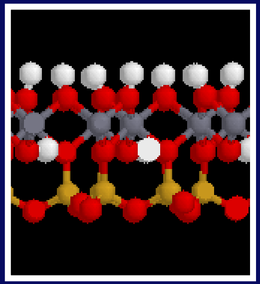
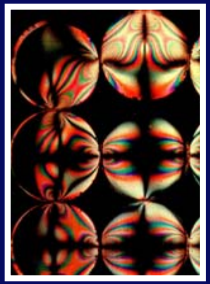
Integrated Ground Behavior

Part A: Particle-level Phenomena & Macroscale Behavior (J. Carlos Santamarina)

Georgia Institute of Technology



fluid

particles

microorganisms

mineral

surface charge
double layers
capillarity

size

forces
specific surface
relative size

shape

sphericity
roundness
smoothness

soil

fine-grained soil fabric
coarse-grained soil packing
platy particles

conduction
diffusion
energy coupling

stiffness
threshold strain

strength
(scales)

rheology
diagenesis

fluid **particles** **microorganisms**

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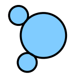
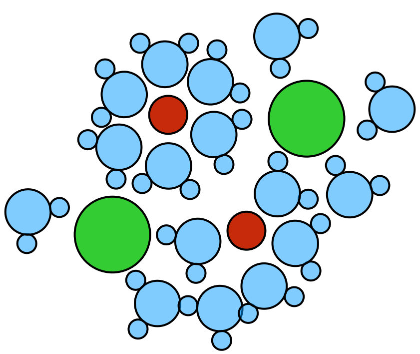
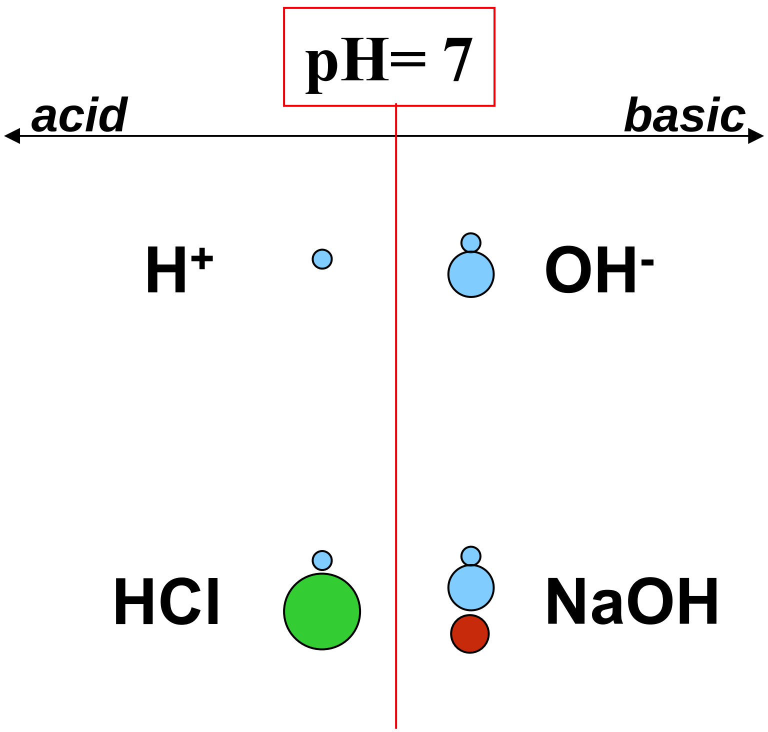
Water 

