A cure for hammer rash: Measuring powder flowability with shear cell testing

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Preventing discharge problems in vessels and containers requires a detailed understanding of your powder's flow characteristics. This article explains how a shear cell tester can simplify and speed tests for measuring a powder's flow behavior. With built-in software to quickly analyze the test results, this instrument is moving shear cell testing from its established place in R&D labs into the world of quality control for day-to-day bulk solids production.

The hoppers of storage vessels and containers in bulk solids processing plants often appear to be afflicted with mumps or measles. But on closer inspection, it's clear that the rash-like disease isn't biological. Rather, it's caused by humans who bash the hopper sides with sledge hammers, steel rods, baseball bats, or anything else that can help dislodge powder buildup inside the hopper and get it flowing again. Not only can this violence lead to arm or back injuries for the worker swinging the hammer, but the noise it generates is ear-rattling. The worst tragedy resulting from a plugged hopper, of course, is when a worker climbs inside the hopper to clean out the blockage and instead is trapped under collapsing powder, with sometimes fatal results.

Plants take different approaches to mitigating hopper blockages. One method is to install a vibrator on the hopper, as shown in Figure 1a. While this may help for a while, the powder will inevitably jam again; if this happens too often, the vibrator itself may become the target of a good hammering. Another approach is to create a hole in the hopper wall, as shown in Figure 1b, so a pole or rod can be inserted to dislodge the powder buildup, but this often leaves some of the buildup behind. Another more expensive technique is to insert air lines into the hopper to blow air into the powder buildup and facilitate flow.

The use of such methods, however, makes it clear that many plant personnel don't understand the factors contributing to powder flow problems. This is often true even after they've conducted flow tests to predict the powder's flow behavior. The reality is that the popular test methods for predicting flow behavior don't correctly simulate conditions inside the vessel.

This hopper has come down with a bad case of hammer rash—an all-too-common result when plant personnel fail to understand a powder's flow behavior.

For instance, two of these test methods — using flow cups to measure the time required to discharge powder through a hole with a known diameter and calculating the angle of inclination in the resulting powder pile — will provide traditional flow data. But these results don't have much relevance for predicting the powder's flow behavior in a vessel because the powder measured by the tests is in an unconsolidated condition. The powder in a vessel, on the other hand, is consolidated, compacted by its own weight as the powder on top compresses the powder below. What may have been a loose or slightly compacted powder in a bag or small container now becomes a consolidated mass of material with completely different flow characteristics. And the longer the powder stays in the vessel, the more likely the compaction will increase.

Figure 1

Devices commonly used on hoppers to promote powder flow

a. Vibrator

b. Hole for inserting a steel rod

The science of predicting flow behavior

Though it's not common knowledge for most bulk solids plant personnel, the science for predicting a consolidated powder's flow behavior is well-established. In the 1960s, a *shear cell* apparatus was developed by bulk solids researcher Dr. A.W. Jenike to provide an analytical procedure for characterizing the shear forces acting on particles as they migrate from top to bottom in a vessel during discharge.[1] The Jenike shear cell was used to test various powders and minerals, and this technique was eventually documented by the American Society for Testing and Materials (now ASTM International [www.astm.org]) as test method D6128. One common design for the shear cell apparatus is the *annular shear cell.* The powder is loaded into an annular (ring-shaped) shear cell and placed on the test apparatus. Then a lid is placed over the cell to compress the powder to various defined consolidation loads. For each load, the powder is sheared rotationally (that is, the lid is rotated horizontally across the shear cell) to determine the yield stress at which the powder yields and flows.

The good news is that today, available shear cell technology encompasses an array of commercial testers that combine a shear cell test apparatus with software for analyzing the results.

The math required to calculate the shear cell test results, however, is enough to frighten away the best-intentioned process engineer. This goes a long way in explaining why predicting powder flow behavior in vessels isn't well understood in most bulk solids plants. The good news is that today, available shear cell technology encompasses an array of commercial testers that combine a shear cell test apparatus with software for analyzing the results. One example is shown in Figure 2a. The tester's software allows the user to cut through all the detailed calculations, greatly simplifying the task of analyzing the relevant flow data. In fact, any lab technician can quickly set up and run one of today's shear cell testers without having a scientific background or extensive training. The technician can then immediately use the results for quality control, whether to qualify raw materials arriving at the plant, evaluate in-process mixtures during production, or certify final product for guaranteed flow performance at the customer's facility.

Before we discuss how to use a shear cell tester and the resulting data to keep your powder flowing, let's start by looking at what happens to flow when powder compacts in a vessel.

