Powder Rheology and Envelope Density Terminology

The most important terms of powders and bulk solids

General Terminology	Description / Comments
Arch, arching, bridging, dead zone, piping, pole hole, rathole, ratholing	Different problems that can occur in a silo/hopper and lead to discharge problems.
Angle of repose	The angle of repose (of a granular medium) is the steepest slope angle in relation to the horizontal plane up to which a material can be piled up without slipping. At this angle, the material threatens to slide down the slope edge.
Big bag	A flexible bulk container for the storage of powders.
Bulk solid / granular media	A bulk solid consists of many solid particles or granules. The particles can be of different sizes and have different chemical compositions.
Bulk density	Density of the bulk solid INCLUDING the air pockets. (not to be confused with the solid density).
Carr Index / Hausner Ratio	Indicator for the compressibility of a powder. Normally measured by tapping the powder. Can be used for a rough estimate of flowability.
Chain conveyor / Auger screw / Screw conveyor	Means for the mechanical transportation of powders. Usually analyzed with a powder shear cell.
Dense phase vs. Dilute phase conveying	In the dilute phase, the materials to be conveyed are suspended in the air and, in contrast to the dense phase are operated at a higher speed. In the dense phase, the materials are extremely heavy and/or abrasive. A vacuum or pressure system can be used for conveying in the dilution phase as well as in the dense phase.
Discharge	Controlled emptying of a silo.
Dosing	Controlled discharge of a certain quantity from a feeder/silo/hopper.
Dynamic friction	Also known as kinetic or sliding friction, it occurs between two objects that move relative to each other and slide against each other.
Electrostatic spraying	Means for applying e.g. powder coatings to car parts.
Filling level (of a silo / hopper)	How full a silo / hopper is influencing the stress conditions at the opening and must therefore be considered when measuring shear cells.
Fines	Very fine particles which can be part of the bulk solid. Are sometimes removed intentionally and sometimes accidentally. Can have a surprisingly large influence on the powder behavior.
Flow aid / flow agent / flow additive	Sometimes additives are used to improve flowability. E.g. fumed silica.
Flow profile (core flow vs. mass flow)	How silos discharge. In a mass flow silo, the entire contents are gradually emptied. In a core flow silo, there is a dead/stagnant zone that is not emptied.
Flow properties	How does the powder flows? This depends on the state of the powder-> is it deaerated (=freely settled) or is it consolidated. How much is it consolidated?
Flowability	Describes, like “flow properties” how well a powder flows, but is actually a value that results from shear cell measurements (see “Flowability ffc” in “powder shear cell” for more information). The flowability depends on many different influences, such as particle size, particle size distribution, particle morphology, stress conditions, humidity, temperature…
Free-flowing vs. cohesive	Free-flowing powders flow well (e.g. polyamide, iron powder …) Cohesive powders do not flow well (e.g. limestone, flour, …).
Silo, bin, hopper, feeder	Different kinds of containers used for the storage and dispense (from bellow) of fine dust.
Normal stress	Stress acting perpendicular to the surface.
Particle size distribution	Describes the size of the different particles inside in a bulk solid.
Pneumatic transport	Means for transporting powders with compressed air/gas. Two possibilities: diluted phase flow and dense phase flow.
Powder	See “bulk solid”.
Ring shear tester / annular ring shear tester / annular shear tester	Device for analyzing the behavior of consolidated powders (as described in the table “powder shear cell”).
Jenike shear tester / Shear tester	A device similar to the powder shear cell, but more cumbersome (one measurement takes about a day of intensive work instead of an automated 45 minutes).
Silo outlet, silo opening, outlet opening	The opening of a silo. Its size can be determined using the results of a ring shear test.
Solid density	Density of the material if it consisted of a solid block, i.e. excluding air-pockets. (not to be confused with the bulk solid density).

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Spray dried / atomized powders	Method for producing powders from liquids. Used in many industries (food, metal, pharma …).
Storage	Storing powders – can be in a silo, big bag, container, etc.
Static friction	In static friction, the frictional force resists a force acting on an object, and the object remains at rest until the static force is overcome.
Wedge-shaped vs. conical hopper vs. pyramidal hopper	Form of the outlet of a silo / hopper. Influences the discharge process.
Shear stress	Stress acting parallel to the surface.

