Unconfined Yield Strength and the Flow of Powders and Granular Material

Powders and granular materials are made up of freely moving particles and air. For powders, the particles are small, ranging in size from nanometers to microns. For granular materials, the particles are typically in the millimeter size range. Because they are made up of freely moving particles and air, powders and granular materials exhibit properties of both solids and liquids. Under certain conditions, they may behave more like liquids and flow easily. Under other conditions, they may behave more like solids and not flow at all or even become solid. In order to understand their behavior, it is necessary to measure how powders and granular materials behave under different conditions.

The strongest factor influencing how a powder or granular material will behave is pressure. When powder particles are pushed together by pressure, called consolidating pressure, they tend to act more like solids. If enough consolidating pressure is applied, they may form strong bonds between particles or groups of particles or even become solid. When the consolidating pressure is removed, the powder may remain in a solid-like state. This behavior is typically referred to as caking. When caking occurs, force is required to break the bonds between the particles so the material again behaves as a powder or granular material.

Understanding how a powder or granular material responds to pressure is very important for industrial applications. The reason is that all powders and granular materials are stored under pressure. This pressure is generated by the material itself due to the force of gravity acting on the material. A powder particle at the bottom of a powder bed is subjected to the pressure formed by the weight of all of the powder particles above it. This pressure increases with bed height. Therefore, the pressure acting on the material is low in small bags and containers and increases as the storage container gets larger. Typically powders and granular materials respond to pressure by becoming more solid-like in their behavior. The time the material is subjected to this pressure also influences the response.

Anyone who has worked with powders or granular materials in industrial applications understands the consequences of solid-like behavior in a powder or granular material. The storage container is opened and the material does not flow out. If the storage container is a silo, the bottom of the hopper is opened and no material flows out. If the storage container is a drum, the drum is inverted and no material flows out. If the storage container is a bag, the bag is inverted and large chunks of material flow out. The longer the material is in the container, the worse the problem becomes.

For silos and hoppers, the problems of solid-like behavior have been well categorized. The main problems are referred to as “arching” and “rat-holing”. Arching (Figure 1) occurs when a powder or granular material forms a stable arch across the outlet of the hopper and prevents material from flowing out. Rat-holing (Figure 2) occurs when the material above the outlet forms a stable wall preventing material from falling into the outlet. For other types of storage containers, the problems are not as well defined. Typically they are referred to as caking and cover a range of behavior, including a material forming a complete solid mass, strong clumps or chunks of solid material forming in the material, and a certain percentage of powder particles sticking together.

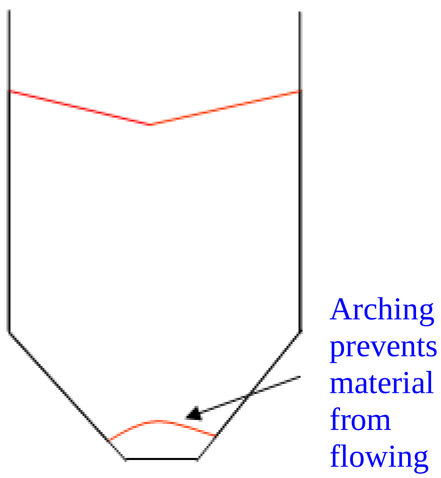

Figure 1: Arching

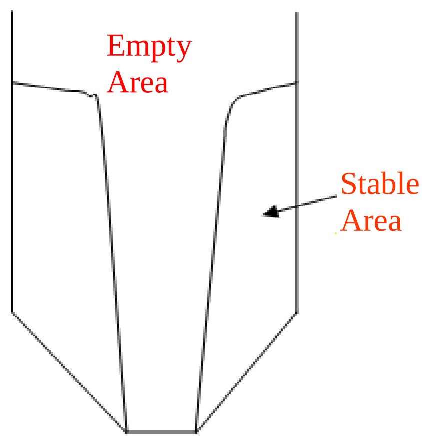

Figure 2: Rat-Holing

The manner in which a material flows from a container is also influenced by its response to pressure. Again for silos and hoppers this flow behavior has been well categorized into two basic categories, “core flow” and “mass flow”. Core flow (Figure 3) describes behavior in which the material flows down a middle channel of the silo from the top down. Material at the walls of the silo does not move until the surface of the material is at the same height. This creates a first in last out cycling of material with the material entering the silo at the beginning of filling not exiting until the silo is completely empty. Mass flow (Figure 4) describes a behavior in which the material flows along the entire cross section of the silo. Material at the walls moves at the same speed as material near the center. This creates a first in first out cycling of material.