Figure 2

Shear cell tester

a. Tester

b. Annular shear cell

c. Vane lid

Powder flow patterns

One of two main powder flow patterns can occur in a vessel: core (*funnel*) flow or mass flow, as shown in Figure 3. *Core flow* (Figure 3a), which can be considered the default pattern, is characterized by powder discharge through a central core — a preferential flow channel above the outlet's discharge point. This produces first-in last-out discharge and, if the vessel is operated in continuous rather than batch mode, the powder around the lower section's walls will remain static until the vessel is completely discharged.

Mass flow (Figure 3b) is the desired pattern for poor-flowing powders or powders that tend to consolidate over time, but achieving this pattern requires the vessel to be specifically designed for the powder's characteristics. Mass flow provides first-in first-out discharge, in which the vessel's entire contents are "live." To achieve this, the vessel's hopper walls must be sufficiently steep and smooth. For a given hopper wall material and converging angle, the powder's *wall friction* (that is, its ability to move against the hopper surface) must be below a critical value. The powder discharge must also be controlled by a valve or feeder that allows powder to flow through the outlet's entire cross-sectional area. In fact, the failure to allow flow across the entire outlet area is what prevents many vessels from operating in mass flow.

In reality, 80 to 90 percent of all vessels and containers in bulk solids applications operate in core flow, not mass flow. The result is that powder is compacted in the lower half of the vessel or container, particularly in the hopper section, which may increase flow resistance, especially as the powder level reduces. When the remaining powder has compacted so much that it can no longer flow, the hopper becomes blocked.

These blockages typically take the form of ratholes or arches. A *rathole,* the principal obstruction in a core-flow vessel, results when the column of powder immediately above the outlet discharges in total, leaving behind a stable core-shaped structure that prevents the remaining powder in the vessel from moving. The rathole appears as a clear circular opening running from the vessel top to the hopper bottom. An *arch,* the principal obstruction in a mass-flow vessel, is a stable bridge of powder across the outlet or across the hopper's converging walls, which leads to erratic flow or even a total flow stoppage.

Using a shear cell tester to measure flow behavior

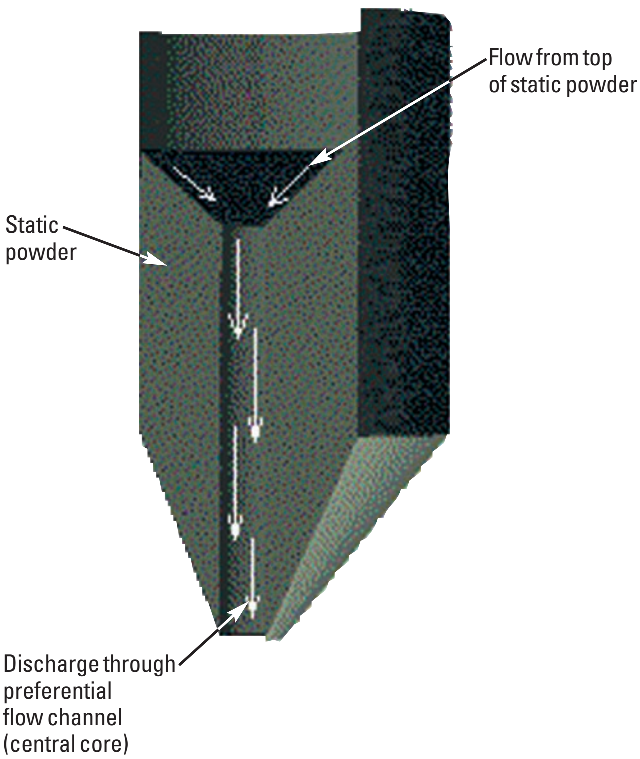
In the past, shear cell test devices were appropriate only for R&D applications, in which the lab technicians were highly skilled and extensive lead time was available for analyzing the results. With today's shear cell testers, the test method is built into the instrument's software and executes automatically, so a technician with minimal training can quickly run standard quality-control tests to meet daily production goals.

The test method for the shear cell tester is the same as with the simple test device: The powder is compressed in the tester's annular shear cell (Figure 2b) with a special vane lid (Figure 2c) and then sheared rotationally. The shear stress values measured by the tester during the rotation accurately indicate the force required to cause the particles to flow against each other. By varying the consolidation load on the powder in the shear cell, the tester can simulate what happens to the powder in a vessel as the fill level changes. This, in turn, gives an accurate measure of how well the powder will flow out of the vessel's hopper.

