Powder Technology
From landslides and concrete to avalanches and chocolate

Prof. P. Bowen, Dr. Peter Derlet

Week 1&2
This week (1) and next week (2)

- Introduction – Brief overview of course contents
- Practical example of importance of particle packing and colloidal stability – particle-particle interactions
  - Transparent polycrystalline ceramics– rheological model …Yodel…
- This week start - Next week finish - Particle packing
  - Spheres and regularly shaped particles (cylinder…)
  - Irregularly Shaped Particles
  - Effect of size on packing
  - Effect of size distribution (log-normal)…..
  - Models - Numerical and Analytical (empirical)
  - Bi-modal distributions – multimodal distributions
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This Week

- Introduction – brief overview of course
- Brief revision of rheology of suspensions
- Example – importance of particle packing and interparticle forces in application
  - Transparent polycrystalline ceramics – rheological model …Yodel…
- This week – Particle packing
  - Spheres and regularly shaped particles
  - Irregularly shaped particles
  - Effect of size on particle packing
  - Effect of the size distribution (log-normal)…..
  - Numerical and analytical models
  - Bimodal- Mutlimodal Distributions
- Next week – Complete particle packing & two examples in Practice and DEM simulations
Particle Packing - Empilement - Compactage

♦ Literature Models
  – Empirical Models
  – Semi-empirical models - physics of particles
  – Numerical and analytical (computer aided simulations)

♦ Models to evaluate packing or porosity in a packed powder as a function of 4 characteristics:
  – Particle Shape - sphericity
  – Modal Size differences in multimodal distributions
  – Mean particle size
  – Size distribution

♦ Effect of agglomeration also plays an important role on particle packing
Particle Packing - Empilement - Experimental

- Calibrated Volume – filled with powder – weigh - get relative density – “apparent or bulk density” – pores included
- Container must be >25 x bigger than particles to avoid wall effects

Random Loose Packing (RLP): weigh after filling. Analogous with apparent or bulk density

Random Close Packing (RCP): weigh after tapping – height and number of taps (TP1 Ceramic Processing course)

Pore Fraction – $\varepsilon$

Solid Fraction – $\phi$

$\phi = 1 - \varepsilon$
Particle Packing - Basics

- Facilitate sintering of powder compacts
  - best packing possible
- Packing of spheres – monosized
  - Cubic 52.4%,
  - Face centred cubic 74%
  - Random close packing 64%

- Limitation - spheres - single size
  - Reality - distribution
  - Shape* - cylinders or discs
  - packing efficiency decreases with length/diameter ratio


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13/09/2019
### Spheres – Monodisperse - pores

\[ \phi = 1 - \varepsilon \]

<table>
<thead>
<tr>
<th>Packing type</th>
<th>Solid Fraction (Vs) - ( \phi )</th>
<th>Pore Fraction (Vp) - ( \varepsilon )</th>
<th>Coordination Number (Np)</th>
<th>Relative pore size (Dp/d)</th>
<th>Pore opening size (Dc/ d)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ordered</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cubic</td>
<td>0.524</td>
<td>0.476</td>
<td>6</td>
<td>0.732</td>
<td>0.414 D</td>
<td>1</td>
</tr>
<tr>
<td>Hexagonal close packed</td>
<td>0.74</td>
<td>0.26</td>
<td>12</td>
<td>0.225-0.29</td>
<td>0.1550</td>
<td>1</td>
</tr>
<tr>
<td><strong>Random</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- RLP</td>
<td>0.516</td>
<td>0.484</td>
<td>5-6</td>
<td>0.463</td>
<td>0.15-&gt; 0.4</td>
<td>2</td>
</tr>
<tr>
<td>- RCP</td>
<td>0.642</td>
<td>0.358</td>
<td>6-7</td>
<td>0.338</td>
<td>0.15-0.2(5)</td>
<td>2</td>
</tr>
</tbody>
</table>


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### Particles - Anisotropic – *regular* shape - *random* packing

