Particle and Powder Flow Properties

by

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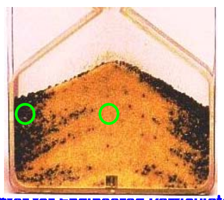
Topics/Outline

- Sampling (Wassgren)
- Particle size (Wassgren)
- Granular Material (Valverde/Castellanos)
- Particle-Particle Interactions
- Dry Particle Coating – Nano-additives
- Cohesion, Flow and Roles of Nano-additives (Valverde/Castellanos)
- Cohesion/Flow Characterization using several powder testers (Dave, Sanchez-Quintanilla, Valverde, Wassgren)
- Contact Modeling – Influence of Nano-additives (Yuhua Chen and Dave)
- Appendices
  - Plasticity Theory for Powders (Sanchez-Quintanilla)
  - Mechanical Properties (Hancock and Morris)
  - Review on Powder Testing Equipment (Sanchez-Quintanilla, Lauren Beach, Yuhua Chen, Laila Jallo)
- Reading material
  - Key papers as PDF files

* Names in blue are students who assisted with notes

Sampling

- The goal of powder sampling is to collect a small amount of powder from the bulk, such that this smaller fraction represents the physical and chemical characteristics of the entire bulk.
  - An example: Two 250 kg bags of material need to be tested, but the test can only handle 2 g samples. How should the bags of material be sampled?
  - Another example: Two samples are pulled from a storage bin. From where should the samples be taken?



Sampling…

- Two “Golden Rules”:
  - The powder should be in motion when sampled.
  - Many samples should be taken from the whole of the flowing stream over short time periods rather than taking a single sample from one location over a long time period.
- Do these same rules apply for nano-powders?

Sampling…

- Types of samples
  - *On-line*: the sample remains part of the running process
  - *At-line*: the sample is removed from the process stream, but is analyzed in close proximity to and shortly after the sample has been removed
  - *Off-line*: the sample is removed from the running process, taken to a remote site, and the measurement is made after some time has passed

Sampling…

- Types of samples…

Measurement Type	Advantages	Disadvantages
on-line	- rapid turn-around time - continuous measurements - can be used for real-time process control - less operator bias - fewer sampling errors	- requires dedicated equipment - more development of the measurement technique is required - measurements must be robust enough to withstand the process environment
off-line	- detailed measurements can be made using well-developed technologies - measurements may be made using a variety of methods - measurements are made in better controlled environments	- increased sample processing can result in increased sampling error - increased chance of operator biasing - increased turn-around time - cannot be used for real-time control of a process - sample may change properties during transport (e.g. changed humidity, vibration, etc.)

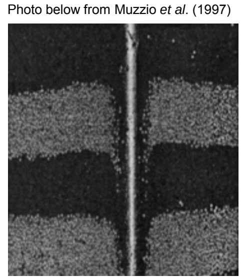
Sampling…

- Types of sampling equipment
  - scoop
    - Pros: easy to use
    - Cons: gives largest sampling errors (favors fines)
      - appropriate for cohesive and homogenous powders (*i.e.* powders that don't segregate)
      - ladles are better since coarse particles don't roll off free surface
      - tend to only sample free surface for static beds

Sampling…

- Types of sampling equipment…
  - thief probe (aka thief sampler, sampling spear)
    - Operation:
      - probe inserted into bulk with sampling chamber closed
      - when probe reaches desired location, open chamber to let in particles
      - close chamber and remove
      - usually sample several sites
    - Pros: easy to use, can access bulk interior
    - Cons: slow, operator bias, probe perturbs bulk, especially poor for sampling cohesive material

Photo below from Muzzio *et al.* (1997)



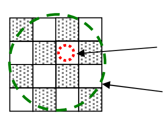
Prof. Muzzio has done nice work in this area about 10 years ago.

Sampling…

- Types of sampling equipment
  - electromagnetic radiation
    - video, X-ray, γ-ray tomography, PEPT, radio “pill”, NIR, NMR
    - can be made in-line on a moving sample
    - Issues to consider:
      - spatial and temporal response
      - access
      - cost
  - “freezing” the sample
    - add a liquid binder to a stationary bed
    - “slice” solidified material to investigate bulk interior
    - Pros: can investigate interior at a variety of sites
    - Cons: time consuming, difficult to implement, flow of binder may bias measurements
    - suitable only for lab measurements due to time involved

Sampling…

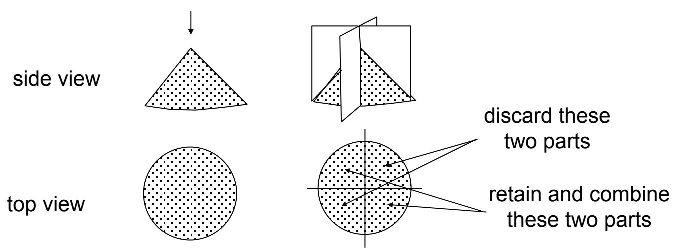
- Sample size reduction
  - “scale of scrutiny”



    - e.g. laundry detergent should be well mixed at a scoop length scale
  - avoid handling bias
    - segregation during transport
    - particle breakage when sieving

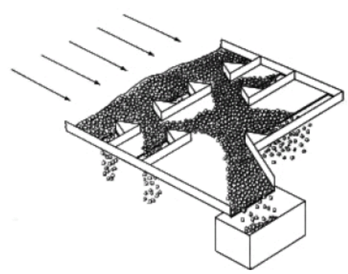
Sampling…

- Sample size reduction…
  - "cone and quartering"
    - for powders that have poor flow (⇒ minimal segregation)
    - considerable operator bias

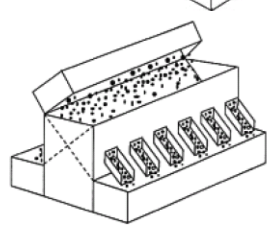


Sampling…

- Sample size reduction…
  - table riffler
    - initial feed needs to be well mixed
    - can quickly sub-divide large quantities of material



  - chute riffler
    - initial feed needs to be well mixed
    - can divide powder sample in half in one pass



Static Powder Sampling

Scoops

Side-sampling probe thief

End-sampling probe thief

Disturbance of layers

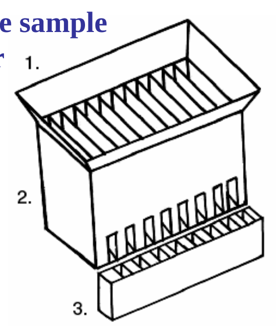
Multilevel tablet sampler

Static probes are suitable only for characterizing materials near homogeneity to look for an impurity which is present at equal levels in all particles.

M. Deleuil, Sampling, In Powder Technology and Pharmaceutical Processes, Elsevier, 1998, Chapter 1.

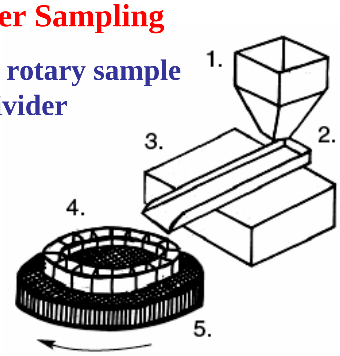
Dynamic Powder Sampling

A chute sample splitter



Powder is fed through the upper baffles (1) and is discharged through the chutes (2) into the sample collection tray (3).

