Consider Wet Agglomeration To Improve Powder Flow

One way to avoid the flow problems associated with fine particles is to enlarge them

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Agglomeration is the process of converting fine powder particles into larger particles by the introduction of external forces. Agglomeration is often desirable because the process yields a product that has a higher bulk density, contains less dust, and has improved flowability. Figure 1 shows samples of fine potash powder and powder that has been agglomerated.

Fine powders often exhibit flow problems in a hopper, bin or silo, such as flow stoppages, erratic flow, flooding and limited discharge rates. Flow stoppages occur when attractive forces between particles, such as Van der Waals forces, valence forces and hydrogen bridges, cause a cohesive arch to develop at the vessel outlet. In some cases, powder may only flow in a narrow channel when a feeder or gate is operated. If the material has enough cohesive strength to become stable as the flow channel empties, flow stoppages will occur when powder along the walls remains stagnant. Erratic flow results when ratholes collapse, causing the powder to arch as it impacts the outlet. (For an illustration of arching and ratholing, see the online version of this article at www.che.com.)

If a stable rathole forms in a hopper, bin, or silo and fresh powder is added, it may become entrained in the air and become aerated. Because most feeders are designed to handle solids and not fluids, flooding may result when the fluidized material reaches the outlet. Flooding can also occur when ratholes collapse into an emptying flow channel. A fine powder sometimes cannot be discharged at the desired rate due to its low permeability, which leads to an adverse pressure gradient at the outlet of the vessel and gas flowing counter to the solids.

Particle size and flow patterns

The manner in which a powder flows in a hopper, bin, or silo has a great effect on the likelihood of these solids flow problems occurring. There are two primary flow patterns that can occur in a bin or silo: mass flow and funnel flow. (See the online version of this article for an illustration of these flow patterns.) In funnel flow, an active flow channel forms above the outlet, with stagnant material remaining at the periphery. Funnel flow occurs when the walls of the converging section of a vessel are not sufficiently steep or low enough in friction for the powder to flow along them.

Mass flow occurs when all the powder inside a vessel is in motion whenever any is withdrawn, and takes place when the walls of the hopper section are steep enough and low enough in friction for the powder to flow along them. As long as the outlet is large enough to prevent arching, all the powder flows when material is discharged, keeping the contents of the bin fully live.

Funnel flow can cause erratic flow, exacerbate segregation and reduce the live capacity of a vessel. Funnel flow can also induce high loads (depending on vessel size) on the structure and downstream equipment due to collapsing ratholes and eccentric flow channels. In addition, if the narrow flow channel empties out, a stable rathole may form. With fine powders, controlling flowrate is often challenging. Since a funnel flow channel is often unstable, its size can change dramatically or it may collapse, creating flowrates that range from no flow at all to complete flooding. In addition, the bulk density at the outlet will vary significantly over time.

FIGURE 1. Fine potash powder is one example of an application that can benefit from particle enlargement

Eliminating flow problems can often be accomplished by ensuring that a mass flow pattern exists in the vessel. Stable ratholes cannot form and because the material is more likely to de-aerate, flooding is less likely. In addition, the bulk density of the discharged powder is less variable.

Mass flow hoppers, bins and silos designed to handle fine powders frequently require steep walls and large outlets due to the material's high cohesive strength, high wall friction and low permeability. Often particle size enlargement allows mass flow vessels to be built with smaller outlets (allowing less expensive feeders to be used), walls that are less steep (which is advantageous if there are height restrictions) and less expensive wall materials.

Designing for mass flow

The flow pattern inside a hopper, bin or silo — funnel flow or mass flow — can be predicted by measuring the friction

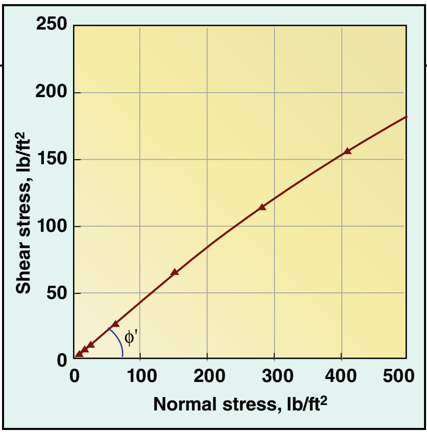


FIGURE 2. The wall yield locus, plotted here for a sample of fine potash powder, is a function of a material's wall friction properties