<table>
<thead>
<tr>
<th>Packing</th>
<th>Form factor (l or h / d)</th>
<th>Solid Fraction (Vs) - $\phi$</th>
<th>Pore Fraction (Vp) - $\varepsilon$</th>
<th>ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Random Loose Packed - RLP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cylinders</td>
<td>64/1</td>
<td>0.05</td>
<td>0.95</td>
<td>4</td>
</tr>
<tr>
<td>cylinders - sticky</td>
<td>1 to 111</td>
<td>0.12 to 0.0077</td>
<td>0.88 to 0.9923</td>
<td>5</td>
</tr>
<tr>
<td><strong>Random Close Packed (Tapped) (RCP)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cubes</td>
<td>1</td>
<td>0.72 – 0.79</td>
<td>0.21 – 0.28</td>
<td>6</td>
</tr>
<tr>
<td>rectangles</td>
<td>(2x5x10)</td>
<td>0.51</td>
<td>0.49</td>
<td>6</td>
</tr>
<tr>
<td>plates</td>
<td>(4x4x1)</td>
<td>0.67</td>
<td>0.33</td>
<td>6</td>
</tr>
<tr>
<td>cylinders</td>
<td>167</td>
<td>0.03</td>
<td>0.97</td>
<td>6</td>
</tr>
<tr>
<td>cylinders</td>
<td>60</td>
<td>0.09</td>
<td>0.91</td>
<td>6</td>
</tr>
<tr>
<td>Cylinders</td>
<td>5</td>
<td>0.52</td>
<td>0.48</td>
<td>6</td>
</tr>
<tr>
<td>Cylinders</td>
<td>1</td>
<td>0.60 – 0.67</td>
<td>0.33 – 0.40</td>
<td>6</td>
</tr>
<tr>
<td>discs</td>
<td>0.5</td>
<td>0.62 – 0.64</td>
<td>0.36 – 0.38</td>
<td>6</td>
</tr>
</tbody>
</table>

From German 89

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Sphericity $\psi$: Irregular particles

- Influences particle packing even for narrow or monosized distributions
- Several definitions of sphericity $\psi$ – generally defined as
- Ratio between the surface of a sphere $S_s$, which has the same volume $V_s$ as the particle, with respect to the real particle surface $S_p$

$$\psi = \frac{S_s}{S_p}$$

$S_s < S_p$

$\psi < 1$

- e.g. SSA from PSD measured by laser diffraction assumed spherical particles ($S_s$)
- SSA for nitrogen adsorption (BET model) all surface ($S_p$)

$$SSA = \frac{6}{\rho} \cdot \left( \frac{\sum n_i d_i^2}{\sum n_i d_i^3} \right)$$

$\psi = 0.645/1.09 = 0.59$

$\psi$ for Portland cement

Normally for single particles – simple method for non-porous powders…


$^\text{§}$ M. Palacios et al Chapter 10:, In A practical guide to microstructural analysis of cementitious materials, Elsevier, 2016
Sphericity $\psi$: influence on packing of monosized particles

- German* - «relative roundness» - sphericity
- Clear Effect
- Decrease in packing fraction when we have particles that deviate from a sphere

Sphericity $\psi$: empirical modelling

- Find an empirical model for well defined particles
- Use for prediction of other systems with similar characteristics
- $f(\psi)$ as a function of sphericity $\psi$ and $\varepsilon_s$, the initial or maximum porosity (e.g. RCP – RLP …)

Yu used empirical model of Brown & et al (YU93)
- cylinders and discs
- Good correlation

$$\varepsilon(\psi) = \varepsilon_s f(\psi)$$

$$\varepsilon(\psi) = \varepsilon_s^{1.785\psi^{1.584} - 0.785\psi^{4.897}}$$
Philipse [PHI96 et PHI97] studied the influence of shape using a random contact equation
- $\rho_n$ is the number density of particles by unit volume
- And the outputs are $\phi$ and $\varepsilon$

Where $<c>$ is the mean number of contacts per particle and $v_{\text{ex}}$ mean orientational excluded volume

This volume for 2 thin rods (with spheroidal caps) can be represented by:

$$v_{\text{ex}} = \frac{\pi}{2} L^2 D + 2\pi D^2 L + \frac{4}{3}\pi D^3$$

$D$ and $L$, being the diameter and length of the particle, respectively.

e.g. glass fibres used in polymer composites (car engine radiator)
Sphericity $\psi$: modelling– analytical

- For a random packing of rods the apparent density decreases drastically as the form factor (aspect ratio) increases - data Philipse and others – Milewski [MIL78] et Nardin et al. [NAR85].

