

Flow Properties of Powders and Bulk Solids and Silo Design for Flow

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Flowability

The phrase "good flow behavior" usually means that a powder or bulk solid flows easily. Products are "poorly flowing" if they experience flow obstructions (arches or pipes, figure 1), or consolidate during storage or transport. The reason for the latter is the compressive strength (unconfined yield strength) of a bulk solid.

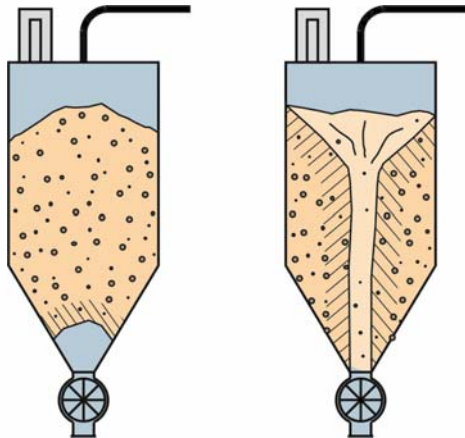


Fig. 1: Arching (on the left), piping (on the right)

Figure 2 shows a hollow cylinder with frictionless walls, filled with a fine-grained, cohesive bulk solid. First the bulk solid is consolidated by the consolidation stress σ_1 . Subsequently the hollow cylinder is removed and the cylindrical bulk solid specimen is loaded with an increasing vertical compressive stress until the specimen breaks (fails). The stress causing failure is called compressive strength or unconfined yield strength σ_c .

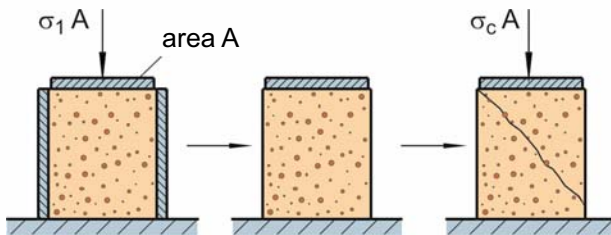


Fig. 2: Measurement of unconfined yield strength

The unconfined yield strength σ_c typically increases with consolidation stress σ_1 . Curve A shows the typical increase of unconfined yield strength σ_c in dependence on consolidation stress σ_1 (figure 3). Usually the ratio ff_c of consolidation stress σ_1 to unconfined yield strength σ_c is used to characterize flowability numerically:

$$ff_c = \sigma_1 / \sigma_c \quad (1)$$

The larger ff_c , the better a bulk solid flows. Often the following classification is applied:

$ff_c < 1$	not flowing
$1 < ff_c < 2$	very cohesive (to non-flowing)
$2 < ff_c < 4$	cohesive
$4 < ff_c < 10$	easy-flowing
$10 < ff_c$	free-flowing

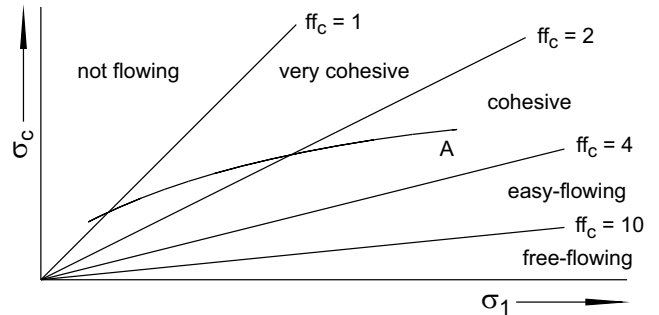


Fig. 3: Unconfined yield strength in dependence on consolidation stress; lines of constant flowability ff_c

Additionally, in figure 3 the boundaries of the ranges of the classifications listed above are shown as straight lines. The ratio ff_c and thus the flowability of a specific bulk solid change with consolidation stress σ_1 . Therefore, for flowability measurements testers are required which make possible the adjustment of defined consolidation stresses. This is fulfilled by appropriate shear testers.

Ring shear tester

Typical shear testers are the Schulze Ring Shear Testers (figures 4 and 5) [1,3] which are widely used in industry and research.

