Pressure Distribution of Stored Bulk Solid Materials

Many bulk solids, such as powders or granular materials, experience extended time periods of static storage in bags or sacks of various shapes and sizes. The storage may take place on the production floor immediately after processing, in holding areas awaiting further movement, during transport to another destination, or in warehouses for long term holding. Unfortunately some powder materials can gain significant strength over time under storage pressure, thereby leading to a product that will not discharge from the sacks or bags when required.

One instrument that has the ability to predict this type behaviour is the Brookfield Powder Flow Tester (See Figure 1). Using shear cell technology, this device shears a small sample of the powder to measure the frictional forces acting between the powder particles.

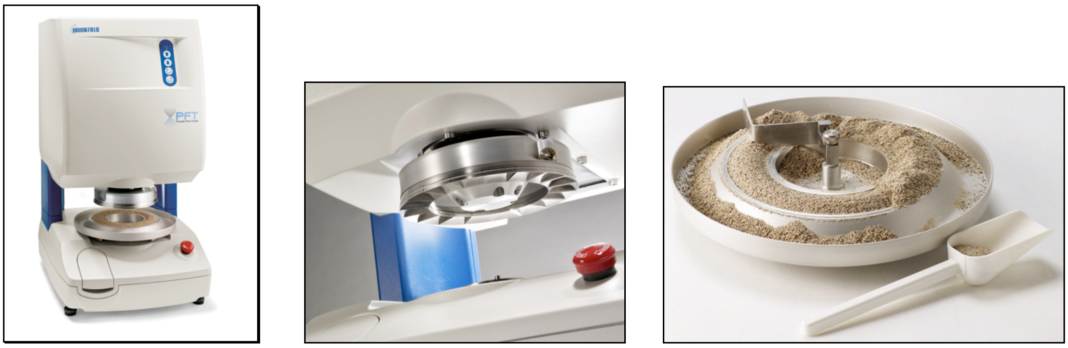


FIGURE 1: Brookfield Powder Flow Tester Is an Example of Shear Cell Technology
Brookfield Vane Lid and trough with powder sample

When the measured force exceeds gravity, there is the possibility that the powder has gained sufficient strength to resist flow. If the powder strength becomes sufficiently high enough, then the powder may harden to a point where it behaves almost like a solid. The test method involves a scientific approach described in several ASTM procedures (D6128, D6337, D6728). Powder is compressed to increasingly higher levels of compaction, then sheared in each case to determine the failure strength of the powder.

The Brookfield Powder Flow Tester, utilizing its easy to use Powder Flow Pro software, realizes a resulting graph called the “Flow Function” (See figure for flow function graph). This shows how the powder gains strength as the consolidating stress increases. A corollary to this test is the Time Consolidated Flow Function test which shows how a bulk solid material will consolidate over a certain time period up to 60 hours.

The Time Consolidated Flow Function test is a useful analytical tool for predicting how the powder can build strength over time when left in a storage container. Physics tells us that gravity is constantly at work in a column of powder, causing the powder particles to settle and fill the void spaces. The Time Consolidated Flow Function test can be repeated on a powder sample that has been allowed to remain static for any period of time. The time interval can be chosen to reflect the storage conditions.

The change in position of the Flow Function gives an indication of how rapidly the powder will build strength in a static situation. For example, Figure 2 shows the same sample of powder tested with a standard Flow Function test and then with a Time Consolidated Flow Function. The Flow Function graph shows how this same sample of powder increased in cohesiveness with time.

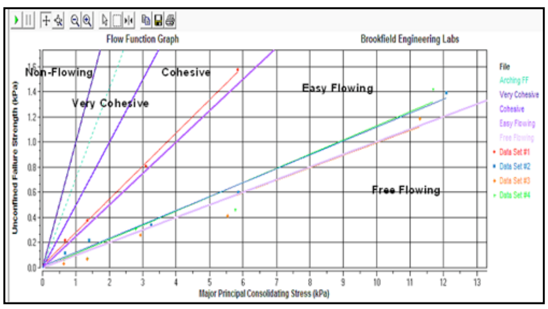


FIGURE 2 Time Consolidation Test and Standard Flow Function Test on Same Sample

Another integral part of the Flow Function test method, when using the shear cell, is to measure the bulk density of the powder. This is done automatically when running a Flow Function or Time Consolidated Flow Function test with the Powder Flow Pro software. Figure 3 shows how bulk density increases from a “loose fill" condition to a higher value as a function of consolidating stress. You can think of consolidating stress as the growing pressure applied to a column of powder as the height of the column increases. This means that the pressure at the bottom of the stack will get higher as more sacks are added.