- Conclusion: random contact equation allows a prediction of long thin rigid rod packing (monosized particles)

- Important for the fabrication of composites – glass-fibre – polymer composites – used in car radiators

$\phi = \rho_n v_p$

Real particle volume $v_p$ [PHI96 et PHI97]
Influence of size – mean particle diameter, $d_{v50}$

- Suzuki et al [SUZ2001] studied quasi monosize fly ash – but not perfect spheres

For sizes greater than 15µm, pore fraction remains constant – no image in article possibly – agglomerates?

$\varepsilon$ - decreases as particle size increases
Suzuki et al [SUZ2001] studied quasi monosize silica spheres again – $\varepsilon$ decreases as particle size increases – upper limit approaching theoretical limits but still not constant.
Influence of size – mean particle diameter, \( d_{v50} \)

- Wakeman [WAK75] using lead glass spheres with a narrow size distribution but with sizes approaching 1mm again – \( \varepsilon \) decreases as particle size increases – upper limit approaching theoretical limits and close to constant value
Relative Forces

- As the particle size decreases*
- There is a relative increase of:
  - friction,
  - adhesion
  - Other « surface » forces
- With respect to:
  - gravitation
  - vibration,
- [YU97] – for sizes < 100µm,
- Van Der Waals (dispersion) forces have an influence on packing

PSD : influence of PSD width (geometric standard deviation, $\sigma_g$) on packing of log-normal distributions

**Empirical Models**

- **Model - Dexter & Tanner**
  - Steel spheres, RLP, d= 0.238 to 1.746cm.
- **Model - Sohn & Moreland**
  - Sand, RCP, d=0.1 à 5mm

Monodisperse

- Ordered - 0.74
- Random - 0.64
Particle Packing – Numerical Models

- Particle size distribution – example log-normal distribution
  - Increase in the width increases packing density

Understood intuitively that the fine particles filled the gaps between the big particle but not enough fine particles!

With very broad distribution some very big particles with 100% density.

Care – effect of distribution width on final microstructure

Target for ceramics – narrow size distribution – more homogeneous microstructure

Multimodal – approach successful in concretes.


Figure 3.5.1.
Particle Packing – Log Normal distribution

**Numerical**

• Model - Nolan & Kavanagh - Spheres, RCP & RLP

Key Points:
- **RCP** - Good correlation with experimental results
- **RLP** – only for $\sigma > 2.5$
- $\sigma < 2.5$ bridging – stable numerically – but not in reality – gravity etc… – need to know forces used in models
Particle Packing and Agglomeration

- Processing of nanosized powders <100nm
- Packing of agglomerated powders poor
  - pores inside the particles and between the primary particles
  - pore distribution - bimodal (inter-particle, intra-particle)
- Densification leads to inhomogeneities - intra-particle pores disappear earlier leaving large stable inter-particle pores
- Want same size pores in particles and between particles – factor of agglomeration useful to quantify state of agglomeration
- Aggregates increase in effective volume effects rheology – cement – YODEL model (FLA 06)
Fine powders have the tendency to form agglomerates (during forming) or aggregates (synthesis).

