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New Methods for Assesing the Frictional Properties in a Mass of Consolidated Powders

The increasing of the necessity of metallic powders in many branches of industries make necessary researches regarding the powder properties. The powder behaviour is dominate by external conditions such as forces, strength stresses, surfaces and their orientations and interactions. The paper shows the physico-mathematical model for the stress state and the shear surfaces studies. It is showed the methodology and apparatus used for researches and some considerations regarding the results interpretation.

Keywords: *powder metallurgy, flow properties, powder characteristics*

1. INTRODUCTION

The chemical industry handles and processes more than 1 trillion pounds of material in particulate form annually. To stay competitive, plant engineers and managers must gain an understanding of the mechanical behavior of these powders.

The powder attributes that will dominate during a given process depend on the dominant external conditions such as forces, displacements, surfaces and their orientations, and interactions.

Regardless of the application, all three attributes — solid-, liquid- and gas-like — must be considered during the design, development and analysis phases of processes and equipment involving powders. Therefore, the theoretical framework and the measurement method must consider and deal with these attributes. Pure solid, fluid and gas theories, when applied to powders, generally lead to disastrous consequences. No one theory can address all of the characteristics of the diverse set of chemical powders, processes and applications. However, one theory - the Mohr-Coulomb model - has been applied effectively to numerous chemicals to adequately characterize the flowability for a large number of applications.

2. PHYSICAL AND MATHEMATICAL MODEL

The Mohr-Coulomb model belongs to a class of theories commonly known as limit state theories. These "go/no-go" theories, when applied correctly, accurately predict the flow behavior of the powder mass.

For a powder to flow, the Mohr-Coulomb model states that the stress state at every location within a powder mass must correspond to that of the incipient flow condition. When this condition is fulfilled, even the most difficult chemical powder will flow. Fortunately, the plant need not consider or analyze every point within the powder mass; only the most critical location(s) must be analyzed carefully. For example, this usually occurs at the outlets such as the withdrawal ports in bins and hoppers.

A powder is said to be in an incipient flow state when the powder mass yields. Yielding can be considered to be the combination of stresses, usually normal and shear that will result in powder flow with a small increase in shear stress. Generally, normal stress is responsible for keeping the powder mass intact, and shear is responsible for producing motion (flow).

The combination of shear and normal stresses that will result in flow cannot be determined from past experience; it is powder-specific. The Mohr-Coulomb model approximates the combinations of shear and normal stress with a straight line, as shown in Fig. 1.

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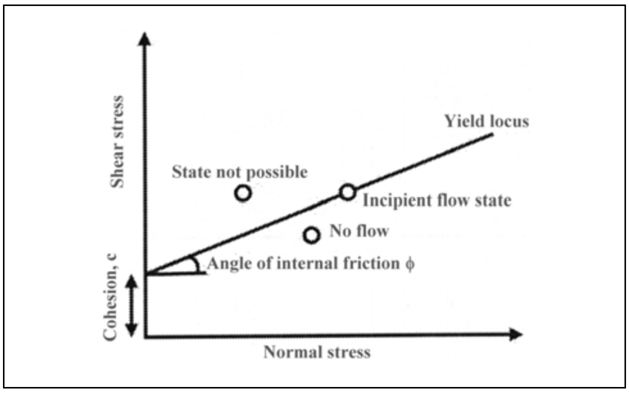

Figure 1: The Mohr-Coulomb model shows the yield locus line and material parameter

This limiting straight line also is referred to also as the yield locus. The mathematical form for the Mohr-Coulomb model is given in Equation 1. If every point in the powder mass is on the yield locus, the powder is in a ready-to-flow, or incipient flow, state.

$$\tau = c + tan(\varphi)\sigma \qquad (1)$$

where:

τ = shear stress in kPa or psi

σ = normal stress in kPa or psi

φ = angle of internal friction in degrees c = cohesion in kPa or psi

Therefore, for flow to occur the applied shear stress must be at least as large or larger than that obtained from calculations using Equation 1.

It is common knowledge that a straight line can be characterized by two parameters: intercept and slope. For the Mohr-Coulomb model, these two parameters have well-defined physical interpretations. The intercept is a measure of the powder's cohesion, and the slope quantifies the internal friction (Fig.1).

