Compression, Consolidation, Permeation & Flow of Ultrafine Cohesive Powders

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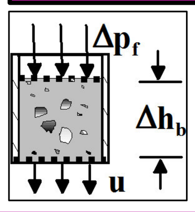
1. Process and handling problems of ultrafine, cohesive powders (d<10 µm)

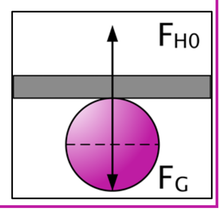
Product design | Conveying | Transport | Dosing & Packing

Macroscopic permeation and flow properties

2. Decreasing particle size d: decreasing pore size and permeability and increasing ratio of adhesion force/weight force



Particle size d µm	Permeability k_f in m/s	Force ratio F_{H0}/F_G
10 – 100	10^{-7} – 10^{-5}	1 - 100
1 - 10	10^{-9} – 10^{-7}	100 – 10^4
0.01 – 1	10^{-13} – 10^{-9}	10^4 – 10^8



Problem Definition

Goal: Understanding of physical **particle** properties at

- Flow-around
- Approach
- Contact
- Detachment
- Sliding

Ultrafine, dry and adhesive particles

Objectives

(1) Combination of Fluid Dynamics (CFD) and Discrete Element Method (DEM) by PFC^{3D} and fluid coupling

(2) Measurement of macroscopic **powder** properties (compression, consolidation and permeation tests)

(3) Evaluation of the process (experiments – simulations)

Cooperation

D. Thevenin – U Magdeburg (MD)
Fluid Mechanics, CFD & DEM coupling

K. Mader-Arndt – U MD
Model "Stiff particles with soft contacts"

A. Bertram – U Magdeburg:
Fundamentals of constitutive laws

Flow & Permeation of Powders

Modeling & Simulation

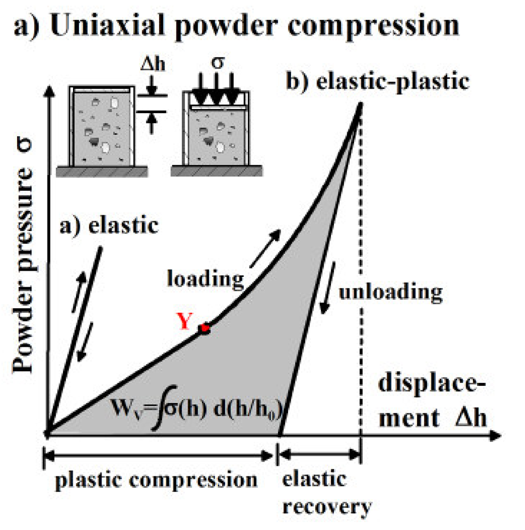
A. Kharaghani – U Magdeburg
Pore network and flow simulations

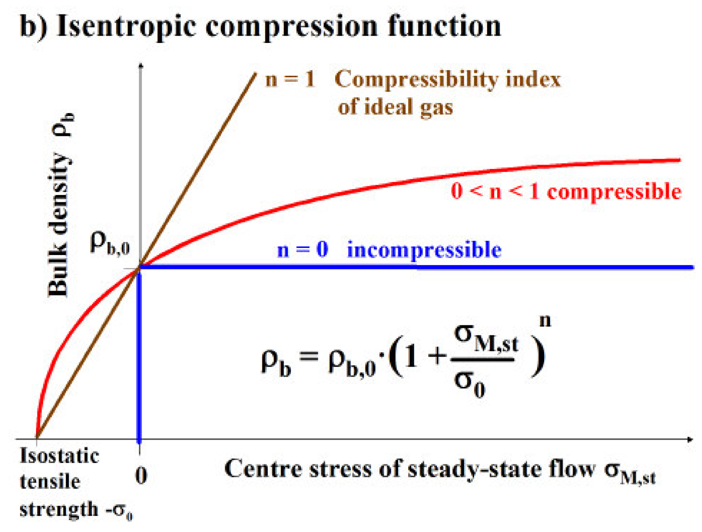
L. Tobiska – U MD:
Numerics of CFD-DEM coupling