Define an agglomeration factor, Fag or agglomeration number, FN*,

\[ F_{ag} = \frac{d_{v50}}{d_{BET}} \]
\[ d_{BET} = \frac{6}{SSA \cdot \rho} \]
\[ F_N = \frac{V_s}{V_{BET}} \]

Fag, very good indication of the degree of agglomeration allows comparison between powders and treatments.

d_{v50} - median diameter (volume, μm), d_{BET} is an average diameter (mm) calculated from specific surface area, SSA (m²/g) measured by nitrogen adsorption (model BET), ρ powder density (g/cm³), V_{BET} volume of sphere from d_{BET}, V_s volume of powder in agglomerate of given size, excluding pore volume (estimated from nitrogen desorption pore volume).
The 6 in the d_{BET} is a shape factor for a sphere, for cubes this is 7.44, parallelepipeds 9.38 and for flakes 24


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Commercial gamma alumina - Degussa C, -(Germany > 99.6 Al₂O₃),

Deg C

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>% α</td>
<td>2.8</td>
</tr>
<tr>
<td>SSA (m²/g)</td>
<td>107</td>
</tr>
<tr>
<td>d_BET (nm)</td>
<td>16.5</td>
</tr>
<tr>
<td>d_v50 (nm)</td>
<td>41.6</td>
</tr>
<tr>
<td>σ_v50 (nm)</td>
<td>32.8</td>
</tr>
<tr>
<td>F_ag</td>
<td>2.2</td>
</tr>
<tr>
<td>F_N</td>
<td>7.5</td>
</tr>
<tr>
<td>Pore dia (nm)</td>
<td>13.3</td>
</tr>
<tr>
<td>ρ_h (g/cm³)</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Colloidal Stability Calculations and Rheology*

- PSD Horiba Capa 700 - roughly spherical primary particles still agglomerates*

- Degussa C, (Germany > 99.6 Al₂O₃)

<table>
<thead>
<tr>
<th>Acid</th>
<th>dᵥ50 [nm]</th>
<th>σᵥ50 [nm]</th>
<th>FₐG</th>
<th>F₍</th>
<th>dₜ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formic</td>
<td>44.8</td>
<td>37.3</td>
<td>2.33</td>
<td>5</td>
<td>37.6</td>
</tr>
<tr>
<td>Acetic</td>
<td>41.6</td>
<td>32.8</td>
<td>2.16</td>
<td>4</td>
<td>25.4</td>
</tr>
<tr>
<td>Propanoic</td>
<td>38.0</td>
<td>27.8</td>
<td>1.63</td>
<td>3</td>
<td>23.3</td>
</tr>
<tr>
<td>Butyric</td>
<td>37.4</td>
<td>44.1</td>
<td>1.94</td>
<td>3</td>
<td>26.7</td>
</tr>
</tbody>
</table>

*Degussa C, (Germany > 99.6 Al₂O₃) Deg C

% α 2.8
SSA (m²/g) 107
d_BET (nm) 16.5
dᵥ50 (nm) 41.6
σᵥ50 (nm) 32.8
FₐG 2.2
F₍ 10
Pore dia (nm) 13.3


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Particle Packing and Agglomeration

Slip Casting
Pour dispersion into porous mould - water drawn out by capillary forces - dry to give powder compact

<table>
<thead>
<tr>
<th>Sample</th>
<th>Experimental</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Packing fraction</td>
<td>Pore dia (nm)</td>
</tr>
<tr>
<td>Deg C - AA</td>
<td>0.635</td>
<td>18.9</td>
</tr>
<tr>
<td>Deg C –PAA</td>
<td>0.766</td>
<td>17.5</td>
</tr>
</tbody>
</table>

L – random loose packing C – random close packing

♦ Calculated packing fraction -taking into account powder porosity
♦ Porosity measured from nitrogen desorption
♦ Very good correlation with model for packing fraction - measured PSD's $\sigma_{v50}/d_{v50}$
♦ Pore diameters more complicated but correct order of magnitude
♦ PAA improves packing from loose to close packing
♦ PSD and model allows us to decide if we have optimum dispersion

PAA -polyacrylic acid (2000 mol wt) – COOH groups – gives larger steric contribution to repulsive force

Compared to Acetic acid (AA)...see week 7
Numerical Models

- Concepts of collective arrangements
  - based on 2 types of long distance forces due to compression and gravity
  - repulsion at short distance due to impenetrability of the particles.