Moisture, chemical reaction, temperature, electrostatic charges and van der Waals forces are but a few of the factors responsible for cohesion. Internal friction, usually written in terms of the angle, is a measure of the ease with which the powder particles will slide on one another.

2.1. Measurement methods and apparatus

The focus within this article is the state-of-the-art CCSC. The methodology discussed for the CCSC is very similar to that used by the Jenike and rotational shear cells.

A schematic of the CCSC is shown in Fig.2. The CCSC consists of three rings: the base, top and mold rings. The rings are approximately 80 millimeters (mm) in diameter and 12.5 mm high. The powder is deposited in the rings with a spoon; the powder is leveled gently as the test cell is being filled.

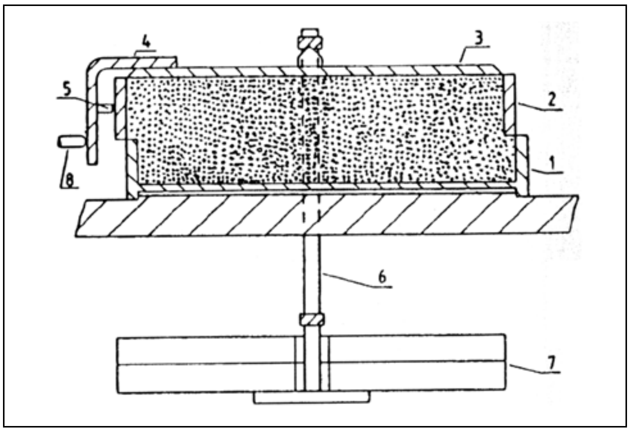

Figure 2: The schematic appearance of CCSC

After filling, a normal stress, called consolidation stress, is applied to the powder mass. Subsequently, 90-degree twists are made in the horizontal plane to critically consolidate the powder sample. The number of twists is a function of the powdered material. A typical response of the powder to twisting is shown in Fig.3.

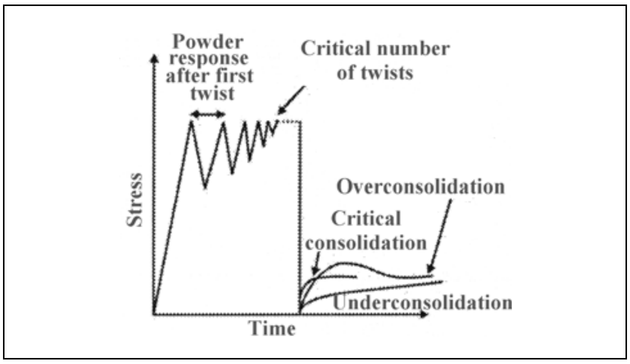

Figure 3: Powder response to twisting

Twisting is performed to critically consolidate the sample and to produce the same initial state in the powder mass for every replicate test.

A critically consolidated powder sample will reach the steady-failure state in the shortest possible travel time or length. After critical consolidation of the sample, the mold ring is removed, excess powder is scraped, and normal stress is reapplied.

Next, pushing (or pulling) shears the powder sample on the top or bottom ring. Generally, the recommended ring speed is between 0.5 mm/minute (min.) to 3 mm/min. During ring motion, the shear stress builds and reaches a steady value (Fig. 3). This is the steady-state point (SSP).

The powder's incipient flow behavior at this normal (or consolidation) stress has been established.

Immediately after the SSP, the lid is permitted to lift as the powder continues to be sheared. This results in a decrease of the normal stress while the shear stress is declining. This is the powder's dynamic yield locus.

The values of normal stress σ_{pre} and shear stress τ_{pre} form the steady state-flow in the σ,τ-diagram (figure 4, right diagram).