S. Luding – U Twente:
Calibration of DEM simulations

Experimental Methods

1) Compression test and model-based data evaluation





Adiabatic gas compression:

$$-\frac{dV}{dp} = \frac{1}{\kappa_{ad}} \frac{V}{p} \qquad (1)$$

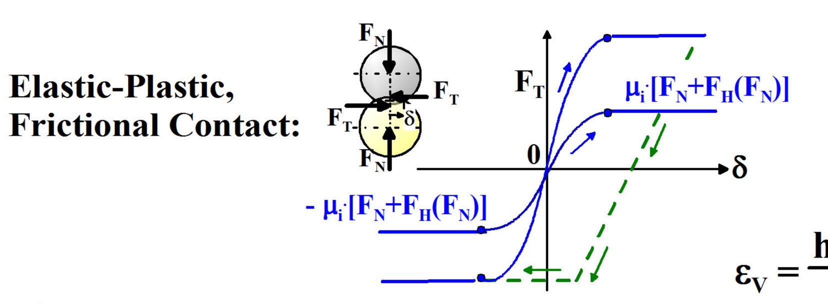
Isentropic powder compression:

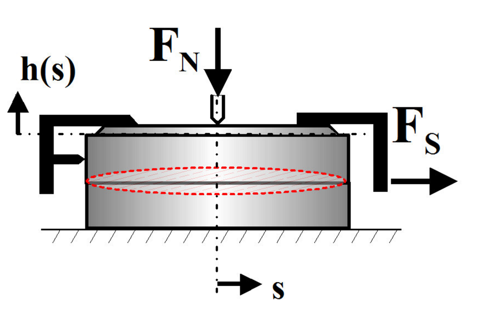
$$\int_{\rho_{b,0}}^{\rho_b} \frac{d\rho_b}{\rho_b} = n \cdot \int_0^{\sigma_{M,st}} \frac{d\sigma_{M,st}}{\sigma_{M,st} + \sigma_0} \qquad (2)$$

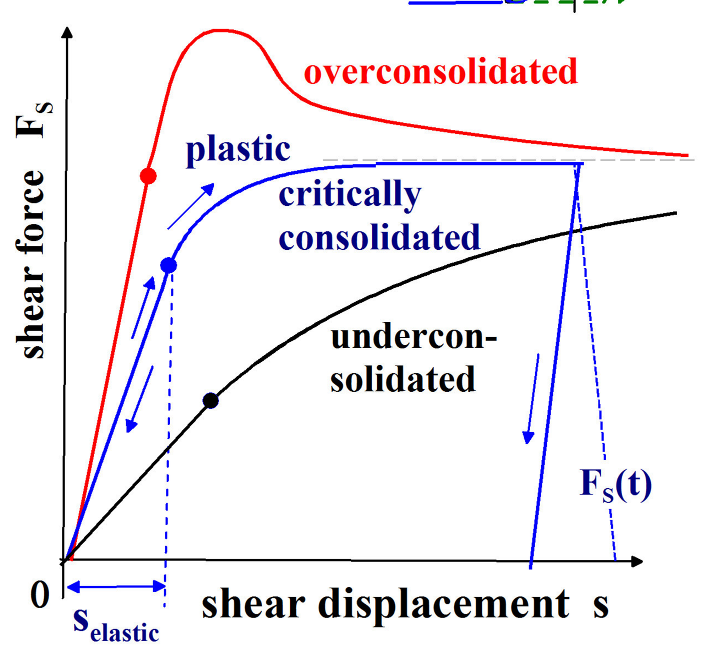
Compressibility index of cohesive powders for small (1 < σ < 50 kPa) and medium pressures (50 < σ < 1000 kPa)