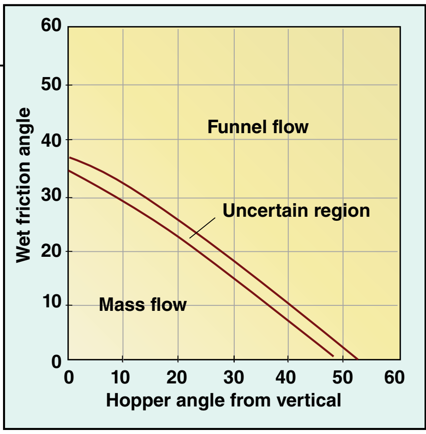


FIGURE 3. In design charts, such as this one for conical hoppers, any combination of wall friction angle (ϕ') and allowable hopper angle (θC) that lie within the mass flow region of the chart will provide mass flow

COMMONLY USED BINDERS

Inorganic binders	Organic binders
Alkali silicates	Asphalt
Gypsum	Maltose
Alum	Asphalt emulsions
Lime	Molasses
Bentonite and other clays	Cellulose
Lime hydrate	Paraffin
Caustic soda	Corn starch
Magnesia/magnesium oxide	Peat
Colloidal alumina and silica	Coal tar
Magnesium chloride	PVA (polyvinyl alcohol)
Cement	Dextrine
Plaster of Paris	Rosin
Dolomite	Gelatine
Sodium borate	Starches
Fuller's Earth	Lignosulfonates (lignin)
	Sucrose

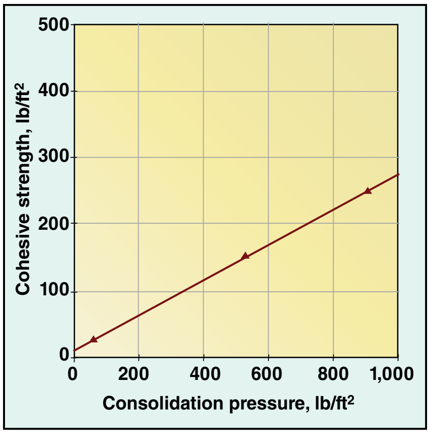


FIGURE 4. The relationship between cohesive strength and pressure is called the flow function, and is shown here for fine potash powder

between the powder and the hopper wall material. Wall friction is measured by a method described in ASTM D-6128 [*1*]. Various normal loads are applied to a sample of powder, which is forced to slide along a coupon of wall material. The resulting shear force is measured as a function of the applied normal force, and a wall yield locus is constructed by plotting shear force against normal force. The angle of wall friction at a particular pressure (ϕ') is the angle that is formed when a line is drawn from the origin to a point on the wall yield locus. A wall yield locus for a sample of fine potash powder on 304, No.-2B finish stainless steel is given in Figure 2.

Design charts originally developed by Jenike [*2*] provide allowable hopper angles for mass flow, given values of the wall friction angle. An example chart for conical hoppers is shown in Figure 3. Values of the allowable hopper angle (θ*C*; measured from vertical) are on the horizontal axis, and values of the wall friction angle (ϕ') are on the vertical axis. Any combinations of ϕ' and θ*C* that lie within the mass flow region of the chart will provide mass flow.

Designing right to the limit of the mass flow region is not recommended for conical bins. If the combination of wall friction angle and hopper angle lies too close to the funnel-flow line, a switch to funnel flow can occur. Hence, a 4–5 deg margin of safety is employed with respect to the mass flow boundary. For the potash powder whose wall friction properties are described by Figure 2, a conical hopper with walls sloped 12 deg from vertical is recommended to ensure mass flow.