A rotary sample divider



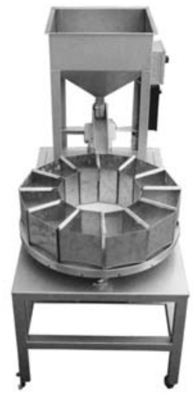
Powder is fed through the hopper (1) into the delivery chute (2), expedited by the vibratory device (3). The subdivided samples are assembled in the collection tray (4), which is mounted on the rotary stage (5).

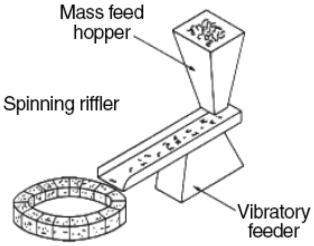
Dynamic sampling is suitable for the subdivision of heterogeneous powders.

H.G. Brittain. Particle-size distribution II: The problem of sampling powdered solids. Pharmaceutical Technology, July 2002, 67

Dynamic Sampling…

- Sample size reduction…
  - spinning riffler (aka rotary riffler)
    - considered the best method of sample size reduction
    - if spinning too fast, fines may be carried away by air currents





Sampling…

- Sample size reduction…

Sample Reduction Method	Standard Deviation of the Composition
cone and quartering	6.81%
scoop sampling	5.14%
table riffler	2.09%
chute riffler	1.01%
rotary riffler	0.125% best method!

Source: Allen (1981)

Sampling…

- Sample size reduction…
  - ASTM standard (ASTM WK5937) in development regarding the use of rifflers for sample preparation
  - ASTM C322-82 Standard Practice for Sampling Ceramic Whiteware Clays
  - ASTM D1900-94 Standard Practice for Carbon Black – Sampling Bulk Shipments
  - ASTM C702-98 Standard Practice for Reducing Samples of Aggregate to Testing Size
  - ASTM D75-97 Standard Practice for Sampling Aggregates
  - ASTM B215-96 Standard Practices for Sampling Finished Lots of Metal Powders
  - BS 3406 Part 1: 1986 British Standard Methods for Determination of Particle Size Distribution Part 1. Guide to Powder Sampling
  - ISO/WD 14888: Sample Splitting of Powders for Particle Size Characterization
  - ISO 2859 Statistical Sampling

Particle Size

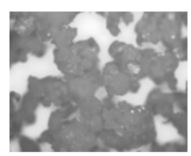
- What is the size of the particle shown below?

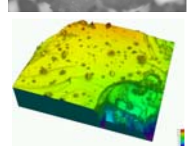
  - The most useful size definition will correlate with how the measurement will be used.
    - e.g. If pneumatic conveying of the particle in a fluid is of interest, then the Stokes or aerodynamic diameter is the most appropriate size measure.

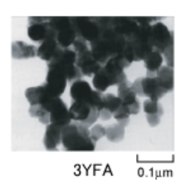
Particle Size

- Why is particle size important?
  - Particle size is important in most handling and processing situations
    - e.g., the magnitude of the forces acting on particles during flow is typically important (e.g. weight ~ size^3)
    - e.g., dissolution time is related to particle size (e.g. dissolution time ~ size^2)
    - can affect bulk thermal and electrical properties

Particle Size…





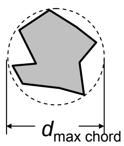


- Microscopy size measures
  - can get particle shape simultaneously
  - labor intensive, but can be automated
    - critical to have representative samples since relatively few particles are measured
  - projected images – can lead to measurement bias
  - optical microscopy: 1 – 150 μm
    - limited depth of field (parts of particles out of focus)
    - confocal microscopy: large depth of field, can generate 3D surface profiles simultaneously with size measurements
  - electron scanning microscopy (SEM): 0.1 - 1000 μm (a Field emission gun would provide better resolution)
  - transmission electron microscopy (TEM): 0.01 – 10 μm
  - SEM and TEM require preparation of the samples
    - Samples preparation may influence the results

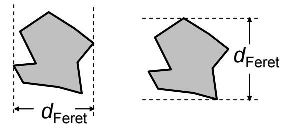
Particle Size…

- Microscopy size measures…

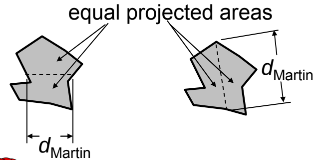
maximum chord diameter



Feret's diameter



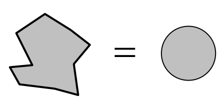
Martin's diameter



Particle Size…

- Microscopy size measures…

equivalent circle/sphere diameters



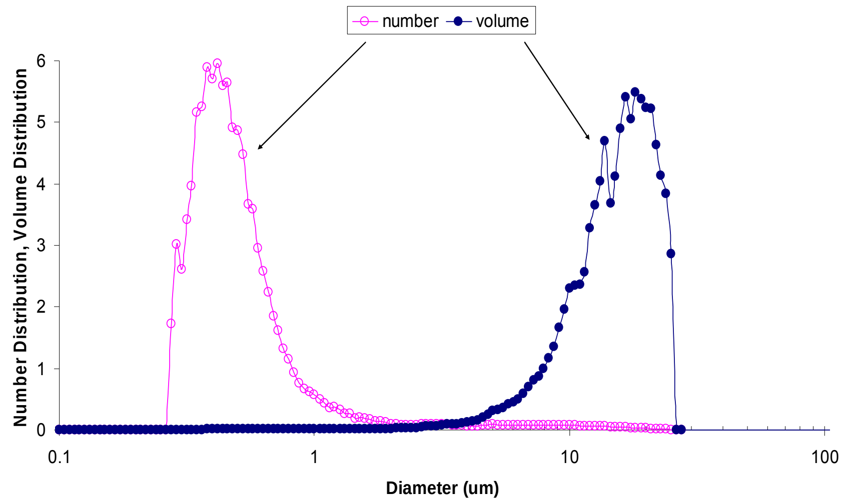
equivalent circle area diameter, d_A $\quad \frac{\pi}{4} d_A^2 = A_{\text{projected}}$

equivalent sphere volume diameter, d_V $\quad \frac{\pi}{6} d_V^3 = V$

equivalent sphere surface area diameter, d_{SA} $\quad \pi d_{SA}^2 = SA$

equivalent sphere volume-to-surface area diameter, $d_{V/SA}$ $\quad \frac{\frac{\pi}{6} d_{V-SA}^3}{\pi d_{V-SA}^2} = \frac{V}{SA}$

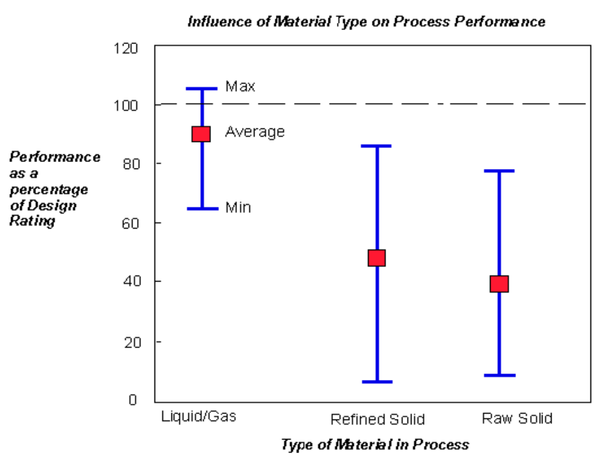
A Caution: Number vs. Volume



One grain is a solid. But a lot of grains together are neither a solid, nor a liquid, nor a gas…

José Manuel Valverde

- A granular material is a conglomeration of discrete solid, macroscopic particles characterized by a **loss of energy** whenever the particles interact.
- Only in the recent years granular materials are being extensively studied. This should be surprising given their **enormous relevance in our world**.
- Most industries handle granular materials in some way. It is estimated that **10% of world energy consumption** is due to the handling and processing of granular.
- Granular materials exhibit a vast amount of interesting phenomena which are **poorly understood**. There are a series of separate experimental results with semi-empirical theories that describe the particular experiments. There are no unifying equations. This makes the field exceedingly hard (and thus very challenging).