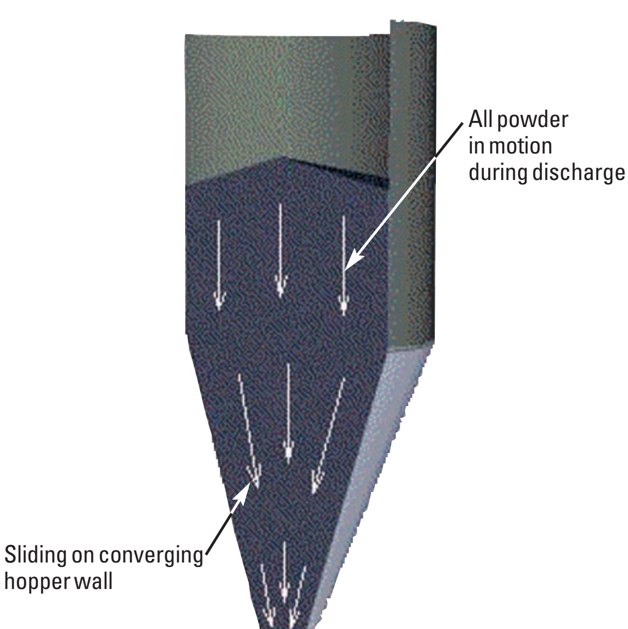
Figure 3

Powder flow patterns

a. Core flow



b. Mass flow



The tester's software provides great flexibility in setting up the test, including the desired consolidation loads to be applied, to suit the powder and the amount of data required. The test typically takes less than 1 hour to execute, depending on the number of consolidation loads used.

Interpreting the data

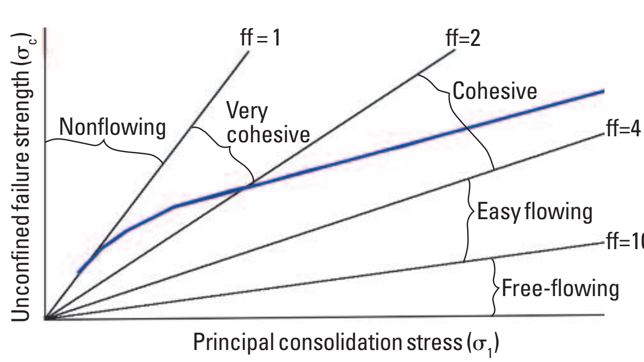
Flow function. The shear cell tester's data provides a graphical picture of how the powder's flowability can change as a function of compaction load. This is known as the *flow function,* as shown in Figure 4. The flow function's *x* axis, the *principal consolidation stress* (σ_1), is directly related to the compaction load applied to the powder in the shear cell, which makes the principal consolidation stress the control parameter that regulates the test. The *y* axis, the *unconfined failure strength* (σ_c), is directly related to the stress required to cause the particles to flow against each other.

The shear cell tester's data provides a graphical picture of how the powder's flowability can change as a function of compaction load.

Interpreting the flow function for your powder is key to getting useful information from the shear cell test. You don't have to be a highly skilled scientist or trained technician to come up with a basic flow analysis of your powder because there's general agreement in the bulk solids indus-

Figure 4

Flow function



tries about what zones on the flow function characterize different flow behaviors. These zones, as shown on Figure 4, are *nonflowing* (flow function [ff]<1), *very cohesive* (1<ff<2), *cohesive* (2<ff<4), *easy flowing* (4<ff<10), and *free-flowing* (10<ff).

As you can see in Figure 4, the flow function for a given powder (indicated by the blue line) can cut across several flow behavior zones. So, for instance, a powder that's free-flowing or easy flowing at higher consolidation stress levels can become cohesive or nonflowing at lower consolidation stress levels. Such lower stress levels correspond to a lower powder fill level in the vessel's hopper. The higher compaction forces from the powder's own weight when the vessel was full may have consolidated the powder in the hopper bottom, which can eventually prevent the powder from moving as the fill level reduces. For this reason, it's important to pay attention to your powder's flow function at lower consolidation stresses.

Many powders exhibit cohesive — or worse — behavior in vessels. Think of a snowball and what happens when you pack it together: It becomes hard, forms a lump, and doesn't want to fall apart until it hits something. Powder behavior in vessels is somewhat analogous: Once a cohesive powder is compacted, it may become nonflowing — the equivalent to a lump of powder in your hopper.