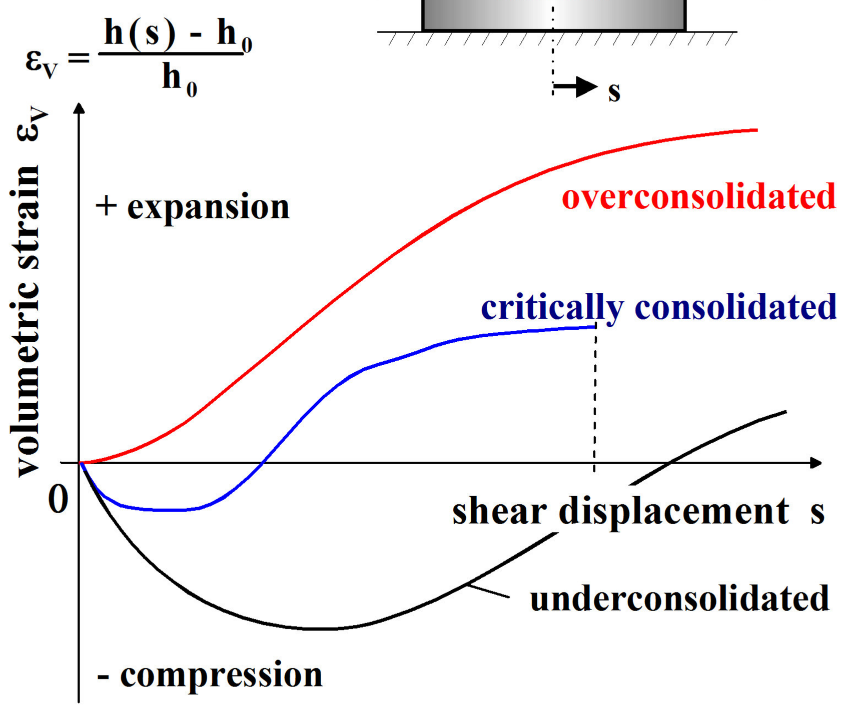
Index n	Evaluation	Examples	Flowabiliy
0 – 0.01	incompressible	gravel	free flowing
0.01 – 0.05	low compressibility	fine sand	
0.05 - 0.1	**compressible**	**dry powder**	**cohesive**
0.1 - 1	**very compressible**	**moist powder**	**very cohesive**

