidly release air.

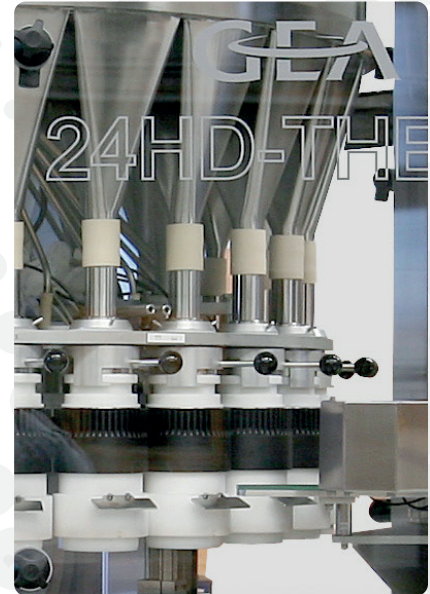
Recognising the impact of the processing environment is fundamental to translating an understanding of powder behaviour into better manufacturing performance. As the preceding discussion highlights, there will be a unique series of powder properties that define performance in any given process or unit operation. There will usually be more than one variable and the combination will vary from application to application.

This is where the single number approach to powder testing fails. The complexity of behaviour and the need for sensitive, differentiating and process relevant information make single number testing techniques both limited and relatively unhelpful.

In contrast, multi-faceted characterisation gives rise to the insight needed to secure a good process-powder match, regardless of the industry, application or powders in question.

This is ultimately what characterising and understanding powders is about. Trying to process a powder that is ill-suited to the processing equipment, and/or not conducive to a high quality final product, will be constantly challenging while a well-matched powder-process combination will contribute to long term productivity, high performance and profitability.

'Matching a powder and process is essential for maximising manufacturing efficiency over the long term.'



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Section 5

In summary

- Powders are multi-component bulk assemblies made up of solids, liquids and gases.
- As a result they exhibit complex behaviour that cannot be predicted from particle properties alone.
- This complexity makes powders challenging to process, and measure, but at the same time gives rise to an array of industrially useful behavioural properties.
- The behaviour a powder exhibits is a function of its inherent properties and the environment to which it is subjected. Therefore, the processing environment is an additional variable which must be considered when determining powder behaviour.
- Measuring a number of powder properties identifies those that are critical for a given application, helping to secure a good process-powder match.
- Making sure that a powder and process are compatible is essential for long term, efficient manufacture and high quality product.

Freeman Technology Head Office

Freeman Technology Ltd
1 Miller Court
Savern Drive
Tewkesbury
Gloucestershire
GL20 8DN
UK

+44 (0)1684 851 551
info@freemantech.co.uk

Global Headquarters

Micromeritics Instrument Corporation
4356 Communications Drive
Norcross
GA 30093
USA

+1 (770) 662 3636
info@micromeritics.com

www.freemantech.co.uk