- 2 mechanisms simulated by placing the particles in a random positions in the boxes with overlap, then allow movements until overlap of particle is negligible - Nolan & Kavanagh (NOL 93)
  - D = 0.1 to 20 in divisions of 0.1 – 200 size classes
  - Modification of previous approach to take into account the size distribution (NOL93)
  - As the Repulsive Force between particles is reduced their mobility is increased–
  - Place particles at centre – avoids stable arrangements
  - Number of movements per particle $\alpha$ 1/D (smallest are most mobile)
Numerical Models – regular non-spherical shapes

- Same model was also used to evaluate the pore size distribution and its connectivity (NOL94)
  - Put a sphere into a vacant position (pore) – allow it to grow until it impinges on neighbouring particles - gives pore diameter
  - Percolation size of porous network – function of standard deviation, $\sigma$ et $\sigma_{\text{pores}}$ increases as $\sigma_{\text{particles}}$ increases
- For irregular particles (NOL95) – model by assembling spheres – otherwise same numerical approach – very good correlation with experiment

<table>
<thead>
<tr>
<th>RCP</th>
<th>cylinders</th>
<th>Ellipsoids (beans)</th>
<th>Nails or T-shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>0.674</td>
<td>0.676</td>
<td>0.519</td>
</tr>
<tr>
<td>Exp.</td>
<td>0.67</td>
<td>0.67</td>
<td>0.52</td>
</tr>
</tbody>
</table>
Numerical Models - Irregular shapes

- Knowledge Based System approach allows the shape to be modelled and packing investigated [SMI97A].
- Principle as above: use a Random Sphere Construction=RSC allows formation of irregular particles from image analysis to then investigate their packing and apparent densities.
- Packing density decreases as irregularity increases.


Water atomised stainless steel powder
Numerical Models – spheres …

An alternative method - Navi & Pignat (LMC-EPFL)

- Take a distribution « model (e.g. log-normal) » or measured PSD - place in volume randomly
- Need to define minimum distance between particles (1nm - 100nm (pixel –mesh size))
- First place the bigger particles otherwise can end up without volume sufficiently big to place them at the end
- If the distribution is too broad – many particles – 1-2 days for the calculations – >50 000 particles (2003….)
- Cut the distribution in a coherent manner e.g. $d_1$ to $d_{99}$ – coherent result for < 20 000 particles – 4-6 hrs calcs
- Used to estimate the coordination number of particles for the Yield stress model predicts the « yield point » for cement pastes Robert Flatt – EPFL Thesis No. 2040 (1999) [FLA06]
- Christian Pignat used it as a starting point for the simulation cement hydration ($C_3S$) – EPFL Thèse No. 2763(2003)
Numerical Models – Discrete Element Methods


- Discrete Element Methods (DEM) – treat as particles

- 4000 particles – can use experimental distributions or log-normal

- Create a « gas » of particles in a large volume – low packing density – 15% Fig. 2 (possible also to use the same approach as Navi et Pignat 45%)

- Then you densify the gas and contacts between particles are created – the contact forces for each contact are calculated and thus the forces on each particle can then be calculated.

- Can have sliding – take into account friction – plastic deformation – as a function the powders’ intrinsic physical properties

- Selective Laser Sintering SLS – surface of contact important for heat transfer and sintering – evolves during sintering and thus the thermal conductivity changes -

DEM – without interaction with friction

C. Martin - (GPM2), INP G (France)

Z - coordination number

With friction

More realistically

No friction
Elastic interactions
All particles of the same size

摩擦
粘附
拉紧
分布
尺寸

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Particle Packing – bimodal - multimodal

- Zok & Lange [ZOK9] – large particles in a matrix of fine particles
- Two monodispersed fractions – fines and large particles
- Packing is disturbed at the interfaces – isolated spheres and between contacts of large particles
- To fill the spaces between the large particle with the fine particles the fine particles need to diffuse into the spaces – this depends on the percolating pore size- the ratio between large/fine diameters needs to be about 10:1
Particle Packing – bimodal - multimodale