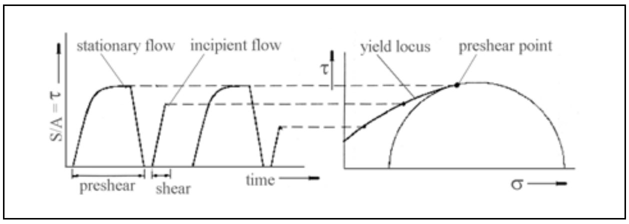

Figure 4: *Plot of shear stresses, yield locus*

Afterwards, the sample is sheared again with a reduced normal stress $\sigma_{sh} < \sigma_{pre}$. This process is called "shear". Since the sample is now sheared under a smaller normal load than at preshear, it will start to flow (break) at a certain shear stress (similar to the breakage of the sample in the uniaxial test, where the horizontal load is reduced to zero by taking away the hollow cylinder in the second step, figure 3). As was previously shown, a bulk solid starts to flow when the Mohr stress circle representing the actual stress state touches the yield locus. The start of flow is connected to a decrease in the bulk density and a corresponding reduction of the shear stress (see figure 4). The maximum in the plot of the shear stress vs. time indicates the start of flow. The corresponding normal and the shear stresses describe a point on the yield locus in the σ,τ-diagram. If several samples of bulk solid are presheared under the identical normal stress σ_{pre} but sheared under different normal stresses $\sigma_{sh} < \sigma_{pre}$, the course of the yield locus in the σ,τ-diagram can be determined.

The parameters which describe the flow properties can be determined from the yield locus (figure 8). The relevant consolidation stress σ_1 is equal to the major principal stress of the Mohr stress circle, which is tangential to the yield locus and intersects at the point of steady state flow ($\sigma_{pre},\ \tau_{pre}$). This stress circle represents the stresses in the sample at the end of the consolidation procedure (stresses at steady state flow). The unconfined yield strength ac results from the stress circle which is tangential to the yield locus and which runs through the origin (minor principal stress $\sigma_2 = 0$). This stress circle represents the same stress state as the one which prevails in the second step of the uniaxial compression test (Stress circle B3, figure 4). In contrast to the uniaxial compression test the unconfined yield strength σ_c has to be determined on basis of the yield locus and does not follow directly from the measurement.

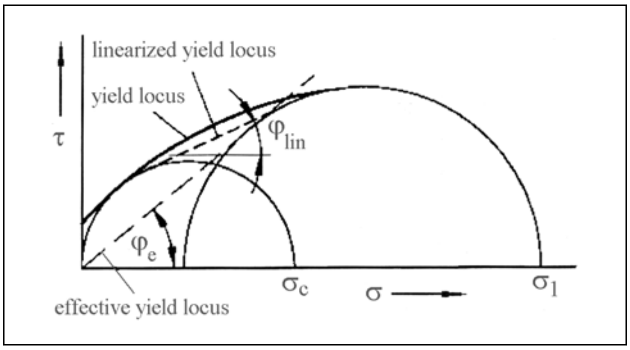

Figure 5: Yield locus

The tangent at the largest Mohr stress circle is called the effective yield locus. It encloses the σ-axis with the angle φ_e (effective angle of internal friction). Because the largest Mohr stress circle indicates a state of steady state flow, the angle φ_e can be used as a measure of the internal friction at steady state flow.

The angle of internal friction φ_i is defined as the local slope angle of the yield locus. Because the yield locus is curved instead of straight, the internal friction angle varies along the yield locus. It is sufficient for most applications to state one internal friction angle. In this case, the internal friction angle is defined by the slope φ_{lim} of the linearized yield locus. The linearized yield locus results from the tangent common to both Mohr stress circles shown in figure 4.

During the normal stress reduction, i.e., lifting of the lid, a series of failure or yield states are maintained in the powder mass. The lid lift speed is a function of the powder. The recommended values are from 0.1 mm/min. to 0.25 mm/min. A test has been completed successfully.

2.2. Integrating measurement and models

From the shear stress-normal stress data, the cohesion and angle of internal friction can be calculated using linear regression. Because the cohesion and angle of internal friction are functions of consolidation (normal) stress and to allow uniform comparisons with other materials, two derived parameters are calculated: the unconfined yield strength and the major consolidation (or principal) stress.

The unconfined yield strength (σ_c) is a measure of the strength of the powder mass when the powder experiences major consolidation stress (σ_1).

Unconfined yield strength is, therefore, the shear stress needed to fail or fracture the consolidated powder mass to initiate powder flow.