Flow stoppages will be prevented if the stresses imparted on an obstruction to flow (such as a cohesive arch or stable rathole) are greater than the cohesive strength that the material gains due to its consolidation in a hopper, bin or silo. The cohesive strength of a bulk solid can be determined using the method described in ASTM D-6128 [*1*] where a direct shear tester is used to measure the shear strength of a material under varying consolidation pressures. The relationship between strength and pressure is called the flow function. The flow function for a sample of fine potash powder is shown in Figure 4.

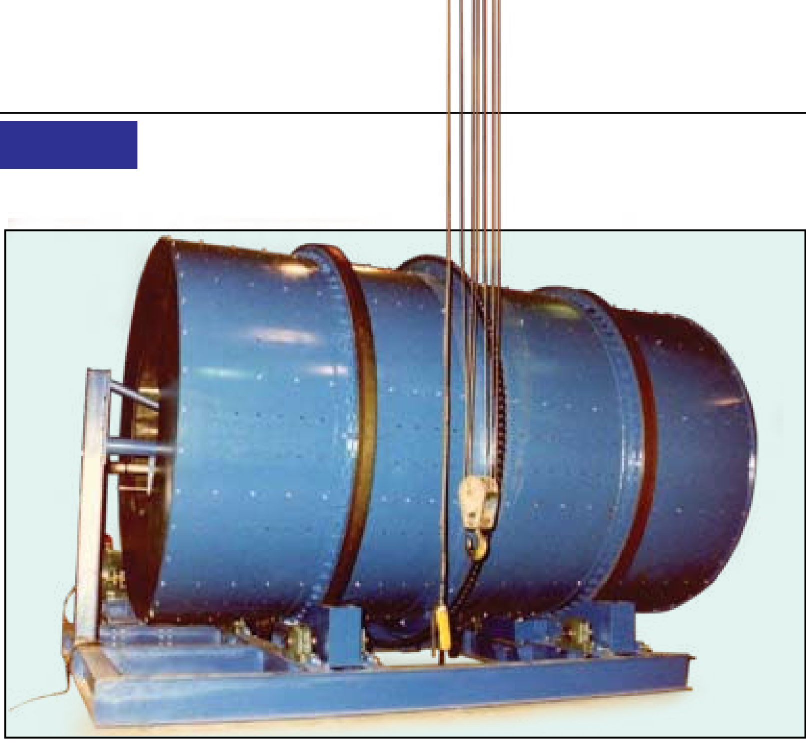
The stresses imparted on an arch of powder that forms at the vessel outlet are proportional to the material's bulk density. Once a material's flow function has been determined and its bulk density has been measured, the minimum outlet diameter that will prevent a cohesive arch from developing can be calculated using an analysis developed by Jenike [*2*]. For the powder whose flow function is given in Figure 4, the analysis shows that a conical mass-flow hopper requires a 6-in. dia. outlet to prevent arching. Note that this outlet diameter will prevent arching but does not ensure that the desired discharge rates can be achieved. Fine powder flowrates are limited because of high permeability, as discussed in Johanson [*3*].

Wet agglomeration processes

Wet agglomeration processes combine powder, liquid (usually water) and, if necessary, a binder, imparting shear to form agglomerates. Also known as tumble-growth agglomeration, wet agglomeration processes (Figures 5 and 6) include rotating drums, disc or pan agglomerators, pin and ribbon mixers, and fluidized beds.

In general, particle size enlargement by wet agglomeration occurs in three stages. The first is a mixing stage where powder, liquid and binder are combined. Next, moist particles are joined together to form so-called green agglomerates. Drying or curing takes place in a final stage. The wet agglomerates are formed by first forming nuclei that then grow into larger aggregates by layering or coalescence. In some cases, nucleation and aggregate growth take place in two separate pieces of equipment that are operated in series.

Nucleation gives rise to seed par-



FIGURES 5 and 6. Wet agglomeration processes combine powder, liquid (usually water) and, if necessary, a binder, imparting shear to form agglomerates. Here, disc (left) and drum (right) agglomerators are shown

ticles, which are formed when several individual particles adhere to each other. The nucleation stage can be time-consuming because the seed agglomerates are weakly bonded and readily disintegrate back into individual particles. Eventually, larger aggregates are formed when small agglomerates coalesce or individual particles adhere to larger agglomerates. Once larger agglomerates are created, growth becomes accelerated as the increased mass and higher kinetic energy of agglomerates cause them to pick up individual particles more rapidly and incorporate them onto their surfaces. The relative rates of size enlargement (nucleation, coalescence and layering) and size reduction (attrition and consolidation) establish the final particle size along with the material's tendency to wick moisture from its core to outer layers.