Agriculture,

Mining,

Civil engineering

Chemical engineering

Pharmaceutical

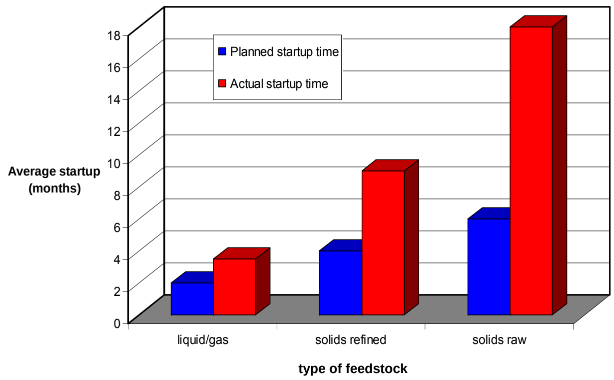
Geological processes

It is estimated that **one-half of the products in the chemical industry** and at least **three-quarters of the raw material** are in granular form. However, handling of these materials represents a serious problem.

Thus even a **small step** in understanding their behavior may represent an **outstanding contribution** to industry

Average startup time of processing plants

Planned versus actual as a function of type of feedstock



- Average extra cost/month = $350,000
- 80% experiment solids handling problems.
- 18 months versus 3 months for liquids
- operation is only 40-50% of the design expected performance
- **Most problems are related to physics and mechanics** rather than chemistry

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Principal Contributor: Valverde

- Thousands of silos collapse every year for unknown reasons…
- In the U.S. the number is above one thousand…
- In Mexico, 30% of corn is lost due to bad design of handling and transport devices.

Rough estimates of the losses suffered in the U.S. economy due to ``granular problems" amount to ... **billions of dollars a year**

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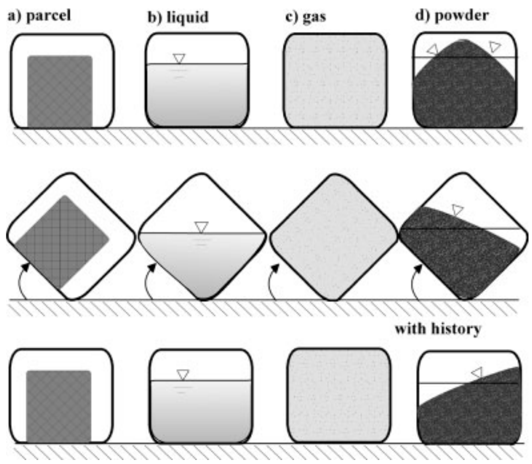
Principal Contributor: Valverde

Why is it difficult to design powder processing systems?

- How are powders different from
  - Solids?
  - Liquids?
  - Gases?
- What comprises a “powder system”?
  - How do we describe (or characterize) it as compared to how a solid or fluid is defined?

Description of a solid

- Basic material properties are usually sufficient
  - They depend on: ????
- Fundamental equations governing the stress-strain behavior are available
- What about liquids and gases?
  - Do we have fundamental equations?



This simple experiment shows how granular materials differ from solids, liquids and gases.

Moreover, their behavior depends on previous processes. They retain **memory**.

How do we describe granular/powder material?

- What properties we may need in addition to the properties of the solid material?
- Can I measure all the properties I need of a single particle and then describe the "bulk" behavior?
- Do we have the governing equations to describe/predict the behavior?
- Will I need to make a distinction between a granular material (e.g., sand, coffee beans) and a powder material (e.g., flour, cement, pharmaceutical active or an excipient)?

From Castellanos

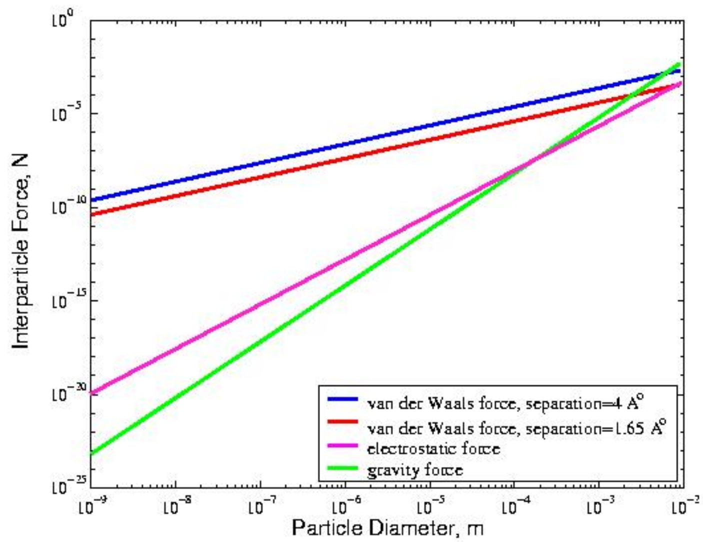
"The physics of granular materials in ambient gases is governed by interparticle forces, gas–particle interaction, geometry of particle positions and geometry of particle contacts. At low consolidations these are strongly dependent on the external forces, boundary conditions and on the assembling procedure. For dry fine powders of micron and sub-micron particle size interparticle attractive forces are typically much higher than particle weight, and particles tend to aggregate. Because of this, cohesive powders fracture before breaking, flow and avalanche in coherent blocks much larger than the particle size. Similarly the drag force for micron sized particles is large compared to their weight for velocities as low as 1 mm/s. Due to this extreme sensitivity to interstitial gas flow, powders transit directly from plastic dense flows to fluidization without passing through collisional regimes with negligible gas interaction. These two features, strong attractive forces and strong gas interaction make powder behaviour differ qualitatively from the behaviour of large, noncohesive grains."

A. Castellanos, *Advances in Physics*, Vol. 54, No. 4, June 2005, 263–376

Inter-particle Interactions

- Van der Waal's attractions
  - They have a major effect on fine powders (micron and smaller)
- Electrostatic forces
  - These forces play a major role in liquids, and allow colloidal stability through electrostatic repulsion
- Liquid bridge/capillary forces
  - They are significant for dry powders

Relative Order of Magnitude of van der Waal's and Electrostatic Forces



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Van der Waal's Forces

- While not as strong as the covalent bond or Coulombic interactions, van der Waal's interactions are always present and play a central role in surface force interactions between two particles
- For various geometries, one can derive these interactions by summing/integrating the inter-atomic van der Waal's pair potential of all atoms in one body with all the atoms of the other body

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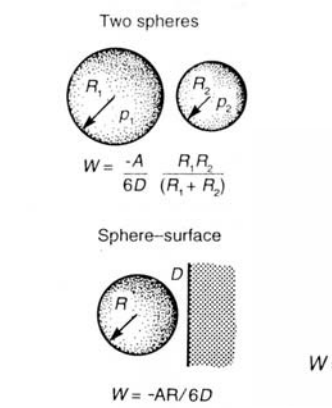
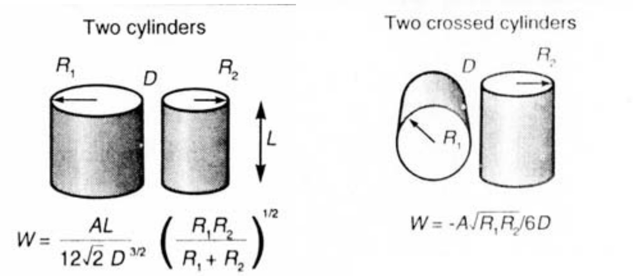
Interactions between Various Geometries



