TOWARD A COMMON LANGUAGE
FOR BULK SOLIDS HANDLING CHARACTERIZATION

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Abstract

We need to establish a common language for discussing solids flow properties and relating them to handling equipment design and selection. Such a characterization system must allow equipment manufacturers, end users, design engineers, and bulk solids suppliers to talk quantitatively to each other about a bulk solid and its interaction with the handling equipment. This article proposes a standard for judging any bulk solids handling characterization system and then evaluates several existing systems against this standard.

Characterization System Standard

Any successful bulk solids flow property characterization system must satisfy these four points.

1) Use fundamental bulk solid flow properties as a basis.
2) Consist of quickly run, reproducible tests that are independent of test operator technique or interpretation.
3) Measure properties at consolidation pressures, time at rest, atmospheric conditions and test samples compatible with the materials handling equipment.
4) Produce numerical values (indices) that relate directly to solids flow problems and handling equipment design parameters.

The *basic bulk solids properties* include:

Bulk unconfined yield strength is the stress level required to fail an angle when at least one of its surfaces is unconfined (unsupported). An example is the stress level to fail an arch or a rathole. This strength is usually a strong function of the compaction pressure to which the bulk solid has been exposed prior to failure. Consequently, any index based on this property must take into account this compaction pressure level as it occurs in the handling equipment.

Bulk density is the weight of the bulk solid per unit volume and is also a function of the compaction pressure.

Air permeability or air flow resistance is measured by determining the superficial air velocity through a bulk solid that causes an air pressure gradient equal to the bulk density. If the air flow were vertical and upward, this velocity would support the weight of the bulk solid in a cylinder. This may vary over three orders of magnitudes as the bulk density changes. The larger the bulk density, the more compact and the lower the air flow measured.

The wall surface friction angle is the angle at which a bulk solid will slide down a flat plate after the initial history dependant adhesion is broken. This is also a function of stress acting on the bulk solid. With soft, solid particles and hard wall materials, larger pressures usually cause a decrease in surface friction angles. Hard solid particles tend to dig into soft wall materials, usually causing increased surface friction angles with larger pressures.

Wall surfaces adhesion is measured by first loading a bulk solid on a flat plate at a predetermined pressure, removing this pressure without disturbing the solid and then measuring the angle of slide before the adhesion is broken. This value is a function of the initial pressure, especially in the low pressure range.

Elastic springback or coefficient of restitution after a load application is the percent springback measured after a load is applied uniaxially to a bulk solid then released allowing the solids to springback. Most bulk solids have a very slight springback. However, some have a springback of 25% or more. This percent is a function of the load applied.

Particle size range and distribution may be given in great detail. Usually at least two values of percent passing or percent retained must be given to describe a size range (for example, the size passing 80% and the size passing 20%).

Particle density or specific gravity is a measure of individual particles, usually by liquid displacement. This density is not usually a function of solids pressure except at extremely large pressures where the physical crystal structure may be compressed or internal particle voids collapsed.

The bulk solids properties influence on handling and processing equipment design and functioning are given in Table I [1,2]. In general, these properties exert multiple influences on equipment design, functioning and design parameters. Because of these multiple influences, combinations of properties, which can be defined as indices, will be required for equipment design parameters. This also indicates that a series of indices will be required to fully characterize a bulk solid’s flow properties although the complete set may not be needed for any specific equipment design parameter.

Test reproducibility requires that test methods are rigorously defined and meticulously followed. Testing quickly and independently of an operator suggests using a tester that is substantially automated.

Measuring the characteristics at conditions existing in the handling equipment requires the test to duplicate environmental conditions as well as carefully selected solids contact pressures. This generally means testing at pressure levels selected for the specific equipment size.

Presenting numerical values or indices that relate directly to solids flow problems and equipment design parameters requires a mathematical linkage between a solid's basic properties and handling equipment design parameters.

Existing Characterization Systems

CEMA and Other Word Definition Approaches

A multiplicity of word-type bulk solids characterization schemes have emerged over the years. CEMA (Conveyor Equipment Manufacturers Association) developed a series of descriptive terms that at least allow us to talk in relative notions [3,4]. Those relative to bulk solids flow include: *particle hardness; particle shape; bulk density (loose and vibrated); size; abrasiveness; angle of external friction; angle of infernal friction; angle of repose (loose); angle of maximum inclination (of a belt); angle of slide; angle of surcharge; cohesiveness; flowability; flow function; packs under pressure; stickiness; adhesion; very light and fluffy (may be windswept).*

A more recent U.K. publication "Guide to the specification of bulk solids for storage and handling applications" by the Institution of Mechanical Engineers [4], lists: *bulk density, shear strength, cohesion, tensile strength, permeability, maximum particle/lump size, surface contact friction, surface adhesion and cohesion, abrasiveness, corrosiveness, setting, clogging, free flowing, cohesive, interlocking, cakes, poured angle of repose, slip properties - contact face, surface finish, friction angle, shear cell test results, and particle size distribution.*