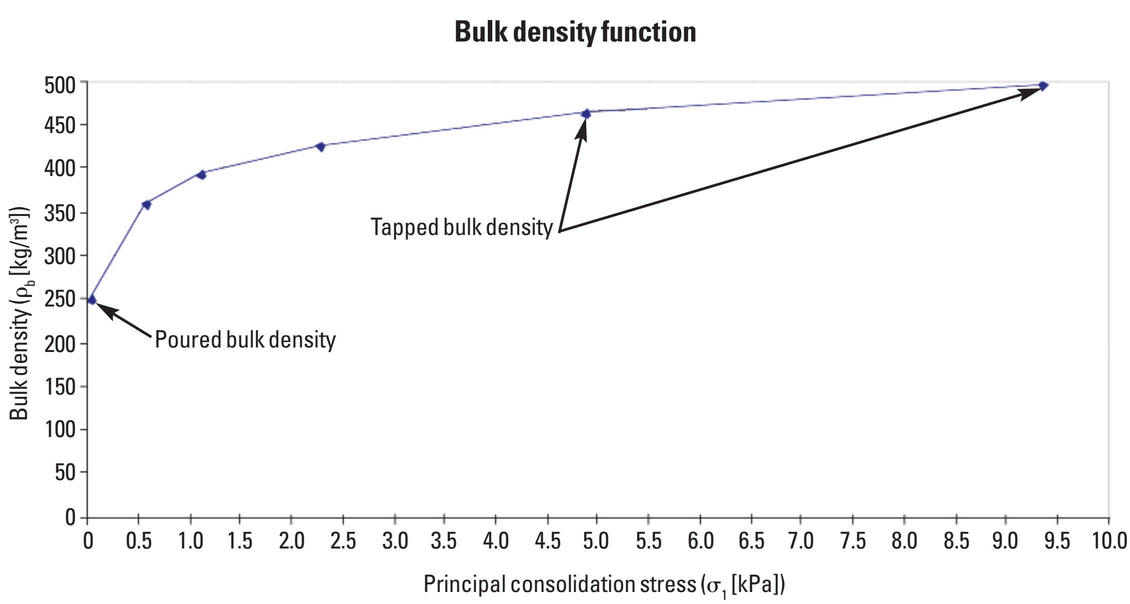
Arching dimension and rathole diameter. Two other calculations built into the shear cell tester's software — the arching dimension and rathole diameter — may provide a simpler indication than the flow function can of whether your powder is likely to exhibit flow problems.

One calculation computes the powder's arching dimension, a numerical value that indicates the powder's tendency to form a stable arch in the hopper. The arching dimension indicates how long the arch could be for your powder. If the hopper outlet is smaller than this value, then your powder could exhibit flow problems, such as flowing erratically or totally blocking the outlet. The other calculation gives your powder's rathole diameter, indicating the powder's potential for forming a rathole and the approximate width the rathole might have.

While both numbers provide quick reference points to alert you to potential flow problems with your powder, be aware that neither is a substitute for interpreting all the information in your powder's flow function.

Powder bulk density. Before you can analyze the data in your powder's flow function, you need to calculate the powder's bulk density for each compaction load applied during the shear cell test. Information needed for this calculation includes the known shear cell volume at the test's start, the powder's weight as measured by the operator before the test starts, and the powder's loose fill density, which is automatically calculated by the software. As the shear cell test progresses to each higher consolidation stress, the tester measures the shear cell's reduced volume and calculates a new density value. The resulting graph, called the *bulk density function,* as shown in Figure 5, shows how the powder bulk density increases from the loose fill density (called *poured bulk density* in the figure) as the consolidation stress increases to the *tapped bulk density.* This provides a convenient basis for comparing the results against results from another standard bulk density test, the *tap density test.* The final bulk density value

Figure 5



obtained at the highest consolidation load by the shear cell tester can be compared with the final density value obtained in the tap density test; ultimately, this could allow the shear cell tester to replace the lab's tap density test, saving time for the operator and better meeting the plant's needs for timely flow data.

Using the shear cell tester for other tests. The shear cell tester can also perform other powder characterization tests, including wall friction and time consolidation tests. In the *wall friction test,* the lid is constructed of the same material that will be used in the vessel hopper that stores the powder to evaluate the powder's ability to move against the hopper surface. In the *time consolidation test,* a variation of the flow function test, the instrument evaluates what happens to the powder when it's left in the vessel for a period equivalent to a plant shutdown, whether over a short lunch break or a weekend. As the powder sits in the vessel, it may continue to consolidate, and this test measures the impact this period has on the powder. The powder's flow function can shift upward during this test, meaning that the powder's flowability drops. **PBE**

For further reading

Find more information on powder flowability testing in articles listed under "Solids flow" in *Powder and Bulk Engineering*'s comprehensive article index (in the December 2009 issue and at *PBE*'s Web site, www.powderbulk.com) and in books available on the Web site at the *PBE* Bookstore. You can also purchase copies of past *PBE* articles at www.powderbulk.com.

Reference

1. A.W. Jenike, *Storage and Flow of Solids (Bulletin 123),* Utah Engineering Experiment Station, University of Utah, Salt Lake City, 1964.

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