Interaction energies are given for various geometries.
A = Hamaker constant
D = Separation between the bodies, 1.65 – 4 A°



Force between two spheres can be given by:

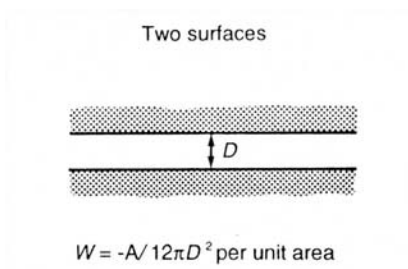
$$F(D) = -\frac{A}{6D^2}\frac{R_1 R_2}{(R_1+R_2)}$$

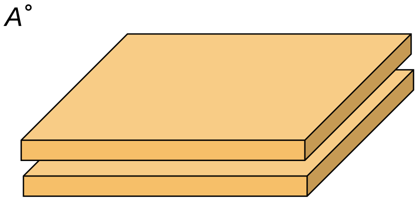
$$F(D) = -\frac{AR}{12D^2}$$

For two equal spheres of radius, *R*

Interactions between Various Geometries (continued)

A = Hamaker constant
D = Separation between the bodies, 1.65 – 4 A°





Between two plates, each of finite thickness (d), the interaction energy per unit area is given by:

$$W(D) = -\frac{A}{12\pi}\left[\frac{1}{D^2} + \frac{1}{(D+2d)^2} - \frac{2}{(D+d)^2}\right]$$

Shape/Contact Effects in van der Waal's Forces

- It is important to realize that at least in principle, the shape of the surfaces and the nature of their contacts significantly influence the order of magnitude of vdw forces
- The influence of the separation distance between the bodies (D) on vdw force differs:
  - **For two spheres or sphere and surface, it is ~ D^{-2}**
  - **For two cylinders in parallel, it is ~ $D^{-2.5}$**
    - **For two crossed cylinders, it is ~ D^{-2}**
  - **For two plates in parallel, it is ~ D^{-3}**
    - **Also, large contact surface area plays a major role – which is most significant for parallel plates**

Liquid-Bridge (Capillary) Forces (1)

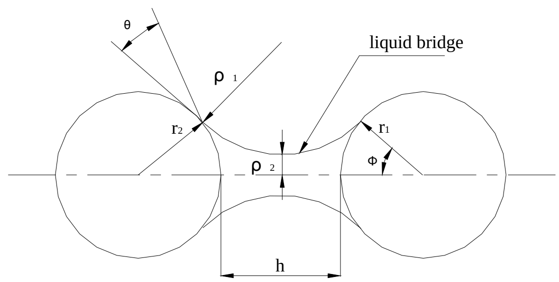
- The liquid bridge forces between fine particles could in fact become more significant than van der Waal's (vdw) forces, and can be a cause of significant problems in handling, and dispersion of particles in presence of humidity
  - **They depend on (and hence may be manipulated by controlling) the amount of liquid and its surface tension and viscosity**
- Unlike vdw, the liquid bridge forces include dynamic effects and also have dissipative effects
- The *static* liquid bridge force is the sum of the surface tension force, as well as the force arising from the pressure deficit in the liquid bridge

$$F_{lb-static} = 2\pi\rho_2\gamma + \pi\rho_2^{\,2}\Delta P$$

Liquid-Bridge Forces (2)

$$F_{lb-static} = 2\pi\rho_2\gamma + \pi\rho_2{}^2\,\Delta P$$

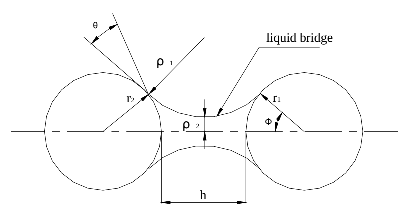
$$\Delta P = \gamma\left(\frac{1}{\rho_1} - \frac{1}{\rho_2}\right)$$



ΔP is the reduction in the pressure within the liquid bridge, as compared to the surrounding, and γ is the surface tension due to the liquid

Liquid-Bridge Forces (3)

The quantities, ρ_1 and ρ_2 are interdependent, and hence the terms may be manipulated (assuming both particles are of the same radius, r) to obtain a simplified final result that is accurate enough for maximum static force at contact



The final expression points to the fact that the static forces are directly proportional to the surface tension of the liquid and the particle size

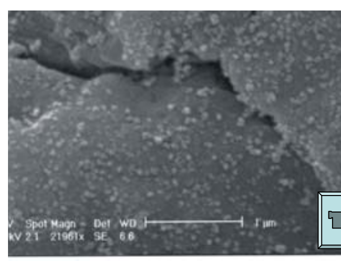
$$F_{lb-static-Max} = 2\pi r\gamma$$

Particle Bond Number

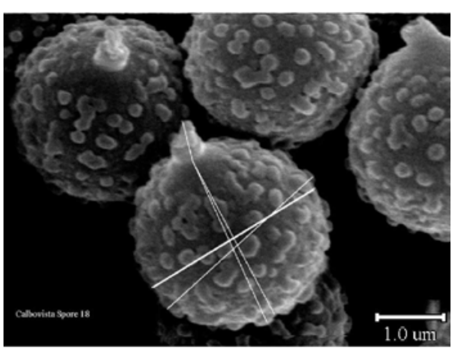
- Defined as the ratio between attractive forces and its weight, $B_o = F_a/mg$
- $B_o = 1$ is taken as a boundary between cohesive and freely flowing particles
  - Usually, $B_o \leq 1$ for non-cohesive, and $B_o \gg 1$ for cohesive powders

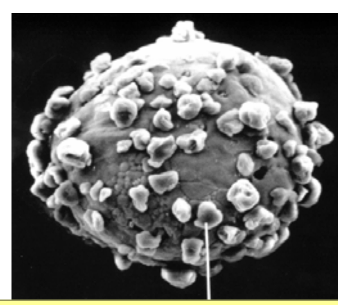
Cohesion-Memory-Flowability

Interparticle attraction leads to **cohesiveness**, which hampers severely flowability



Coating fine particles with "hard" nanoparticles helps to reduce interparticle adhesion for a given load force. Powder **Memory is minimized** and flowability is inhanced.