- Maximum packing (minimum apparent volume)
- Is obtained for a large fraction - 0.735 – fine fraction 0.265 = (26.5% fines)
- $\rho=0.87$ ($\rho_0=0.64$, monosized) – difficult to get ordered mixture in practice without segregation

- Multimodal can achieve $>0.9$ but relative sizes not often interesting for ceramics but for concrete multimodal particle mixtures are used
DEM – bi-modal

Mixtures of two sizes

Size ratio – 1:10

Furnas relation  
C. Martin - (GPM2), INP G (France)
Multi-modal – YODEL de Larrad*

- Used YODEL yeild stress model for mixtures of powders
- key parameter for multimodal distributions is \( \phi_m \) of mixtures.
- Used de Larrad compressive packing model - to give \( \phi_m \) for mixtures
- from their individual particle size distributions.
- YODEL predicts yield stresses of multimodal suspensions within 10% of the experimental results.

- De Larrad looked at 2 limits of bi-modal

I) large particles (1) close to \( \phi_m \) prevented by a loosening effect of the small particles (2)

\[
\gamma_1 = \frac{\beta_1}{1 - (1 - \alpha_12 \beta_1 / \beta_2) \times v_2}
\]

where \( \beta_1 \) and \( \beta_2 \) are the \( \phi_m \) for components 1 and 2, \( x_{v,2} \) is volume fraction of component 2

II) small particles (2) close to $\phi_m$ in the space left by the large particles (1), prevented by imperfect packing at the surface of the large particles.

\[
\gamma_2 = \frac{\beta_2}{1 - [1 - \beta_2 + b_{21} \beta_2 (1 - 1/\beta_1)] x_{\gamma 1}}
\]

- maximum packing of the mix is taken as $\gamma_1$ or $\gamma_2$, whichever is the lowest.
- The treatment is easily extended to more components as shown by de Larrard*

\[
\gamma_i = \frac{\beta_i}{1 - \sum_{j=1}^{i-1} [1 - \beta_i + b_{ij} \beta_i (1 - 1/\beta_j)] x_{\gamma j} - \sum_{j=i+1}^{n} [1 - a_{ij} \beta_i/\beta_j] x_{\gamma j}}
\]

- de Larrard calibrated model with mixes of sand and aggregate of different sizes and shapes (coarse and rounded).
- Obtained robust equations that would predict $a_{12}$ and $b_{21}$ as a function of the relative average size (mean diameters $d_i$) of these components

\[
a_{ij} = \sqrt{1 - (1 - d_i/d_j)^{1.02}}
\]

\[
b_{ij} = 1 - (1 - d_i/d_j)^{1.50}
\]

Agglomeration Factor

- Packing of agglomerated powders low
  - Pores in aggregate between primary particles
- $F_{ag}$ gives a comparative figure to quantify the state of aggregation and the effect of different dispersion treatment (milling, ultrasonic)
- Packing of agglomerates - if the agglomerate is also not spherical another source to reduce the apparent density – important for transport as well as rheology and powder processing.

**Gamma Alumina**
- $F_{ag} > 2500$!!!
- And irregular shape – flow of such a powder difficult to control – nevertheless it is used for the fabrication of synthetic - Sapphire or ruby

Cr –doped – synthetic ruby
DEM – Shape and aggregation (compaction)

Agregates of particles or non spherical particles

C. Martin - (GPM2), INP G (France)
Dry pressing – ceramics

- Compaction of granules from spray drying process
- Effect of powder characteristics on green density of compact
- Compaction - 3 stages
  - Packing and re-arrangement
  - Deformation of the granules
  - Fracture of the granules (rarely occurs in practice for < 200 MPa)

*Traité des Matériaux p.196-220

Primary Particle (1µm)
Granule for pressing (50-300µm)
DEM – applied to many aspects of powder processing

Particulate nature of the material to be processed

Matrix filling → Compaction → unloading ejection → sintering

- Elastic
- Electrostatic
- Capillary ...