The optimal amount of liquid added to a powder — the amount that gives the resultant agglomerates their greatest integrity and resistance to breakage — is typically 40–90% of its liquid saturation. The liquid saturation is the fraction of total void space that can be filled with the liquid. When water (or another liquid) is added to a dry bulk solid, liquid bridges will begin to form at contact points between particles. This is known as the pendular stage of saturation. All free moisture is attracted to the interfaces between the solid particles by capillary effects, and surface tension draws the particles together. As saturation levels are increased, the funicular stage is eventually reached where all internal solid surfaces become surrounded by liquid. At this point, the mixture becomes more fluid-like, tensional forces disappear, and the agglomerates become weaker. When the powder becomes fully saturated, it reaches its capillary state, and at higher moisture levels, the system begins to behave as a slurry. Saturation states of powder are illustrated in Figure 7.

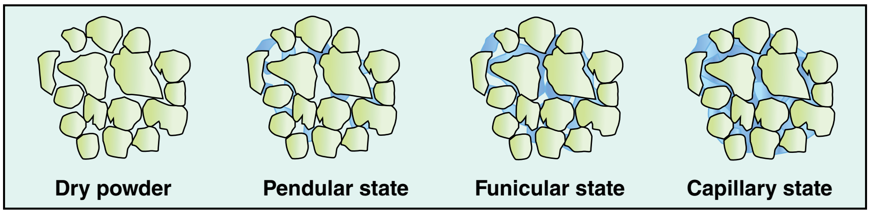
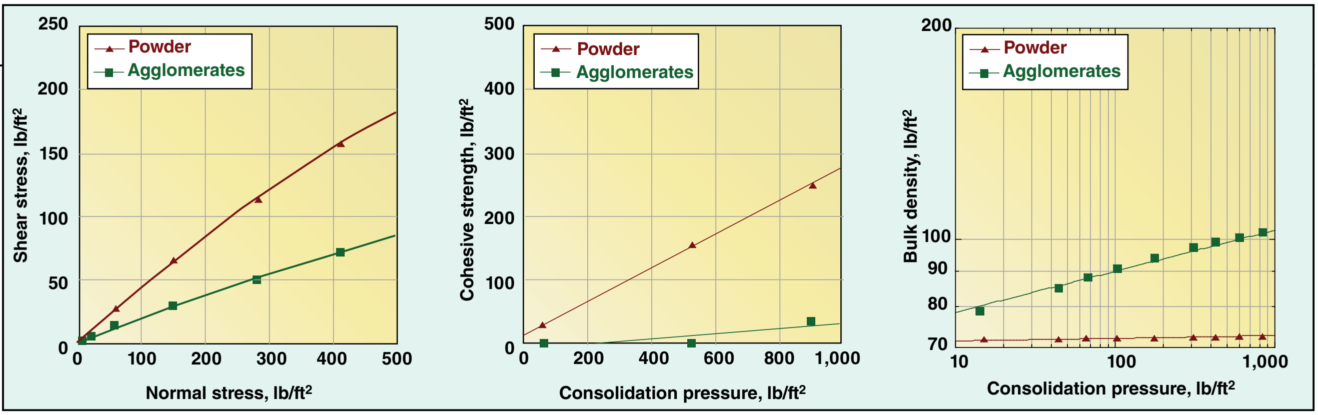


FIGURE 7. The liquid saturation is the fraction of total void space that can be filled with the liquid. The four saturation states of powder are shown here

An under-saturated bulk solid can be converted to a saturated state by compaction (dry agglomeration) alone, without further addition of moisture [*4*]. Likewise, pendular and funicular states of the same powder can be reached at different moisture contents. Hence, the optimal amount of liquid that must be added to a powder to resist breakage often depends on the device, scale and properties of the material undergoing agglomeration.