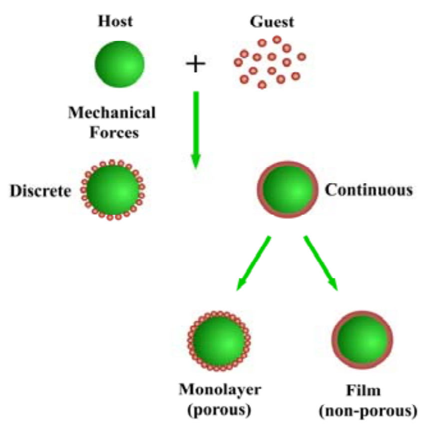


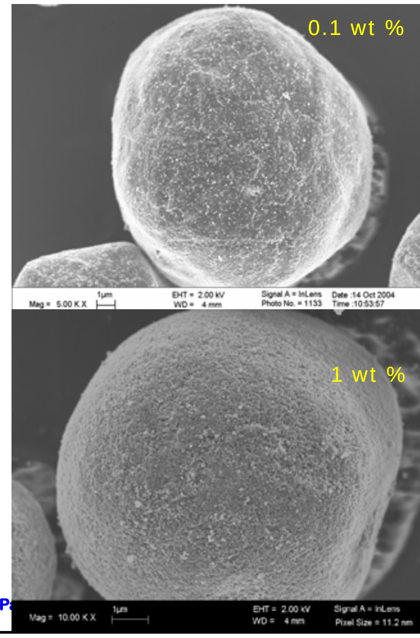
Yuhua CHEN- models

Taking cues from nature; puff-ball spores --- A practical solution in xerography is to use big carrier particles that flow easily to transport the fine and highly cohesive xerographic toner

Principal Contributor: Valverde/Castellanos

Dry Particle Coating





Schematic Sketch of Dry Particle Coating

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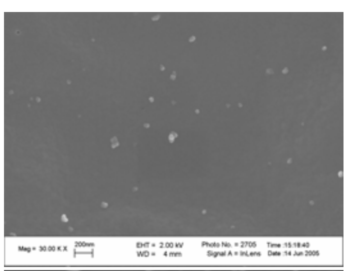
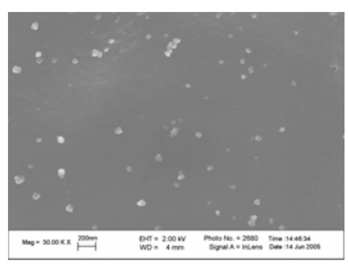
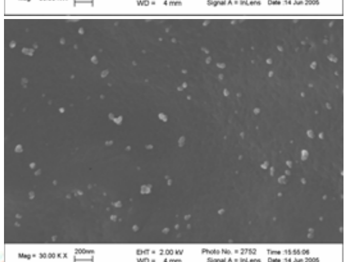
Surface Area Coverage (SAC)



Left, 0.01 %,

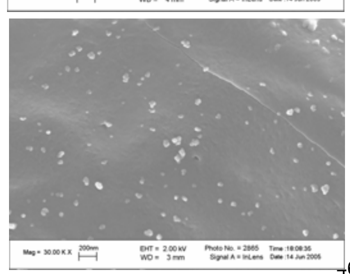
Right, 0.025 %,





Left, 0.04 %,

Right, 0.05 %,



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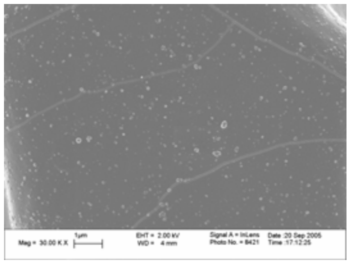
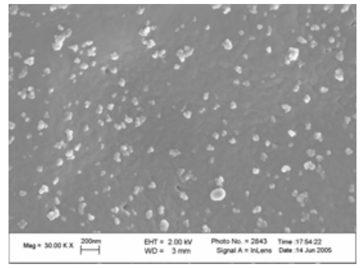
Principal Contributor: Chen

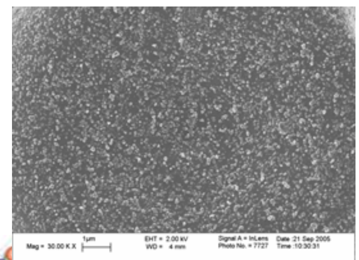
Surface Area Coverage (SAC)



Left, 0.08 %,

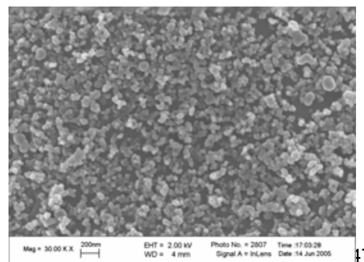
Right, 0.1 %,





Left, 0.5 %,

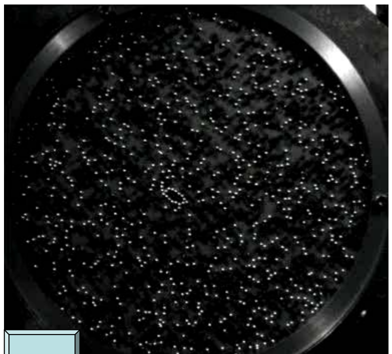
Right, 1.0 %,



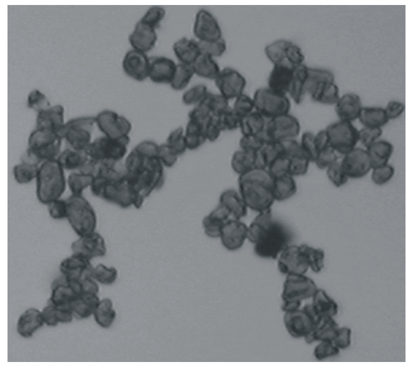
Surface Area Coverage (SAC) by Dry Coating

	Weight Percentage of Fume Silica (%)	Theoretical Surface Area Coverage (%)	Experimental Surface Area Coverage (%)
Cornstarch + Aerosil R972	0.01%	1.17	1.09
	0.025%	2.92	2.86
	0.04%	4.67	3.85
	0.05%	5.84	4.89
	0.08%	9.35	8.14
	0.1%	11.69	8.50
	0.5%	58.44	46.94
	1%	100.00	89.76

Interparticle attraction leads to **agglomeration**.
Agglomerates behave differently than individual particles



Magnetic beads



Fine particles

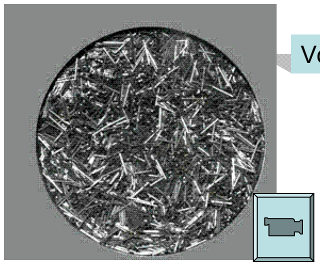
The **mechanism of particle agglomeration** determines the structure of the agglomerates and thus the bulk behavior of the material

Gas-solid interaction

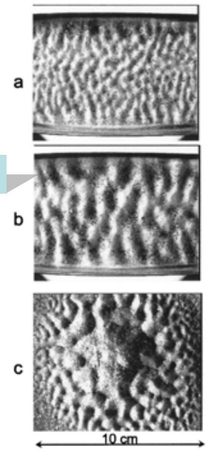
Highly porous agglomerates of fine particles interact with the surrounding gas leading to **fluidization**

The dynamic of large beads is determined by interparticle collisions, leading to **inertial** regime

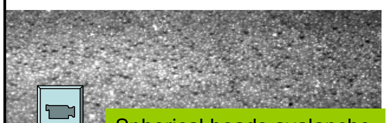
Shape of particles is also a relevant parameter.



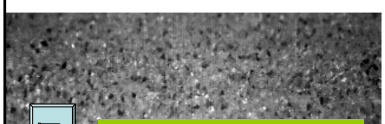
Vortex-like structures



Superficial waves



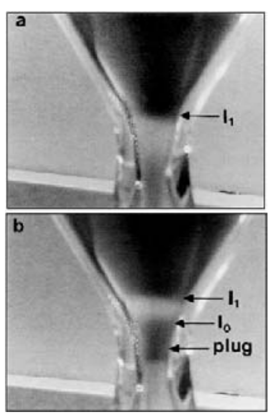
Spherical beads avalanche

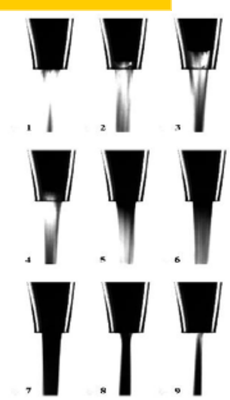


Irregular beads avalanche

Gas-solid interaction can be relevant even for the flow of large grains

The hourglass "ticks". The flow stops briefly and then starts again, over and over, at regular intervals as the stress chains across the opening form and then break apart

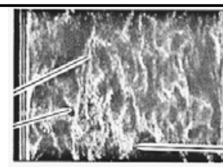




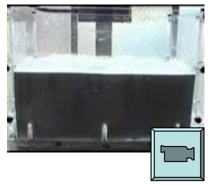
A slight rise in air pressure from below is enough to stabilize the arches and stop the flow entirely.