- Plasticity
- Fracture
- Rearrangement

- Elastic unloading
- Cohesion of some contacts

- Diffusion
- Viscoplasticity
- Rearrangement

Particulate material !!
General Trends from the models

- **Sphericity**: packing of particles lower apparent densities if sphericity decreases.
- **Aggregates or agglomerates**: reduce strongly the packing densities – if the aggregates are not spherical a further reduction is observed for randomly packed systems.
- **Particle size**: as the particle size increases the relative contribution of gravity versus interparticle forces (e.g. Van der Waals) increases and packing increases.
- **Particle size distribution**: a broader distribution allows higher packing densities and for bimodal or multi-modal systems this increases further – if the ratio of particles sizes is suitable.
- **Coordination number**: this increases with increasing packing density.
- **For log-normal size distributions**, the empirical models Sohn & Moreland [SOH68], Dexter & Tanner [DEX72] and the numerical models - Nolan & Kavanagh [NOL93] and DEM give coherent results.
- **For irregular shaped powders** such as a ground alumina, the model of Yu et al [YU97] is also an interesting alternative and a good comparative method.
- **Future modelling** of « real particles » with irregular shapes is being developed at NIST – Nic Martys (USA) [FLA04b] – for the moment the code is not in the public domain and the computational power is very heavy (2-3 weeks 30 parallel computers).
Two examples of powders in application or research where particle packing and rheological behaviour linked to particle shape and dispersion (leading us to the next section of the course colloidal dispersions) will be presented.


- Landslides or Apline Debris Flow…..Eric Bardou (Thèse EPFL-2479(2002))

- Typical questions you should be able to answer on the particle packing section

- And a guest speaker on the use of Granular Dynamics DEM simulations for several examples – Dr. Mark Sawley (EPFL)
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La nomenclature et les abréviations utilisées

<table>
<thead>
<tr>
<th>Expression</th>
<th>Abbr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution en taille des particules</td>
<td>PSD</td>
</tr>
<tr>
<td>Réseau de neurones</td>
<td>NN</td>
</tr>
<tr>
<td>Porosité initiale</td>
<td>$\varepsilon_0$</td>
</tr>
<tr>
<td>Porosité</td>
<td>$\varepsilon$</td>
</tr>
<tr>
<td>Sphéricité</td>
<td>$\psi$</td>
</tr>
<tr>
<td>Densité</td>
<td>$\rho$</td>
</tr>
<tr>
<td>Volume spécifique</td>
<td>$V=1-\varepsilon$</td>
</tr>
<tr>
<td>Fraction volumique des petites/grandes particules</td>
<td>$X_S/X_L$</td>
</tr>
<tr>
<td>Diamètre des petites/grandes particules</td>
<td>$d_S/d_L$</td>
</tr>
<tr>
<td>Efficacité d’empilement</td>
<td>$P_e$</td>
</tr>
<tr>
<td>Rapport en taille</td>
<td>$R$</td>
</tr>
<tr>
<td>Taille médiane</td>
<td>$d_{50}$</td>
</tr>
<tr>
<td>Déviation standard PSD</td>
<td>$\sigma$</td>
</tr>
<tr>
<td>Déviation standard PSD absolue</td>
<td>$\sigma_a$</td>
</tr>
<tr>
<td>Déviation standard PSD géométrique</td>
<td>$\sigma_g$</td>
</tr>
<tr>
<td>Volume apparent</td>
<td>$V_a$</td>
</tr>
<tr>
<td>Pression de compactage appliquée</td>
<td>$P$</td>
</tr>
<tr>
<td>Densité et porosité crue</td>
<td>$\rho_c, \varepsilon_c$</td>
</tr>
<tr>
<td>Densité apparente</td>
<td>$\rho_0$</td>
</tr>
<tr>
<td>Température</td>
<td>$T$</td>
</tr>
<tr>
<td>Taille diamétrale des grains</td>
<td>$G$</td>
</tr>
<tr>
<td>Densité frittée</td>
<td>$\rho_f$</td>
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