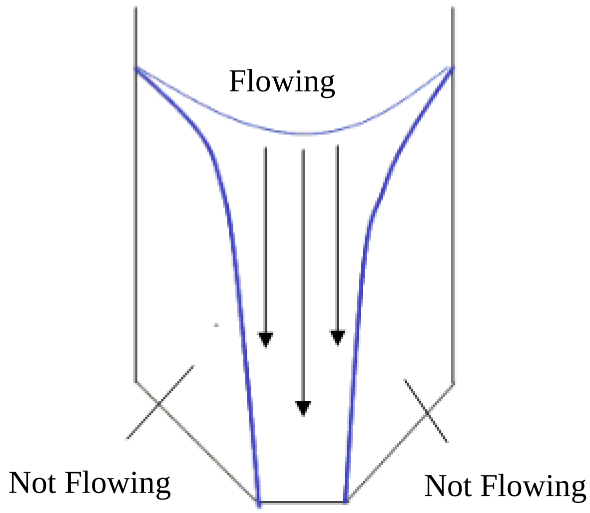

Figure 3: Core Flow

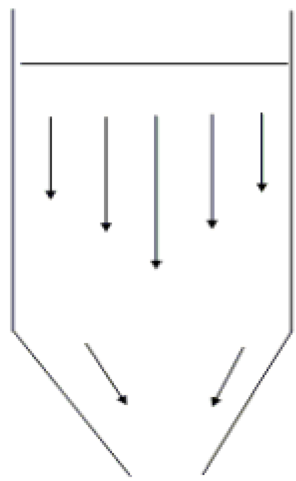

Figure 4: Mass Flow

Clearly measuring a powder or granular material's response to pressure is critical for controlling and predicting its behavior in industrial applications. There are many test methodologies for this but the simplest, easiest to understand, and most full-proof is the Unconfined Yield Strength test. The Unconfined Yield Strength test measures the strength a powder or granular material retains at a stress free surface after compression to a given pressure. In order for a powder to flow, the force acting on it must be greater than the strength of the powder at the outlet, as in the arching example in Figure 1. If the powder strength is stronger than the downward force due to the wright of the powder above it, an arch will form and block the outlet.

The Unconfined Yield Strength tests consists of three steps: 1) Consolidation in test cell (Figure 5); 2) removal from test cell (Figure 6); 3) strength analysis (Figure 7). Sample material is filled into a cylindrical mold and pressure is applied to the top of the sample. This pressure is referred to as the Major Consolidation Stress $\sigma 1$ and is chosen to match the pressure that the material will be under in the application. After some time, the pressure is removed and the consolidated sample is removed from the cylindrical mold so it is free standing. This is referred to as an unconfined sample as no walls are confining it to a fixed shape. Then increasing pressure is slowly applied to the top of the sample until the sample breaks or yields. The maximum pressure before the sample yields is referred to as the Unconfined Yield Strength σc . The Unconfined Yield Strength is the strength of the powder mass after it has been compressed by the Major Consolidation Stress. This means that the material will flow only if the force acting on it is greater than its unconfined yield strength.

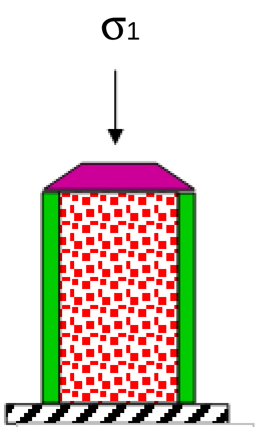

Figure 6: Major Consolidation Stress

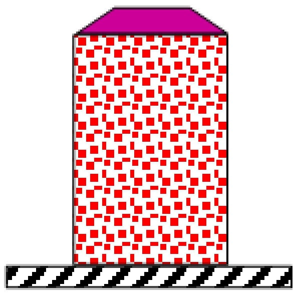

Figure 7: Unconfined Sample

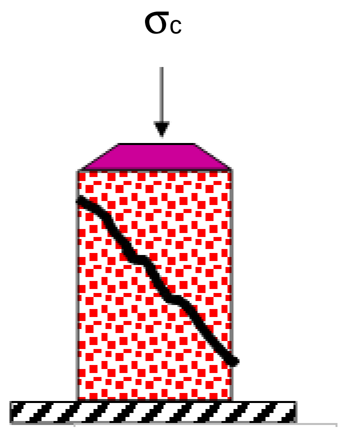

Figure 8: Unconfined Yield Strength

To have meaning, the unconfined yield strength must be expressed in combination with the major consolidation stress. The reason is that powders and granular materials typically gain strength when consolidated with more pressure. A flow factor can be calculated by dividing the major consolidation strength by the unconfined yield strength. The greater the value of the flow factor the better the material will flow at any given pressure. Table 1 presents generally accepted classification of powders and granular materials with different flow factors.