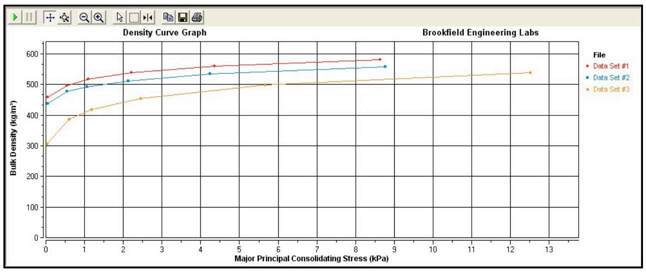


FIGURE 3: Bulk Density Curve for Powder vs. Consolidating Stress

Shear Cell Testers can be used to calculate the consolidation pressure acting through a stack of bags on a pallet as shown in Figure 4. This analytical approach can be used to determine the stack height above which flow problems will occur after a given time period as show in Figure 4a. Alternatively, for soft or plastic particles, the PFT can determine the pressure or stack height above which flow problems should be expected as shown in Figure 4b.

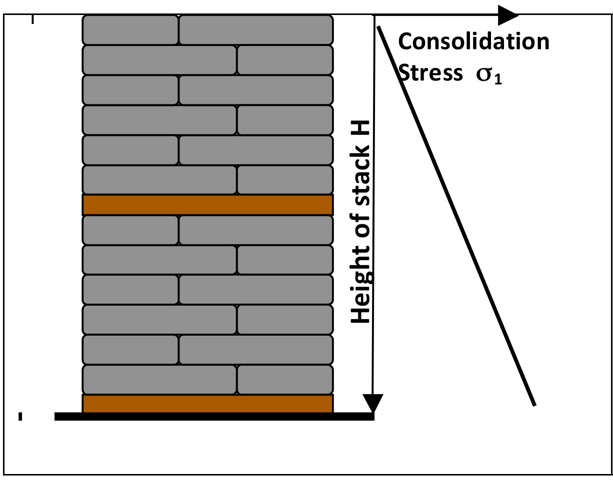


Figure 4: illustrates a stack of sacks on pallets. The vertical consolidation stress at the base of the stack of bags can be determined using the equation below:

$$\sigma_1 = \rho_b \cdot g \cdot H$$

<u>Note that this equation is valid only for flexible walled vessels (bags) and not for rigid silos</u>

Where:	s_1	Vertical consolidation pressure in the stack of bags	Pa
	g	Acceleration due to gravity	ms^{-2}
	r_b	Compacted Bulk Density of the powder	kgm^{-3}
	H	Total height of the stack of bags	m

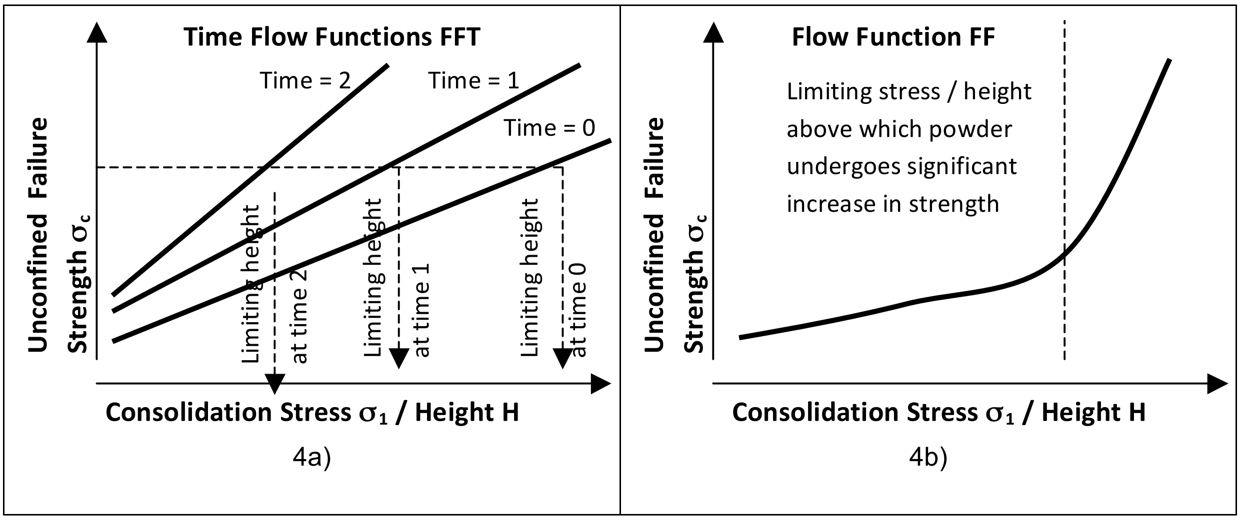
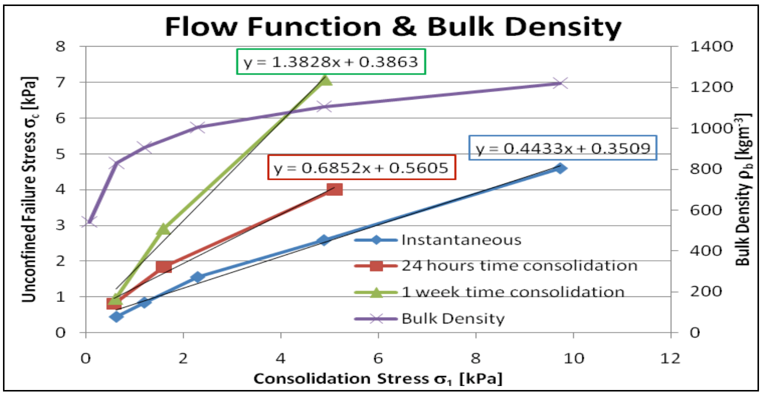