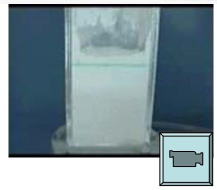
Flow of granular materials through narrow pipes can be severely affected by small alterations of air pressure.

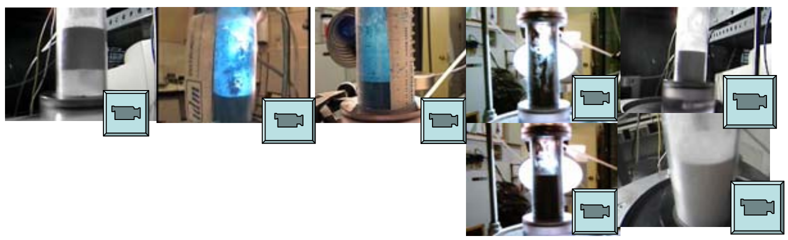
Types of gas-fluidization



clusters and gas pockets by vertical laser sheet image Tsukada 1995





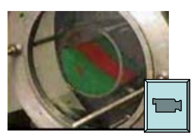


The high surface area-to-volume ratio of fine particles makes fluidization very attractive for gas-solid reaction catalysis. **Fine cohesive powders** are difficult to fluidize if **pre-conditioning** process to erase memory is not applied.

Principal Contributor: Valverde

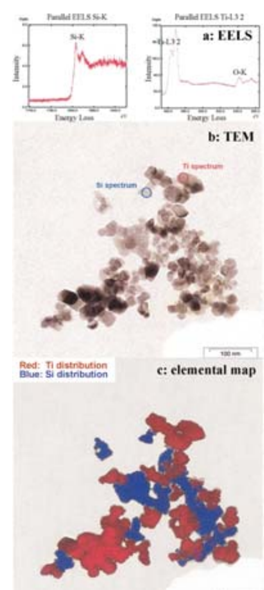
Segregation and mixing

•Amplification of local perturbations gives rise to **segregation, a common phenomenon** in granular materials. Segregation makes almost impossible to mix different types of grains, which is a relevant problem in industries such as food and pharmaceutical.



•The problem gets worse in the case of **cohesive powders** for which deagglomeration is required. This occurs when mixing nanoparticles to form nanocomposites with many potential applications.

D. Wei, R. Dave and R. Pfeffer. *Journal of Nanoparticle Research* **4:** 21–41, 2002.

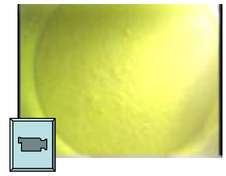


Solvent-based method coupled with ultrasonic agitation. TEM image

Principal Contributor: Valverde

$V_s = \frac{1}{18\eta} \rho_p g d_p^2$ ~ 25 mm/s for **10μm** particles in **air**

Vs (**10μm, air**) ~ Vs (**100μm, water**) ~ Vs (**10cm, hot lava**)

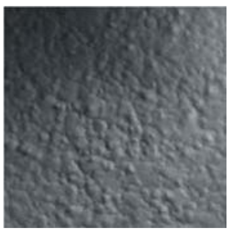


Free surface of a gas-fluidized of fine powder showing volcano-like eruptions

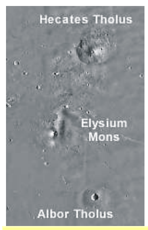
Gas-fluidization of fine particles

liquid-fluidization of granular beads

Lava-fluidization of rocks (volcanos...)



Frozen picture of gas-fluidized of fine powder



Mars surface

Some features of the physics of super **fine powders in air** can mimic the behavior of **granular beads in liquids** as well as of **rocks in hot lavas**. This might help us to better understanding of geological processes (Duran).

•Granular materials **do not constitute a single phase of matter**

•Bulk flow characteristics of granular materials do differ from those of homogeneous fluids and solids in several important ways

•Granular materials are ubiquitous in nature and are the second-most manipulated material in industry (the first one is water).

What is "Flowability"?

- Flowability is a measure of how well a powder flows.
  - Useful in predicting hopper flow, die filling, and other powder handling behavior
- There is no single standard for measuring a powder's flowability.
- Flowability will be a combined measure of powder properties and local flow conditions.

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Principal Contributor: Wassgren

What process is of interest?

1. Flow out of a hopper
   - Can material "break" or "yield" under stress to cause flow?
     - Would knowledge from solids- e.g. material failure theories help?
2. Die compaction to make a tablet
   - What kind of tests are needed on a tablet?
3. Filling a capsule, die cavity, mixing in a blender

Can we use the same test(s) for all these cases?

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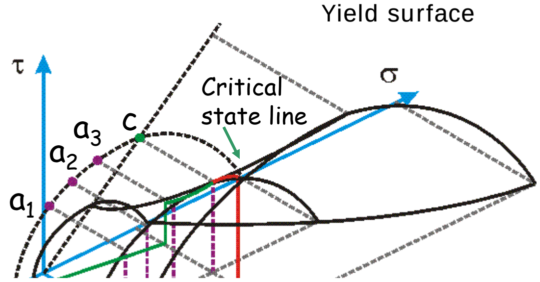
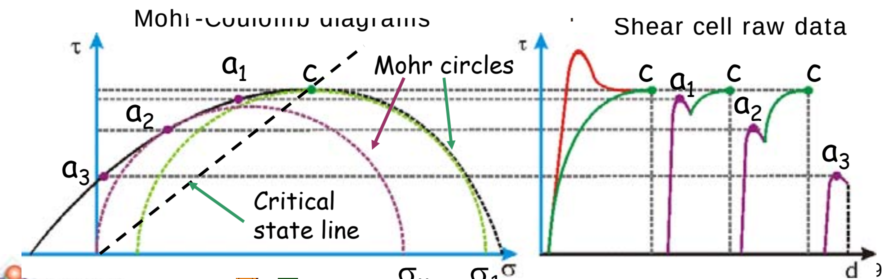
Yield surface and Mohr-Coulomb diagrams

Over-consolidated sample

Under-consolidated sample



More Later



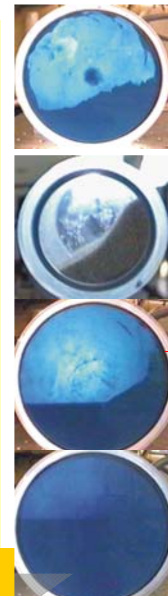
Flow Regime Boundaries

Granular materials exhibit several regimes of behavior: **solidlike, inertial, fluidlike,** and **suspension**, but not all materials can pass through all of these states. Our concern is with the criteria that determine the **transition** from one regime to another and with the **boundaries** to the various flow regimes that these criteria define. Experimentally we have focused on fine, cohesive powders, where the interparticle cohesive force dominates over gravitational force and where entrained air can cause moving powder to become fluidized.