2) Micro-macro aspects of cohesive powder consolidation and shear

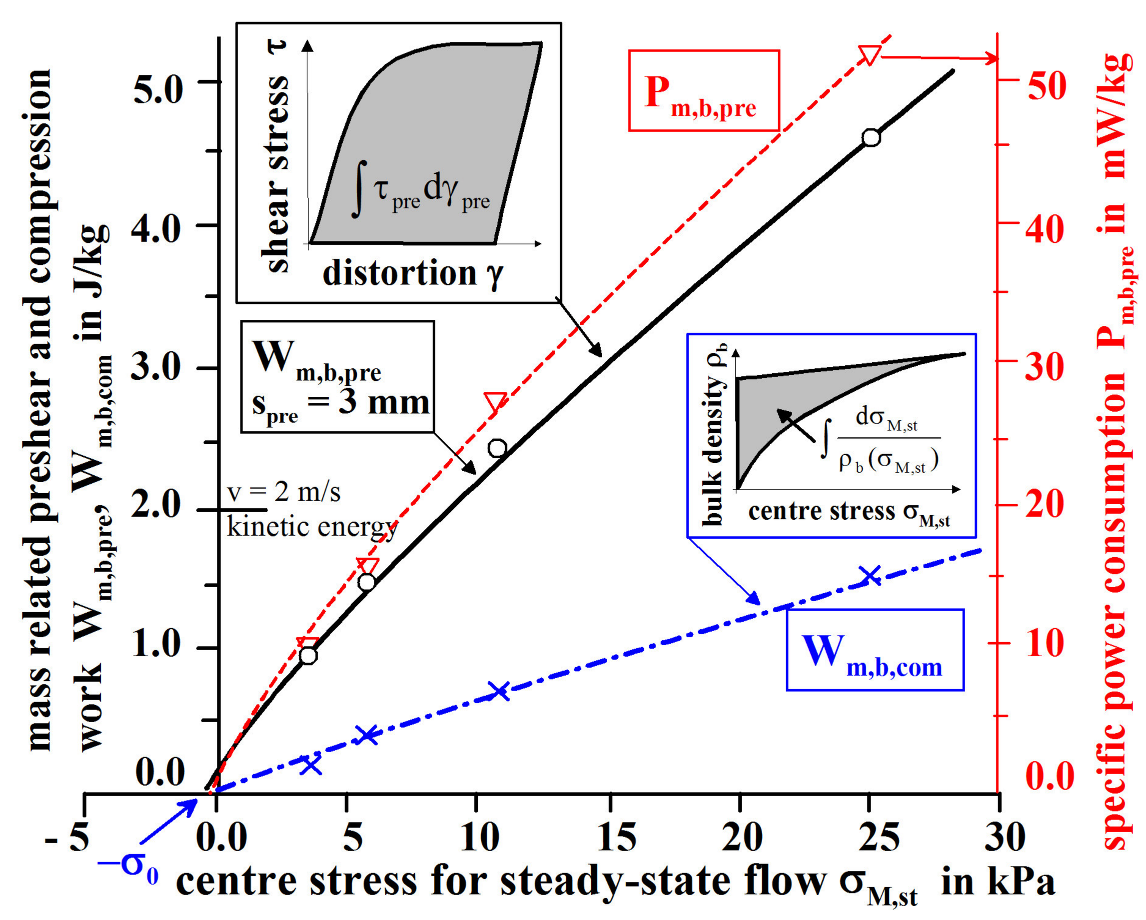




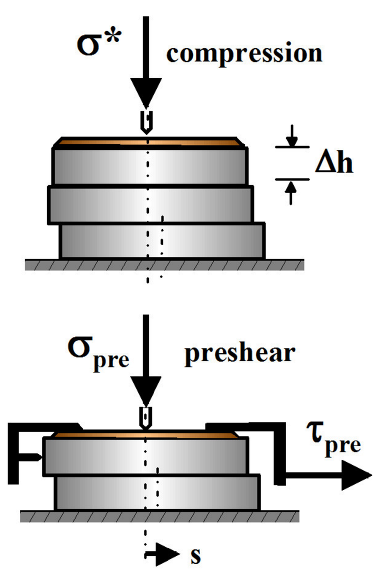




3) Model-based data evaluation of compression and shear work

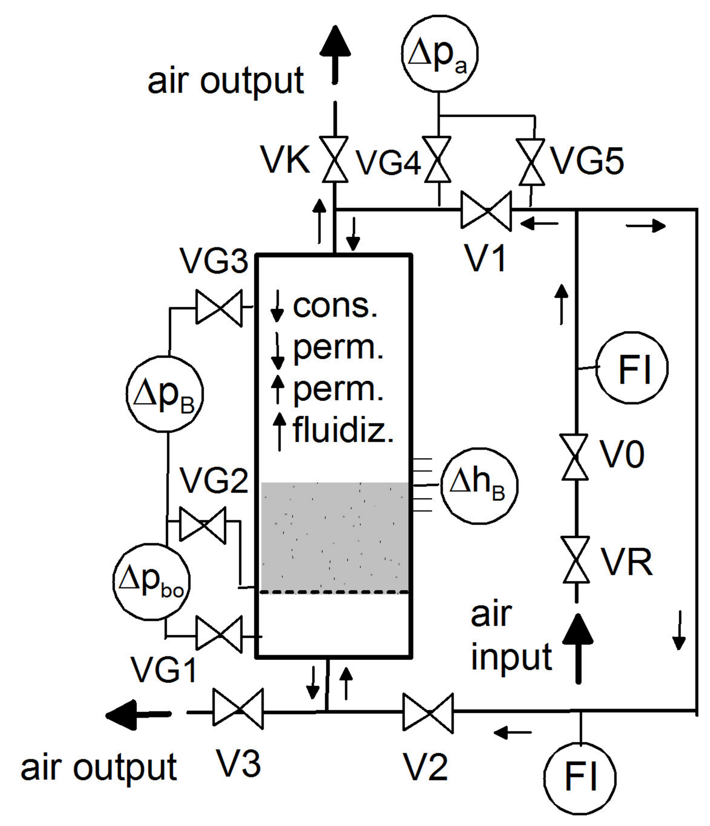


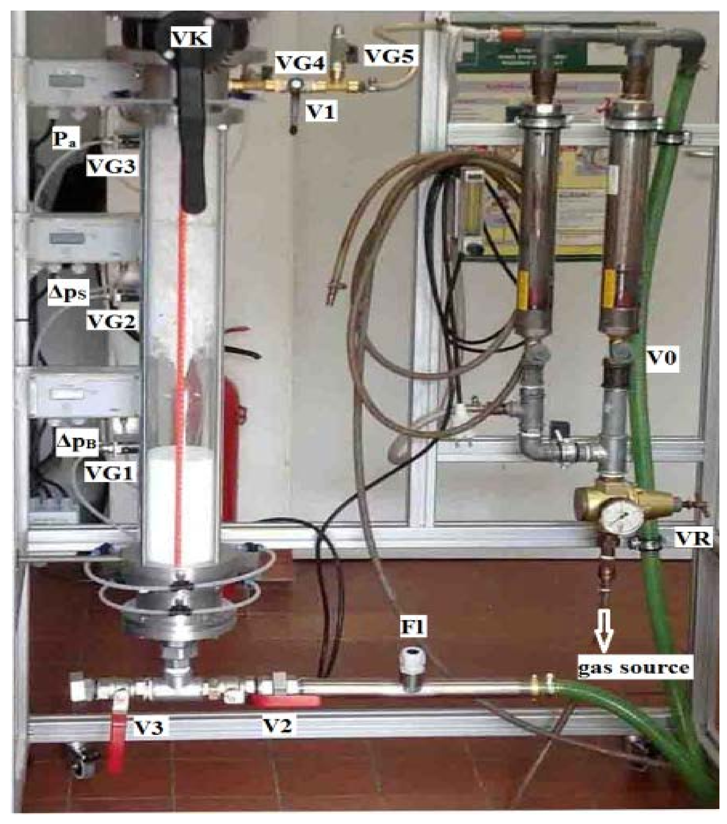
Data of a very cohesive limestone powder (d_{50} = 1.2 µm)



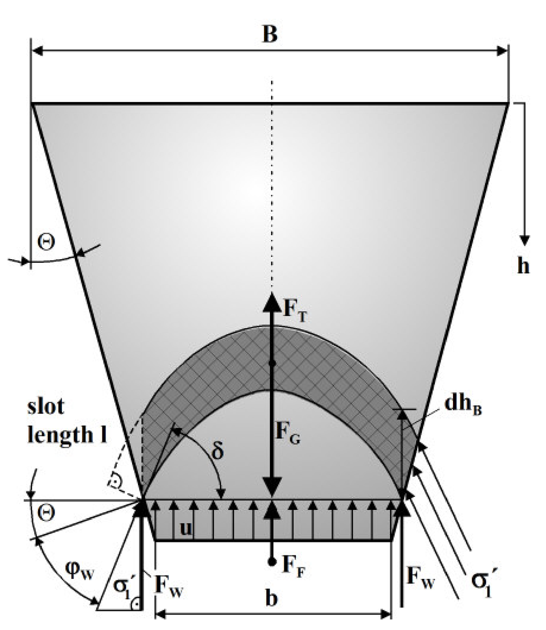
New Home-built Test Rig

4) PI-flow chart and side view of compression, consolidation & permeation cell





Analytical Description



Macroscopic Force Balance at Air Permeated (Counter-flow) Cohesive Powder Bridge:

$$\Sigma F \uparrow = 0 = -F_G + F_T + F_W + F_F$$

Dead weight as driving force:

$$F_G = \rho_b \cdot b \cdot dh_B \cdot l \cdot g$$

Wall force (cohesive resistance):

$$F_W = \sigma_1' \cdot \sin\delta \cdot dh_B \cdot \cos\delta \cdot 2l$$

Force of inertia:

$$F_T = \frac{F_G}{g} \cdot \frac{dv}{dt}$$

Drag force of air permeation resistance:

$$F_F = Eu_B \cdot \frac{3 \cdot \rho_f \cdot u_r^2 \cdot (1-\varepsilon)}{4 \cdot d \cdot \varepsilon^2} \cdot b \cdot l \cdot dh_B$$

5) Micro-macro aspects of hindered powder flow

Air permeation resistance =
- **particle** flow-around drag +
- macroscopic **powder** bed resistance (pressure drop)

Macroscopic **powder** flow resistance in a convergent hopper =
- cohesive flow resistance +
- air permeation resistance