Often, binders are added prior to or during agglomeration to increase the strength of the agglomerates. Binders are generally liquid solutions, suspensions of fine solids, or dry powders. Commonly used inorganic and organic binders, are listed in the box (opposite page) [*5*, *6*]. Highly viscous binders, such as colloidal silica, are effective since both the adhesive forces at the binder-solid interface and the cohesive forces within the viscous binder act to strengthen the aggregates. Solid bridges form when dissolved matter in liquid bridges precipitate during cooling or drying. Similarly, colloidal particles form solid bridges when they become concentrated in diminishing liquid bridges and become consolidated due to the liquid's surface tension.

Even if a binder has no solid components, drying may still increase the strength of the agglomerates by drawing the particles closer together, because capillary forces associated with the interstitial liquid increase as the liquid content is reduced. Once in close proximity, the magnitude of Van der Waals and other molecular forces between adjacent individual particles increases. This leads to further densification and greater integrity of the agglomerated product. In some



FIGURES 8. Agglomeration reduces the cohesive strength (left) of potash, reduces its wall friction (center) on 304, No.-2B finish stainless steel and also increases its bulk density (right)

instances, a material to be agglomerated has natural binding properties that are simply activated by the addition of moisture.

As a general rule, flowability improves with increasing particle size. Cohesive strength usually increases with decreasing particle size due to greater specific surface-area and a greater number of contacts between particles. There are many exceptions to the rule; for instance, sub-micron particles are often added to powders as parting agents to increase the distance between individual particles and reduce the magnitude of interparticle forces. Fortunately, shear cell testing is straightforward, and cohesive-strength and wall-friction tests can be quickly conducted to confirm the potential benefits of particle size enlargement on a material's flowability.

As an example of improved flowability that can result from agglomeration, potash was agglomerated on a continuous basis by adding fine powder, water and a dry organic binder to a pin mixer, followed by a disc agglomerator, and finally a direct fired rotary dryer. The resulting pellets were then screened to separate the desired pellets (Figure 1) from the undersize and oversize fractions. The green agglomerates contained 8–14% moisture and 1.5–3.5% binder.

The cohesive strength, wall friction and bulk densities of the fine potash powder and agglomerates of potash are compared in Figure 8. Note that agglomeration reduces the cohesive strength of potash, reduces its wall friction on 314, No.-2B finish stainless steel, and increases its bulk density. Powders with lower strength, less friction, and higher bulk density flow more readily.

While a 6-in. dia. outlet is recommended to prevent the fine powder from arching in a conical hopper, the shear cell tests and subsequent analysis reveal that cohesive arching will not occur in a hopper, bin, or silo that handles the agglomerated product. Instead, the outlet size of a vessel that handles the agglomerates should be selected by consideration of particle interlocking or desired discharge rates. In addition, the agglomerated material requires significantly less-steep walls to allow mass flow. If a conical hopper, bin, or silo with a 6-in. dia. outlet is fabricated or lined with 304, No.-2B finish stainless steel, walls sloped 25-deg from vertical are recommended to ensure mass flow (versus 12-deg if the material is handled in a fine powder form).

Final remarks

Flowability of fine powders is often improved by agglomeration. Agglomeration results in powder with a higher bulk density and often reduces its cohesive strength and wall friction.

A key to producing quality agglomerates in a wet process is to ensure that the proper ratio of powder, moisture and binder is used. If insufficient liquid is added, layering is difficult, and excess dust in the product is produced. If liquid content is too high it will yield agglomerates with poor integrity, as the bonds between individual particles will be weak.

In a continuous wet-agglomeration process, the hopper that feeds the equipment should also be designed for mass flow to ensure its reliable operation since the performance of most agglomeration systems is strongly influenced by feedrate of the powder and any binder used. In mass flow, the bulk density of the powder is independent of the level of powder inside the hopper, flowrates are steady (assuming that the outlet is large enough to prevent flowrate limitations that result from counterflow of air), and ratholes cannot form. The proper ratio of powder, moisture and binder is easier to maintain if systems designed for mass flow are used, which allow agglomerates with the greatest integrity to be produced. ■

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