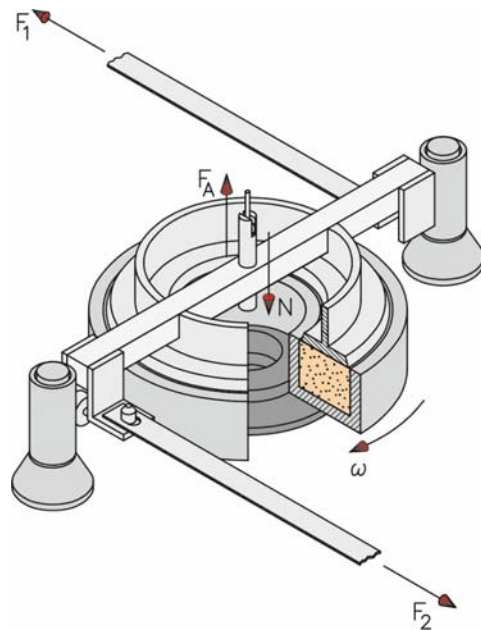


Fig. 4: Ring Shear Tester (shear cell, in principle)

The bulk solid specimen (figure 4) is contained in an annular shear cell ("ring") and loaded from the top with a vertically acting force N through the lid in order to adjust the stress level. During testing the shear cell rotates slowly in direction of arrow ω , while the lid is prevented from rotation by two tie rods. Thereby the bulk solid specimen is sheared. Forces (F_1+F_2) acting in the tie rods are measured. From the results of a prescribed test procedure the flow properties of the bulk solid are calculated [1,2,3].

With the automatic Ring Shear Tester RST-01.pc (figure 5, right) the test procedure, including loading of the specimen and shearing, and also the evaluation are performed computer-controlled. For very small samples of fine powders as occurring, e.g., in pharmaceutical industry, the smaller automatic Ring Shear Tester RST-XS.s is available, which is also operated computer-controlled (figure 5, left).



Fig. 5: Computer-controlled Ring Shear Testers RST-01.pc and RST-XS.s

Advantages of Ring Shear Testers RST-01.pc and RST-XS.s are:

- Measurement of well defined flow properties, e.g., flowability, caking, bulk density
- Different stress levels.
- Easy operation.
- Automatic testing & evaluation.

Thus a Ring Shear Tester is an advantageous alternative to so-called simple flowability testers, since it is easy to operate, whereby nevertheless clearly defined physical quantities are measured [2,3].

Flow of bulk solids in silos

When a silo is discharged, two different flow patterns can prevail: mass flow and funnel flow (figure 6) [3,4]. In case of mass flow the whole silo contents, i.e., every particle, move during discharge. Mass flow is only possible if the hopper walls are sufficiently steep and/or smooth. If the latter is not the case, funnel flow prevails. In case of funnel flow, only a portion of the bulk solid in the silo moves downwards during discharge while the rest of the bulk solid remains stationary thus forming stagnant zones.

The most frequent problems emerging when powders or bulk solids are stored or discharged are [3,4]:

- Arching (figure 1)
- Piping (figure 1)
- Irregular flow and flooding
- Broad residence time distribution: The bulk solid in the stagnant zones of a funnel flow silo remains in the silo for extremely long time periods
- Segregation due to particle size, density or shape, which leads to an unsteady product composition at the outlet in funnel flow silos

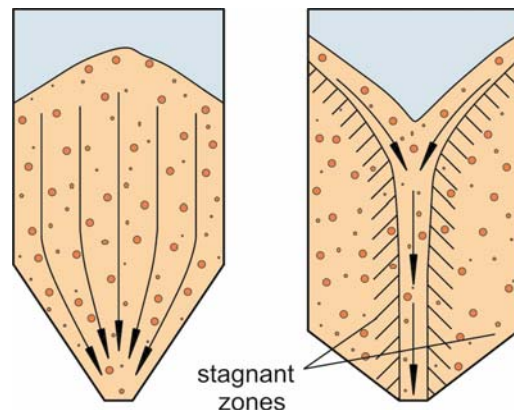


Fig. 6: Mass flow (on the left), funnel flow (on the right)

In a funnel flow silo all problems listed above can appear, while in the case of mass flow only the problem of arching must be considered. Also practical experience shows that funnel flow is a primary cause of flow problems.

For the design of a mass flow silo the slope of the hopper walls to ensure mass flow and the minimum outlet dimension required to avoid stable arches have to be determined. For this the flow properties of the bulk solid have to be measured with an appropriate shear tester [3]. With sufficient experience in the application of these quantities one can design new silos as well as redesign existing silos or other equipment exhibiting flow problems.

Literature

- [1] Schulze, D.: Powder Handling & Processing 8 (1996) 3, pp. 221-226
- [2] Schulze, D.: Powder & Bulk Engineering 10 (1996) 4, pp. 45-61 and 10 (1996) 6, pp. 17-28
- [3] Schulze, D.: Powders and Bulk Solids - Behavior, Characterization, Storage and Flow, 2nd ed., Springer, Berlin Heidelberg New York (2021)
- [4] Jenike, A.W.: Storage and Flow of Solids, Bull. 123, Engng. Exp. Station, Univ. Utah, Salt Lake City (1964)

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