Particle size, particle density, cohesiveness, gas-solid interaction and kinetic energy determine which of these types of behavior should be expected

Flow regimes of granular matter

1. **Solidlike regime – Plastic flow**
   - Velocities are zero or small
   - Stresses are independent of velocity
2. **Inertial regime**
   - Spacing between particles much less than their size
   - Stresses due to transport of moment by interparticle collisions
3. **Fluidlike regime**
   - Spacing of the same order of particle size
   - Interstitial fluid velocity determines the stresses
4. **Suspension**
   - Spacing much greater than particle size
   - Interaction between particles negligible



Fine particles do not pass through the inertial regime. Why?

Principal Contributor: Valverde

Typical transition velocities

- Solid plastic to fluidization onset:

$$\Delta p/h \simeq 100\frac{\mu}{d_p^2}\frac{(1-e)^2}{e^3}U$$

$$\Delta p = \rho g h\left(1+\frac{\sigma_t}{\rho g h}\right)$$

$$U_{of} \simeq \frac{0.01}{\mu}\frac{e^3}{(1-e)^2}\rho g d_p^2\left[1+\frac{\sigma_t}{\rho g h}\right]$$

$$\frac{\sigma_t}{\rho g h} = \nu + B\frac{d_a}{d_p^2}$$

- Gas velocity for suspension of a particle:

$$U_s = \frac{\rho_s g d_p^2}{18\mu}$$

- Shear velocity for transition to inertial flow (Savage and Hutter 1988):

$$\frac{\rho_s d_p^2 (U/\delta)^2}{P} \sim 0.1$$

P is total normal stress, and
δ is shear-layer thickness

Castellanos et al, Phys Rev Lett., 1999, Vol. 82(6), pp 1156-9.

Principal Contributor: Valverde

Some estimations…

Layer of 10μm toner particles 1cm deep:

- Transition from plastic to fluidized state

$$U_1 \sim 1\text{cm/s}$$

- Transition from plastic to inertial flow

$$U_2 \sim 100\text{cm/s}$$

Conclusion: *Toner does not exhibit inertial flow.*

Layer of 200μm carrier beads 1cm deep:

- Transition from plastic to inertial flow

$$U_1 \sim 10\text{cm/s}$$

- Transition from plastic to fluidized state

$$U_2 \sim 100\text{cm/s}$$

Conclusion: *Difficult to fluidize carrier.*

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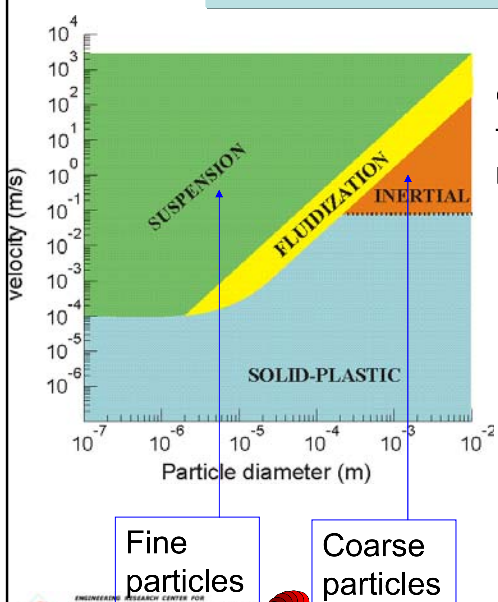
Principal Contributor: Valverde

Flow regimes of granular materials



Granular materials can display four different dynamical regimes:

- Plastic flow
- Inertial flow
- Fluidization
- Suspension

Small particles in a gas experiment a direct transition from solid-plastic flow to gas-fluidized regime

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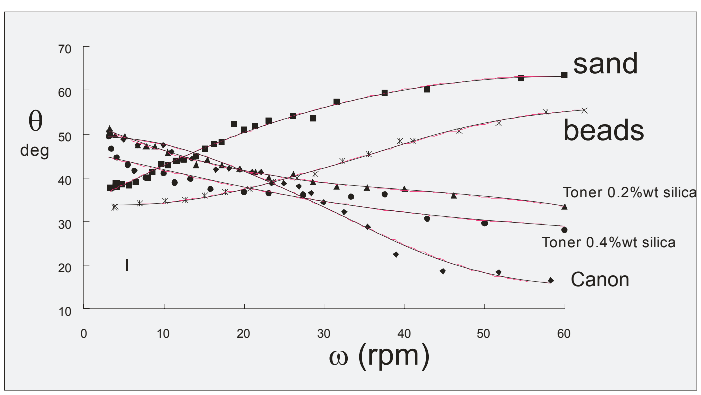
Principal Contributor: Valverde

Gas-solid interaction

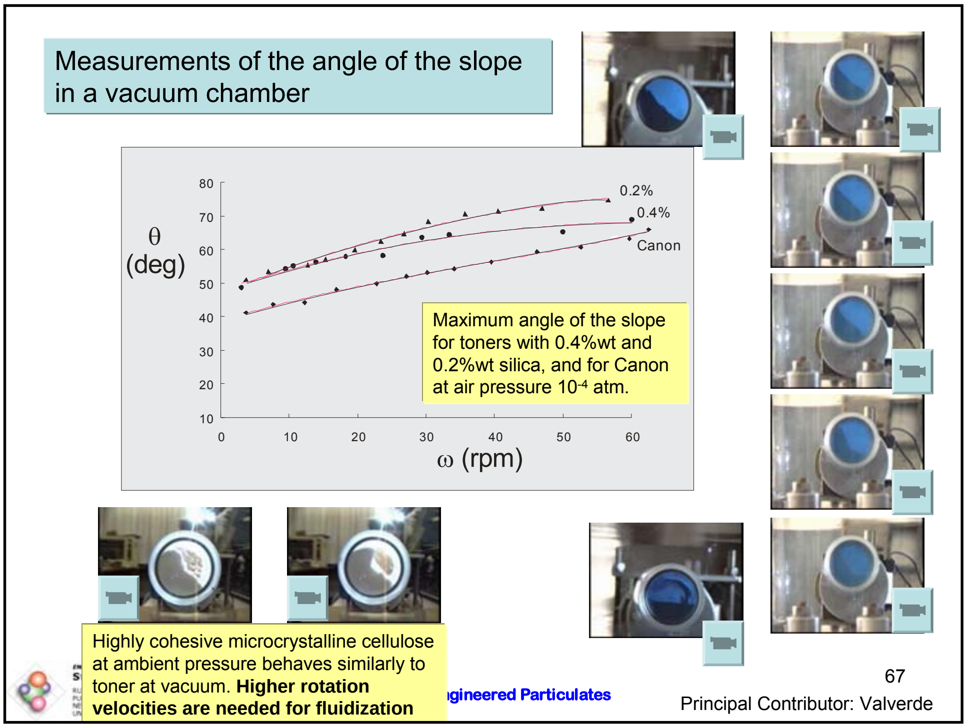
Highly porous agglomerates of fine particles interact with the surrounding gas leading to **fluidization**

The dynamic of large beads is determined by interparticle collisions, leading to **inertial** regime

Measurements of the angle of the slope in a rotating drum



Maximum angle of the slope of sand and beads (same resin as Xerox toners) and average angle of Canon CLC 500 and model Xerox toners (with 0.4%wt silica and 0.2%wt silica) at fracture as a function of rotation rate in a rotating drum at atmospheric pressure.