Powder **Shear Cell** Terminology	Description / Comments
Adhesion τ_{ad}	The tendency of the powder to stick to the wall material. Results from the measurements of the “wall friction” (where the “wall yield locus” intersects the vertical axis).
Angle of internal friction φ_{sf} (at steady state flow)	Internal friction with steady-state flow in the cutting plane parallel to the shear velocity. Result of the shear measurement (and its analysis with Mohr stress circles).
Angle of the linearized yield locus φ_{lin}	Similar to the internal friction angle and is often used when a constant value of the angle can be assumed.
Bulk density ρ_b	Density of the bulk solid INCLUDING the air pockets. Not to be confused with the solid density.
Caking / time consolidation	Increase in the strength of a powder over time. Can be caused by chemical effects, better packaging, Van-der-Waals forces, etc.
Cohesion τ_C	Describes the cohesion of samples. Is defined by the intersection of the yield locus and the vertical axis. (not to be confused with “cohesion strength”).
Compressibility	Measurement of how the relative volume or density changes when a stress is applied to the bulk solid. The relative compressibility is often given as the “Carr Index” or “Hausner Ratio”.
Consolidation time	Time selected for the “caking / time consolidation” measurements. Should correspond to reality (e.g. powder lies in a silo for 2 days), but normally not more than 72 hours are analyzed.
Consolidation, consolidation stress	Application of (normal) stress to powder.
Dilation	Expansion of the powder bed during shearing (= decreasing bulk density).
Effective angle of internal friction φ_e	A measure of the internal friction at steady-state flow. Is the slope of the effective yield locus?
Flowability ffc	ffc is used for the numerical characterization of the flowability as the ratio of unconfined yield strength and principle stress ($ff_c = \sigma_1 / \sigma_c$).
Linearized yield locus	Straight line tangent to the two Mohr circles.
Major principle stress σ_1	Actual stresses in the powder (consolidation stress + shear stress).
Mohr circle / stress circle	Part of the Mohr-Coulomb diagram.
Mohr-Coulomb diagram / Mohr diagram	Diagram used to analyze the stress conditions in the powder.
Not flowing / very cohesive / cohesive / easy-flowing / free-flowing	Flowability-categories: • Not flowing: $ff_c < 1$ • Very cohesive: $1 < ff_c < 2$ • Cohesive: $2 < ff_c < 4$ • Easy-flowing: $4 < ff_c < 10$ • Free-flowing: $10 < ff_c$
Pre-compaction	Normal stress applied during shearing (usually 3/6/9 kPa)
Pre-shear	Crucial step in the measurement, in which the sample is “pre-sheared” = sheared, while a controlled normal stress is applied to bring the powder bed into a homogeneous state.
Pre-shear points	Different normal stress values for pre-shearing (e.g. with a pre-compaction of 3, 6 and 9 kPa)
Residence time	How long a particular part of the powder remains in the silo/hopper. This time should be considered when measuring “caking” and used for the “consolidation time”.
Sample preparation bench	A tool to ensure that the sample preparation is as uniform as possible.
Shear (shear-to-failure)	The measurement step that follows each shearing process. The normal stress is lower than during shearing. The sample is sheared until failure (i.e. until it starts to flow again).

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Shear points (shear-to-failure points)	How often is the shear-to-failure performed for each shear point. (e.g. pre-shear at 3 kPa and three shear-to-failure points at 1, 1.5 and 2 kPa).
Steady-state flow / stationary flow	During pre-shear: when the friction forces between particles are at their maximum at the applied normal stress. The shear stress is constant when steady-state flow is reached.
Tensile strength σ_T	'Force' needed to separate particles from other particles (NOT the force needed to break particles).
Time consolidation bench	A tool which is used to run time consolidation tests outside a rheometer.
Time yield locus	Similar to the "yield locus" – but is acquired for "time consolidation" / "caking" tests.
Unconfined yield strength σ_C	Strength of the powder – i.e. when does it yield when not confined.
Wall friction	Friction between a powder and a wall material (e.g. silo wall). Material can be stainless steel, aluminium or PTFE for example.
Wall friction angle	The result of the wall friction measurement is used to determine the silo/hopper-angle.
Wall yield locus	Used to analyze wall friction measurements. Yields properties such as adhesion and wall friction angle.
Yield locus	Result of shear measurements - is used to represent the flow properties of powders. Is a result of the Mohr-Coulomb diagram?

Powder **Flow Cell** Terminology	Description / Comments
Air-retention (air holding capacity)	(see deaeration)
Cohesion Strength	The cohesion strength describes the internal flow resistance of the powder and is therefore a measure of the powder flowability (not to be confused with "cohesion", see above).
Deaeration	The deaeration behavior of a powder describes how the powder retains air after fluidization. It is a characteristic property of a powder and depends mainly on the particle size and particle morphology.
Dustiness	Describes the tendency of a powder (or parts of a powder) to become airborne.
Fluidization	A gas flow through a powder bed can overcome gravity and the inter-particle forces. The powder is then in a fluid-like state. Fluidization can take place in a silo during discharge. Fluidization can cause segregation. Not all powders can be fluidized (depending on density, surface, etc.)
Fluidized bed viscosity / apparent viscosity / shear-rate sweep	The shear-rate-dependent behavior ('viscosity') can be measured as a function of the fluidization state of the powder (non-, sub- and fully fluidized state). This can, for example, provide information on the difficulties to be expected in a pneumatic transport process.
Full fluidization	Defines the "volumetric flow rate" at which the sample is completely fluidized.
Incipient Fluidization	Defines the "volumetric flow rate" at which the sample starts to fluidize.
Permeability	Air flow resistance of powders. Additionally, can be analyzed as a function of the degree of consolidation. Interesting for: aerosolization processes, tableting and filling.
Pressure drop	Measurement method for determining the fluidization properties (i.e. "full and incipient fluidization").
Segregation	Particle segregation or demixing is the segregation of solids according to their physical properties such as size, volume, density, shape, etc. Can be analyzed qualitatively with "Cohesion Strength".
Tensile strength	'Force' needed to separate particles from other particles (NOT the force needed to break particles).
Warren Spring Cohesion	Method to qualitatively analysis of the flowability of consolidated powders.
Wall Friction	See "Wall friction" in table "Powder shear cell".
Fluidized bed reactor	Reactor used for chemical reactions. In it, a gas is passed through a powder.
Pneumatic transport / conveying	Method for transporting powders within a system. The powder is 'blown' through pipes.
Compressibility	Compressibility is a measure of the relative volume change that a sample undergoes when pressure is applied or changes. It is the relationship of bulk density to the applied pressure.
Volumetric flow rate / fluidization velocity	Gas flow rate through the powder bed, usually specified in 'L/min'.

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Envelope Volume	The external volume of a particle, powder or monolith obtained by enclosing the sample with a displacement medium (incl the pores and voids of the sample).
Envelope Density	Envelope density (also known as bulk or geometric density) describes the density of a material including all open and closed voids, pores and cracks.
Absolute Density	The mass of a particle divided by its volume, excluding open and closed pores. (also called true, real, apparent or skeletal density) → typically obtained using a gas pycnometer