These and other classification schemes of this type provide us with descriptive terms only, without any real quantification. Even a relatively well understood term like bulk density is relied on without defining the solids contact pressure causing the density. Using the four point characterization standard to evaluate these classification methods we find that: 1) only some of the basic flow properties are used; 2) no reference to test technique is usually given; 3) there is no reference to consolidation pressures or duplication of handling equipment conditions; and, 4) numerical values given are not related directly to handling equipment

Quantifying solids properties in these schemes is left to the scientific community. Properties like unconfined yield strength, bulk density, air flow resistance or permeability, internal friction angles, surface friction angles are all measured meticulously as a function of bulk density or major principal compressive stress. These measurements create multiple data and test methods only the experts can decipher. The rest of the industry wonders what the experts are talking about and do not know which data is really needed and which is valid for their application.

Jenike Flowability Classification

Dr. A. W. Jenike in the late 1950's attempted to classify a bulk solid's cohesiveness using the ratio (FF) of major principal consolidation stress to the unconfined yield strength [5,6]. Unfortunately this ratio (FF) is often highly dependent on the magnitude of the consolidation stress and is not a constant. For example, a wet clay or a damp, coarse sand typically has an unconfined yield strength that is essentially independent of consolidation stress. This causes FF to vary from zero at zero consolidation stress, to over 20 at consolidation pressures associated with a 15 foot-diameter bin. Consequently, (FF) is not an identifiable solids property constant.

Using the four point standard, this early attempt is: 1) based on a fundamental bulk solids flow property (unconfined yield strength); 2) based on tests that are not quickly run and require a skilled operator for both running tests and test interpretation; and, 3) based on tests that can be run at conditions representative of the materials handling equipment; and 4) Unfortunately FF, although a numerical value, is not a constant for a given solid and does not relate directly to solids flow problems and equipment design parameters.

The Carr Indices

Dr. Ross L. Carr proposed another approach in the 1960's [7,8] with his *angle of spatula, angle of fall,* angle *of repose, angle of difference, aerated and tapped bulk density, dispersibility and uniformity (measured size range).* Dr. Carr then correlated these measurements with empirical observations to arrive at extrapolations from one situation to another. Unfortunately, this approach requires a large, well organized empirical data set and assumes that all the important variables and flow phenomena are represented by these measurements.

Using the four point standard with this set of indices we find that: 1) the indices are not based on fundamental bulk solids flow properties (except density); 2) the tests are quickly run, fairly reproducible from one operator to another but subject to a wide range or interpretation; 3) the tests are done at low consolidation pressures having little resemblance to conditions in materials handling equipment; and, 4) the tests produce numerical values; however, their interpretation in terms of solids flow problems or equipment design parameters is highly dependent on imperial correlations.

The Hall Flow Meter

This tester was developed for use in the powder metallurgy industry to characterize metal powder flow into a plunger press [9]. It is an excellent example of a tester simulating full-scale equipment requirements. The meter consists of a funnel with an outlet about the same size as the press feed hopper outlet. As a result, the indices, consisting of the measured time required to empty the full funnel, correlates well with the maximum powder feed rate into the press feed shoe. As long as the test is used for materials like metal powders that flow freely through the prescribed funnel, the test is very useful. When used with a more cohesive solid, however, the test produces a very consistent but useless result of zero flow.

This phenomenological approach to defining solids flow properties has great appeal. The extreme of this method is determining whether or not the material will handled successfully in a piece of equipment by trying it in the full-scale equipment at full-scale operating conditions. While this approach is viable for small hoppers associated with powder metal presses, it has limits for large pieces of equipment unless the equipment is sold on a “try-it-and-see” basis.

Using the four point standard, we find: 1) the test technique is not based on fundamental bulk solids flow properties; 2) the Hall flow tests as standardized by ASTM description B213-90 are reproducible, quickly run, and independent of operator technique or interpretation; 3). the measurements represent conditions in the material handling equipment associated with powder metal compaction; and, 4) the indices obtained relate directly to solids flow problems and equipment design parameters. In general, this has the potential for successfully characterizing metal powder flow rates in presses.

Unfortunately, since the test is not based on fundamental solids flow properties, the results cannot be extrapolated to general equipment applications.

The Johanson Indices System

This system [10, 11], developed by Dr J.R. Johanson, attempts to link the practical needs of handling equipment manufacturers and users with the rigors of science. This linkage relies on mathematical descriptions of solids flowing into equipment, practical experience and observation accumulated since the late 1950’s. The nine Indices defined in Table II are based on pressures and conditions associated with bins, hoppers, feeders conveyors and chutes. The uniaxial compaction [12] provides a quick, reproducible method of duplicating a solids initial consolidation pressure in a piece of equipment. This represents a worst-case compaction level, and consequently an appropriate design and selection criteria.