Measurements of the angle of the slope in a vacuum chamber
θ (deg)
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
ω (rpm)
0.2%
0.4%
Canon
Maximum angle of the slope for toners with 0.4%wt and 0.2%wt silica, and for Canon at air pressure 10-4 atm.
Highly cohesive microcrystalline cellulose at ambient pressure behaves similarly to toner at vacuum. Higher rotation velocities are needed for fluidization
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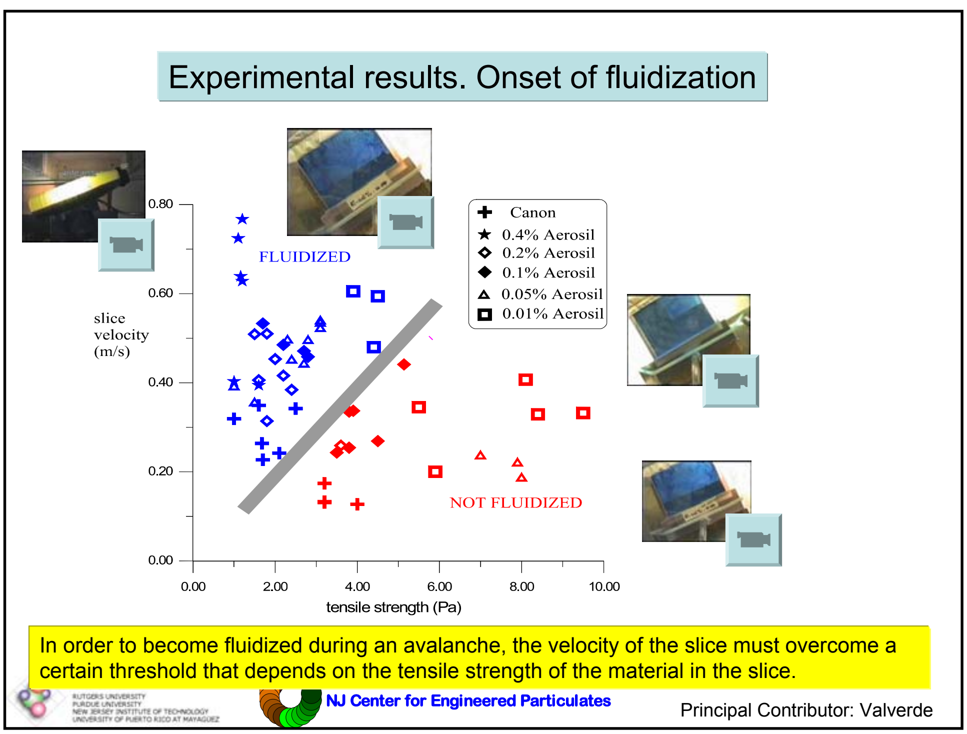

Experimental results. Onset of fluidization
slice velocity (m/s)
0.80
0.60
0.40
0.20
0.00
0.00
2.00
4.00
6.00
8.00
10.00
tensile strength (Pa)
FLUIDIZED
NOT FLUIDIZED
Canon
0.4% Aerosil
0.2% Aerosil
0.1% Aerosil
0.05% Aerosil
0.01% Aerosil
In order to become fluidized during an avalanche, the velocity of the slice must overcome a certain threshold that depends on the tensile strength of the material in the slice.
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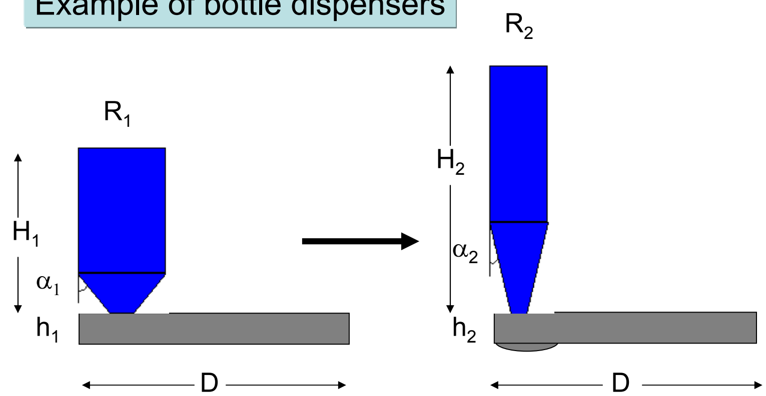
Example of bottle dispensers

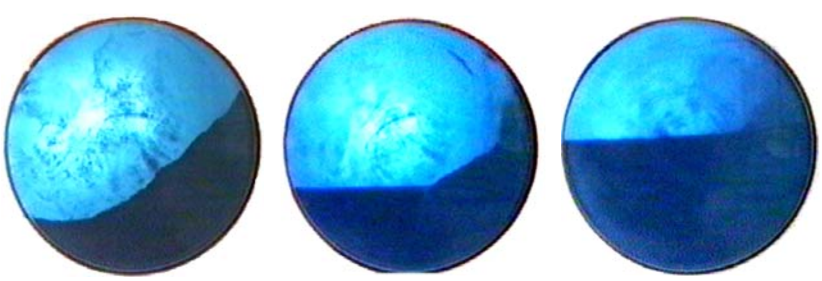


$H_2 > H_1$ kinetic energy of toner at impact greater in right bottle

$\alpha_1 < \alpha_2$ less compaction of toner in right bottle

Both effects results in better flow

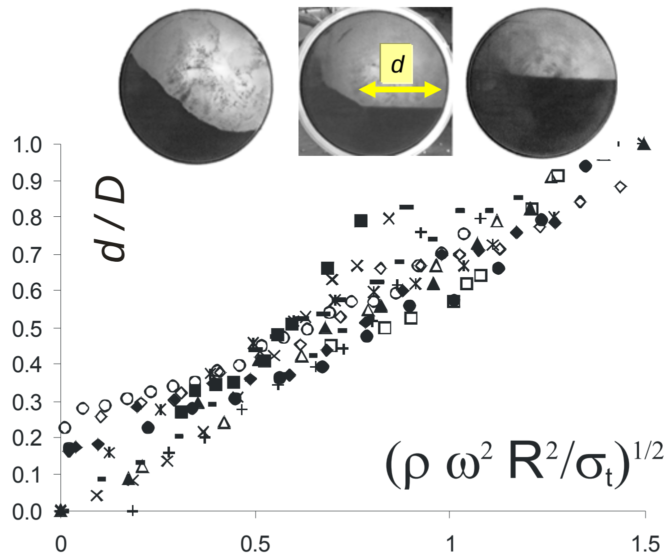
Transition from rigid-plastic flow to gas-fluidized regime



ω = 10 rpm | ω = 45 rpm | ω = 100 rpm

$\omega \Uparrow$

Periodic avalanches → fluidization



For a set of powders of varying cohesiveness and for different geometries, fluidization is universally ruled by the ratio of the kinetic energy density $\rho\ \omega^2$ **R^2** to the powder tensile strength σ_t.

Principal Contributor: Valverde

- The **flow regime diagram** provides a useful way of interpreting the flow properties of both fine, cohesive powders and coarse granular materials.
- In general the motion of coarse granular material is characterized by transition from **plastic to inertial flow**, whereas fine particle motion at atmospheric pressure is characterized by the transition from **plastic to fluidized flow**.
- Fluidized flow, however, requires an ambient gas and at low gas pressure the fluidization process is suppressed.

Bulk measurements (bulk density, tensile strength, etc.) are needed to predict the behavior of a particular powder.

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Principal Contributor: Valverde