FIGURE 4a shows the Time Flow Functions of a powder illustrating the limiting stack heights as a function of storage time period. **FIGURE 4b** shows the Flow Function of a powder illustrating limiting stress /stack height above which material undergoes a rapid increase in strength.

Example calculations

1.) Instantaneous and time flow function of a powder exhibiting severe time consolidation, indicating the limiting safe stacking heights as a function of storage time. (Note that this is an approximate calculation). The flow function of a material has been measured for instantaneous and two time consolidation periods, 24 hours and 1 week. The flow functions and bulk density function are presented in the figure below. To determine the maximum stacking heights as a function of storage time, first estimate the maximum unconfined failure strength or arch span.



Assuming that the maximum arching dimension is 0.5m for reliable flow into the process. Use the arching dimension equation to determine the maximum level of unconfined failure strength, assuming the maximum measured bulk density, in this case 1200kgm^{-3}.

$$\sigma_c = \frac{B \cdot \rho_b \cdot g}{2000}$$ Thus $$\sigma_c = \frac{0.5 \times 1200 \times 9.81}{2000} = 2.9$$

To determine the limiting consolidation stress that can be achieved at each time period substitute the limiting unconfined failure strength into the linearised flow function equations

$$\sigma_1 = \frac{\sigma_c - c}{m}$$ Thus for instantaneous conditions $$\sigma_1 = \frac{2.9 - 0.3509}{0.4433} = 5.75$$

Where m is the gradient and c is the intercept of the best linear fit flow function

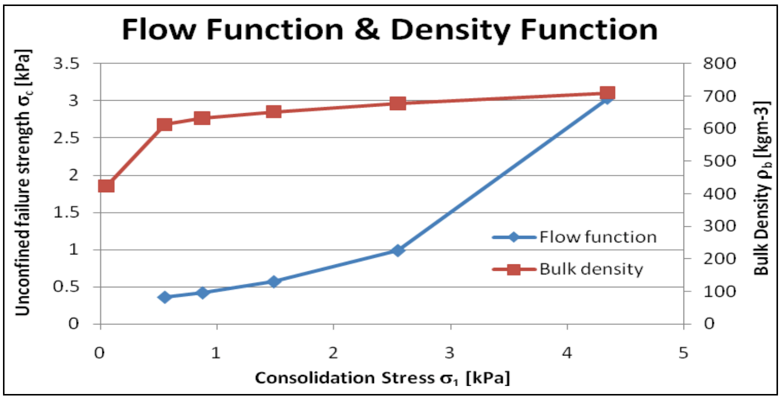
The limiting stack heights are calculated by rearranging the hydrostatic stress equation to make the height the subject and solving for the consolidation stress and maximum bulk densities for each of the relevant time periods. For the instantaneous condition, the limiting stack height is

$$H = \frac{\sigma_1}{\rho_b g}$$ Thus $$H = \frac{5.75 \times 1000}{1200 \times 9.81} = 0.49$$

Thus for instantaneous conditions the limiting stack height is 0.49m. The limiting consolidation stresses and equivalent stack heights for 24 hour and 1 week storage times are presented in table 1 below.

	Instantaneous (time = 0)	24 hour static storage	1 week static storage
Consolidation stress s1 [kPa]	5.75	3.41	1.89
Height of powder H [m]	0.49	0.29	0.16

2.) Flow function of a pressure sensitive material indicating the maximum safe stacking height (Note that this is an approximate method). The measured flow function and density function of a soap powder are presented in the figure below.



The flow function shows a significant increase in strength between consolidation stresses of approximately 2.5 and 4.3kPa, the effective head material that this stress range represents is calculated as follows:

Assume the maximum measured bulk density from the density function, in this case 710kgm^{-3}. Rearrange the hydrostatic stress equation to make the depth the subject. Calculate the depths required to generate consolidation stresses of 2.5 and 4.3kPa.

$$H = \frac{\sigma_1}{\rho_b g}$$ Thus $$H = \frac{2.5 \times 1000}{710 \times 9.81} = 0.36$$ and $$H = \frac{4.3 \times 1000}{710 \times 9.81} = 0.62$$

Thus the critical stack height above which this soap powder develops significant strength is between 0.37 and 0.62m.

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