The Johanson Indices (except **CI)** are specific to the bin diameter D. **FDI** and **FRI** are specific to the hopper outlet diameter **d.** These dimensions, **D** and **d,** are the basis for the Indices. It’s important to know the Indices measurement basis before applying them to handling problems. Generally, Indices for a larger bin diameter are conservative for small bins. For example, although the measured properties basis is for a 10-foot-diameter bin, the Indices can be used to over design a five-foot-diameter bin and feeder. Conversely, they may produce a 20-foot-diameter design that could have hang-up problems.

HI and **CI** are dependent on the hopper or chute liner material. **AI** and **RI** are usually time-dependent. Knowing the increase in instantaneous **AI** and **RI** with time is especially useful in selecting flow aids.

Applying the four point standard, we find that all nine of the Johanson Indices are: 1) derived from basic bulk solids flow properties; 2) are measured in a few minutes (except for the wear Index), are reproducible, operator independent, and result directly in measurements without interpretation; 3) measured at pressures and conditions specifically associated with bins, hoppers, feeders, conveyors, and chutes; and 4) produce numbers that are used directly to size bin outlets, feeder inlets, define hopper and chute angles, predict when flow aids are required and define wear rates.

Summary and Conclusion

Table III summarizes the four characterization systems discussed and their conformity to the four point standard put forth. In general, the word description, Jenike flowability and Carr Systems generally satisfy only two of the three criteria and consequently, have limited use. The Fall Flow Meter satisfies three of the four when applied to non-arching metallic powders. This is typical of other full-scale type tests. They work well for the particular application, but without the mathematical linage to basic flow properties, the results cannot be extrapolated without further tests, The Johanson Indices Characterization System satisfies all four standard points and provides a complete extrapolatable characterization system for quantifying bulk solids behavior in handling equipment.

Table I
Basic Bulk Solids Properties that Influence
Handling and Processing Equipment Design and Functioning

Property	Influences on Equipment Design and Functioning
Bulk unconfined yield strength	Hangups such as arching and ratholing, segregation potential, density variation, feeder accuracy, blender efficiency, feeder sizing, fluidizability.
Bulk density or bulk weight per unit volume	Hangups such as arching and ratholing, segregation potential, limiting flow rates from hoppers, feeder and conveyor power, equipment structural design, feeder accuracy.
Air flow resistance or permeability	Deaeration time in equipment, limiting flow rates from hoppers, fluidizability, air required to increase powder flow rates, air required to break bridges and ratholes.
Wall surface friction angle or kinematic slide angle on a flat plate	Flow patterns in bins, chute angles, hopper angles, maximum conveyor belt slope, screw conveyor and feeder effectiveness.
Wall surface adhesion on static slide angle on a flat plate	Chute plugging, chute design parameters, screw feeder and conveyor efficiency, belt conveyor, cleaning problems, blender efficiency, pneumatic conveyor pipe buildup.
Bulk modulus of elasticity	Hangups such as arching and ratholing, bin geometry, feeder design parameters, feeder accuracy.
Particle size range and distribution	Segregation potential. May influence all the other bulk properties.
Particle density or specific gravity	Rate of air injection to effect flow or destroy hangups.

Table II
The Johanson Indices

Symbol	Name	Directly Calculates	Basis for Measurement
AI	Arching index (linear)	The size of hopper outlets and feeder inlets and predicts segregation potential.	Proportional to the unconfined yield strength/bulk density ratio measured at initial solids pressures at the hopper outlet.
RI	Ratholing Index (linear)	The size of the outlets of funnel-flow bins to prevent ratholing. Also predicts lump formation in bags, containers, trucks and railroad cars.	Proportional to the unconfined yield strength/bulk density ratio measured at initial solids pressures in funnel-flow bins.
HI	Hopper Index (degrees)	The hopper and chute angles for flow and predicts chute segregation.	Derived from the wall surface friction angle determined at either the hopper outlet or at the top of the hopper, whichever has the greater friction angle.
CI	Chute Index (degrees)	The chute angle at impact points and predicts buildup in conveying systems.	Derived from the chute surface adhesion after impact from a bulk solid.
BDI	Bin Density Index (wt/vol)	The bin capacity and bin loads.	Equivalent to the bulk density measured at uniaxial applied pressures associated with the bin.
FDI	Feed Density Index (wt/vol)	The feeder capacity and loads.	Equivalent to the bulk density measured at uniaxial applied pressures associated with the hopper outlet.
SBI	Springback Index (percent)	The special hang-up potential of solids that windup elastically.	The elastic bulk modulus measured uniaxially.
FRI	Feed Rate Index wt/time)	The maximum feed rate for a deaerated powder, the need for air injection, segregation potential and flooding potential.	The air flow resistance (permeability) measured at the hopper outlet. Bulk density and density changes within a hopper.

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