Both the unconfined yield strength and major consolidation stress are related to cohesion, angle of internal friction and the powder's SSP. Equations 2 and 3 can be used to determine the two stresses, σ_c and σ_1, respectively.

$$\sigma_c = \frac{2c(1+\sin\varphi)}{\cos\varphi} \tag{2}$$

$$\sigma_1 = \left(\frac{A-\sqrt{A^2\sin^2\varphi-\tau_{SSP}^2\cos^2\varphi}}{\cos^2\varphi}\right)(1+\sin\varphi)-\left(\frac{c}{\tan\varphi}\right) \tag{3}$$

where:

A = σ_{SSP} + (c/tan φ)

Subscript SSP designates the value at the steady state point.

Each consolidation or normal stress will produce a unique pair of unconfined yield strength and major consolidation stress values. When such pairs are plotted using unconfined yield strength vs. major consolidation stress, the resultant graph is called the flow function (FF) plot. A flow function is a quantitative measure and visual display of flowability of powders. Often, a flow index value for a powder is calculated using the inverse value of the slope of the FF plot. The position and orientation of the FF curve for a given powder provide useful information about the ease (or difficulty) with which the material will flow. Generally, the closer the powder FF is to the x-axis (major consolidation stress axis), the more easily the powder will flow.

The wall friction, i.e. the friction between a bulk solid and the material used for the wall of, for example, a silo, is important for the design of silos. On one hand the wall friction is necessary for the static design of the silo, on the other hand it is necessary when designing the steepness of a hopper, a chute, etc. The measurement of the wall friction can also be carried out using the Jenike tester. In such a case the bottom ring is replaced by a sample of the wall material which has to be examined (figure 6). The shear force or the shear stress τ_w which are necessary to move the shear cell with the bulk solid across the wall material are measured under different normal stresses σ_w.

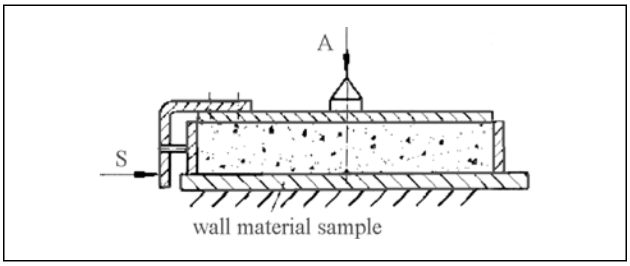

Figure 6: Measurement of wall friction with the Jenike shear tester

If the measured pairs of values (σ_w, τ_w) are plotted on a σ_w, τ_w-diagram, then the result of connecting the measured points is the so-called wall yield locus. A straight line through the origin as shown in figure 7 occurs frequently. The wall friction angle φ_x comes from the resulting slope of the wall yield locus. If the wall yield locus is not a straight line or does not run through the origin, then the wall friction angle φ_x depends on the wall normal stress σ_w.

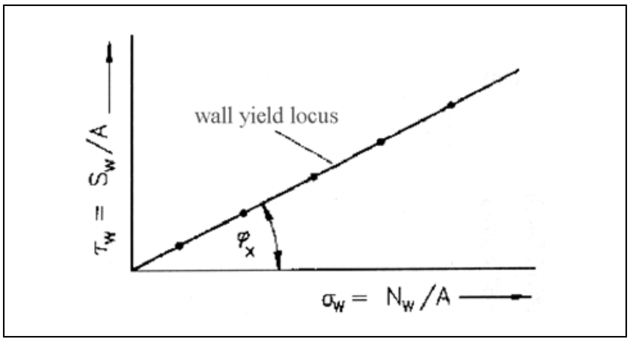

Figure 7: Wall yield locus

In this case it has to be calculated for each wall normal stress from the ratio of wall shear stress and wall normal stress:

$$\tan(\varphi_x) = \frac{\tau_w}{\sigma_w} \tag{4}$$

All kind of wall materials (e.g. concrete, mild steel, stainless steel, aluminum), coatings or liners can be tested with the device shown in figure 6. It is possible to decide whether or not the polishing of the wall surface or the use of a liner would have advantages in the flow of the bulk solid on the basis of the relatively simple wall friction measurement.

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