Flow Factor	Classification
< 1	Not flowing
1 < ff < 2	Very Cohesive
2 < ff < 4	Cohesive
4 < ff < 10	Easy Flowing
< 10	Free Flowing

Table 1

A plot of the unconfined yield strength σc versus the major consolidation stress $\sigma 1$ is referred to as a flow function and represents the material's flowability under a wide range of pressures. Flow functions are excellent for understanding and predicting a powder or granular material's behavior in a wide range of equipment. In addition, the unconfined yield strength of a powder or granular material typically increases the longer it is under the major consolidation stress. For this reason, it is very important to measure the time unconfined yield strength for materials that will be stored for any length of time. A plot of the time unconfined yield strength versus the major consolidation stress is typically called the time flow function. Flow functions can also be created for different environmental conditions like relative humidity and temperature extremes.

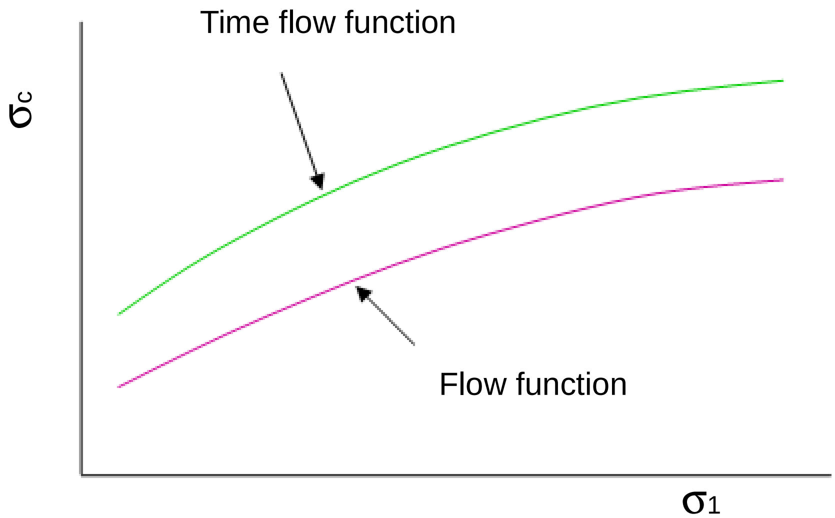

Figure 9: Flow Function and Time Flow Function

Flow function data can be plotted against the categories in Table 1 to give a presentation of the flow of a real material as compared to idealized categories. The behavior of real materials may be linear or not and may cross from one flow category to another depending on the slope of its flow function (Figure10). This is why flow tests must be run under application conditions. Time of compression, temperature, and humidity can all move the material into a poorer flowing category. A material that is easy flowing after a five minute compression can be cohesive or very cohesive after one or two hours.

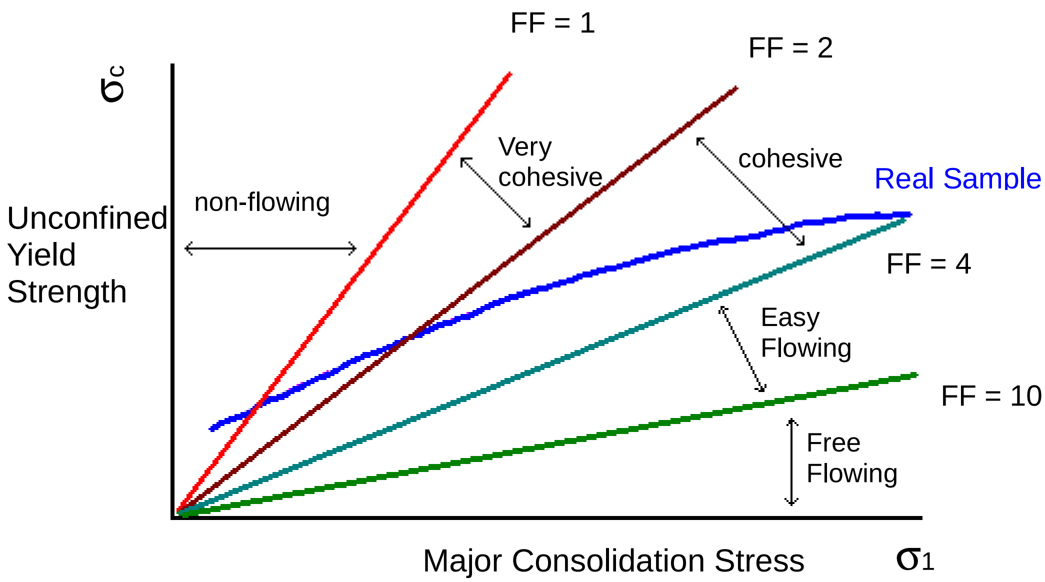

Figure 10: Real flow function relative to idealized behavior

From the flow function and time flow function several additional values can be calculated. These tend to be index type values that allow easy comparison between samples. They are useful but should be used with caution as their meanings depends on the situation in which the are used and the geometry of the powder handling equipment. Two additional calculated values include:

1) estimated critical arching dimension, the minimum outlet size for reliable mass flow gravity discharge.

$$D_C = \frac{2 * \sigma_C * 1000}{\rho_B * g}$$

Conical Hopper

$$D_P = \frac{\sigma_C * 1000}{\rho_B * g}$$

Wedge Hopper

σ_c is calculated at the intersection of the flow function with a flow factor stress line, typically ff = 1.4

2) estimated critical rat-holing dimension, the minimum outlet dimension to prevent the formation of a stable rat hole in core flow;

$$D_{RH} = \frac{2 * \sigma_C * 1000}{\rho_B * g}$$

σ_c is calculated at the intersection of the flow function with a flow factor stress line, typically ff = 2.5

The unconfined yield strength, flow function and time flow function are very useful in predicting and controlling the behavior of powders and granular materials. Their uses include:

1) Comparing the flow properties of one powder to another to select the best material for the application;
2) maintaining the specified flow behavior of a material over all batches or during continuous production;
3) formulating new powders and granular materials to have the best flow properties possible for the application
4) Avoiding putting a poorly flowing material into an application and causing a shutdown or process problem
5) ensuring that flow properties of a material do not degrade under normal storage conditions and time.

In general, powders and granular materials with low unconfined yield strengths and flat flow function are the easiest to handle. They form only weak arches in hoppers, tend not to rat-hole and also exhibit mass flow at lower angles in hoppers and silos. Weaker materials also form less clumps and aggregates on storage meaning that they are more stable and easier to control. Therefore it is generally best to select or design powders and granular materials with low unconfined yield strength. However, this may not be possible due to the application requirements. In this case, the unconfined yield strength and flow function is useful for setting pressure limits, maximum storage times, and handling requirements to avoid problems.

Evolution Powder Tester Overview

The Evolution Powder Tester (EPT) is an economical and easy to use powder flow tester that measures the unconfined yield strength of a material (a critical flow property) at pressures up to 500kPa. The unconfined yield strength can be measured at one pressure or at many different pressures in order to create a flow function. The flow function presents the material's gain in strength as more pressure is applied to it. The Evolution Powder Tester is the perfect powder tester for measuring the flowability and compressibility of materials in low to high stress situations such as silos and storage containers. The system also measures how materials react to the storage conditions over time.

The Evolution Powder Tester (EPT) offers many advantages over traditional shear and other uni-axial testers. The EPT is a standalone instrument designed just for powder testing and is not an accessory to a general purpose instrument. This allows the design to be cost effective, easy to operate and suitable to any laboratory or manufacturing environment. In addition, it takes approximately 3 minutes for a user to test one sample. This is significantly less testing time than other shear or uni-axial testers. With the EPT, time consolidation tests can be performed with sample cells and weights that allow a material to be subjected to various pressures over long periods of time. The EPT time cells are designed so that they can be easily placed in ovens or humidity chambers to study their effects on materials in storage situations. Studying the effects of humidity and pressure over long periods of time are difficult with traditional shear testers and uni-axial testers. The analysis cells for many these instruments are very expensive and do not include the means of applying pressure for significant periods of time.

The Evolution Powder Analyzer uses uni-axial compression to assess the flowability of powders. The operator begins the flowability test by filling the analysis cell with either 25 cc or 75cc of sample. The cell is then placed in the Evolution and the material is compressed to a predefined pressure. This pressure is referred to as the major consolidation stress. This stress can also be applied using weights over a long period of time to measure the effects of time, humidity, and temperature.

After compression, the Evolution removes the sample from the cell and applies force to the material until it breaks. The pressure required to break the sample is the unconfined yield strength. The unconfined yield strength represents the force required to make the material flow. A flow factor can be calculated by dividing the major consolidation strength by the unconfined yield strength. The greater the value of the flow factor the better the material will flow at any given pressure. A plot of the unconfined yield strength versus the major consolidation stress is referred to as a flow function and represents the material's flowability under a wide range of pressures.