Process Variables	Hopper Discharge and Laminar Permeation through a Cohesive Powder Bridge
Differential equation of motion	$\frac{dv}{dt} + \frac{2(m+1)\tan\theta}{b} \cdot v^2 + \frac{g \cdot B(\varepsilon)}{v_{s,St} \cdot \varepsilon} \cdot v = g \cdot \left(1 - \frac{b_{min}}{b} - \frac{dp_a/dH}{\rho_b g}\right)$
Permeation resistance acc. to Molerus[1]	$Eu_B = \frac{24}{Re} \cdot \left\{1 + 0.692 \cdot \left[\frac{\sqrt[3]{1-\varepsilon}}{0.95 - \sqrt[3]{1-\varepsilon}} + \frac{1}{2} \cdot \left(\frac{\sqrt[3]{1-\varepsilon}}{0.95 - \sqrt[3]{1-\varepsilon}}\right)^2\right]\right\} = \frac{24}{Re} \cdot B(\varepsilon)$
Discharge velocity-time law	$v(t) = \frac{g \left(1 - \frac{b_{min}}{b} - \frac{dp_a/dH}{\rho_b g}\right) \cdot \tanh\left(\frac{t}{t_{76,lam}}\right)}{\frac{g \cdot B(\varepsilon)}{2 \cdot v_{s,St} \cdot \varepsilon} \cdot \tanh\left(\frac{t}{t_{76,lam}}\right) + \frac{1}{t_{76,lam}}}$
Stationary discharge velocity	$v_{st,lam} = \frac{b}{2(m+1)\tan\theta} \cdot \left[\frac{1}{t_{76,lam}} - \frac{g \cdot B(\varepsilon)}{2 \cdot v_{s,St} \cdot \varepsilon}\right]$
Characteristic discharge (relaxation) time	$t_{76,lam} = \left[\left(\frac{g \cdot B(\varepsilon)}{2 \cdot v_{s,st} \cdot \varepsilon}\right)^2 + \frac{2g(m+1)\tan\theta}{b} \cdot \left(1 - \frac{b_{min}}{b} - \frac{dp_a/dH}{\rho_b g}\right)\right]^{-1/2}$
Velocity-displacement law	$v_{(1)}(h) = \frac{g \cdot \left(1 - \frac{b_{min}}{b} - \frac{dp_a/dH}{\rho_b g}\right) \cdot \tanh\left(\frac{v_{s,St} \cdot \varepsilon}{g \cdot t_{76,lam} B(\varepsilon)} \left\{\frac{4(m+1)\tan\theta}{b} \cdot h + \ln\left[v'_{(0)}\right]\right\}\right)}{\frac{g \cdot B(\varepsilon)}{2 v_{s,St} \cdot \varepsilon} \cdot \tanh\left(\frac{v_{s,St} \cdot \varepsilon}{g \cdot t_{76,lam} B(\varepsilon)} \cdot \left\{\frac{4(m+1)\tan\theta}{b} \cdot h + \ln\left[v'_{(0)}\right]\right\}\right) - \frac{1}{t_{76,lam}}}$
Differential equation	$\frac{dh(t)}{dt} = \frac{g \left(1 - \frac{b_{min}}{b} - \frac{dp_a/dH}{\rho_b g}\right) \cdot \tanh\left(\frac{t}{t_{76,lam}}\right)}{\frac{g \cdot B(\varepsilon)}{2 \cdot v_{s,St} \cdot \varepsilon} \cdot \tanh\left(\frac{t}{t_{76,lam}}\right) + \frac{1}{t_{76,lam}}}$
Displacement-time law	$h(t) = g \cdot t_{76,lam}^2 \cdot \left(1 - \frac{b_{min}}{b} - \frac{dp_a/dH}{\rho_b g}\right) \left\{\frac{1}{1 - t_{76,lam}^2 b'^2} \cdot \ln\left[\tanh\left(\frac{t}{t_{76,lam}}\right) + \frac{1}{t_{76,lam} b'}\right] - \frac{1}{2(1 - t_{76,lam} b')} \cdot \ln\left[\tanh\left(\frac{t}{t_{76,lam}}\right) + 1\right] - \frac{1}{2(1 + t_{76,lam} b')} \cdot \ln\left[\tanh\left(\frac{t}{t_{76,lam}}\right) - 1\right]\right\}$
Discharge time	Only numerically solvable

[1] Molerus, O., (1993). *Principles of Flow in Disperse Systems*. Chapman & Hall, London

DFG-Graduate School 1554 "Micro-Macro-Interactions in Structured Media and Particle Systems"