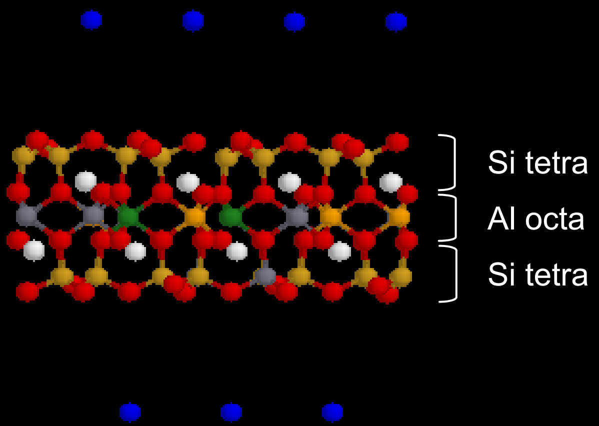
Ionic concentration



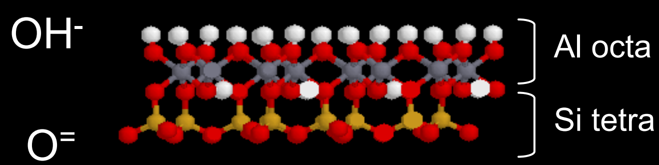


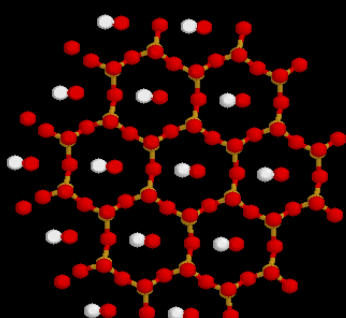
Minerals

montmorillonite

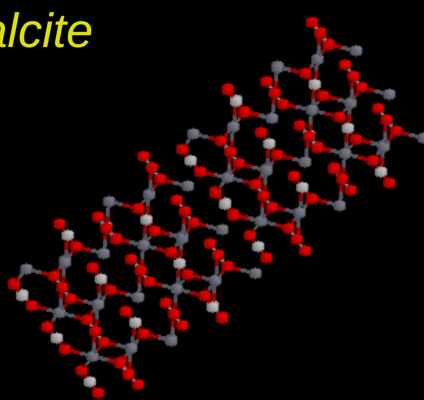


kaolin



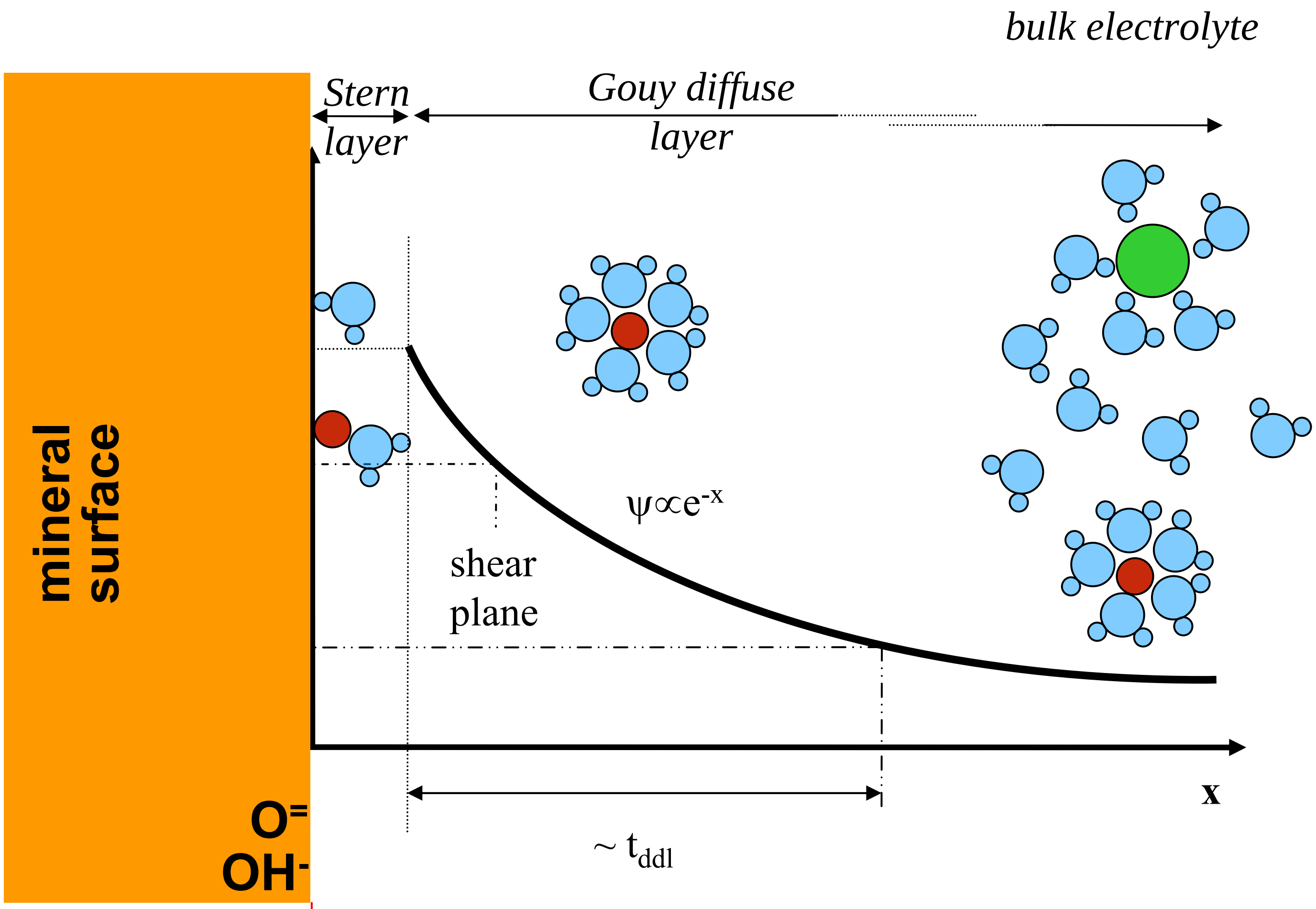


calcite



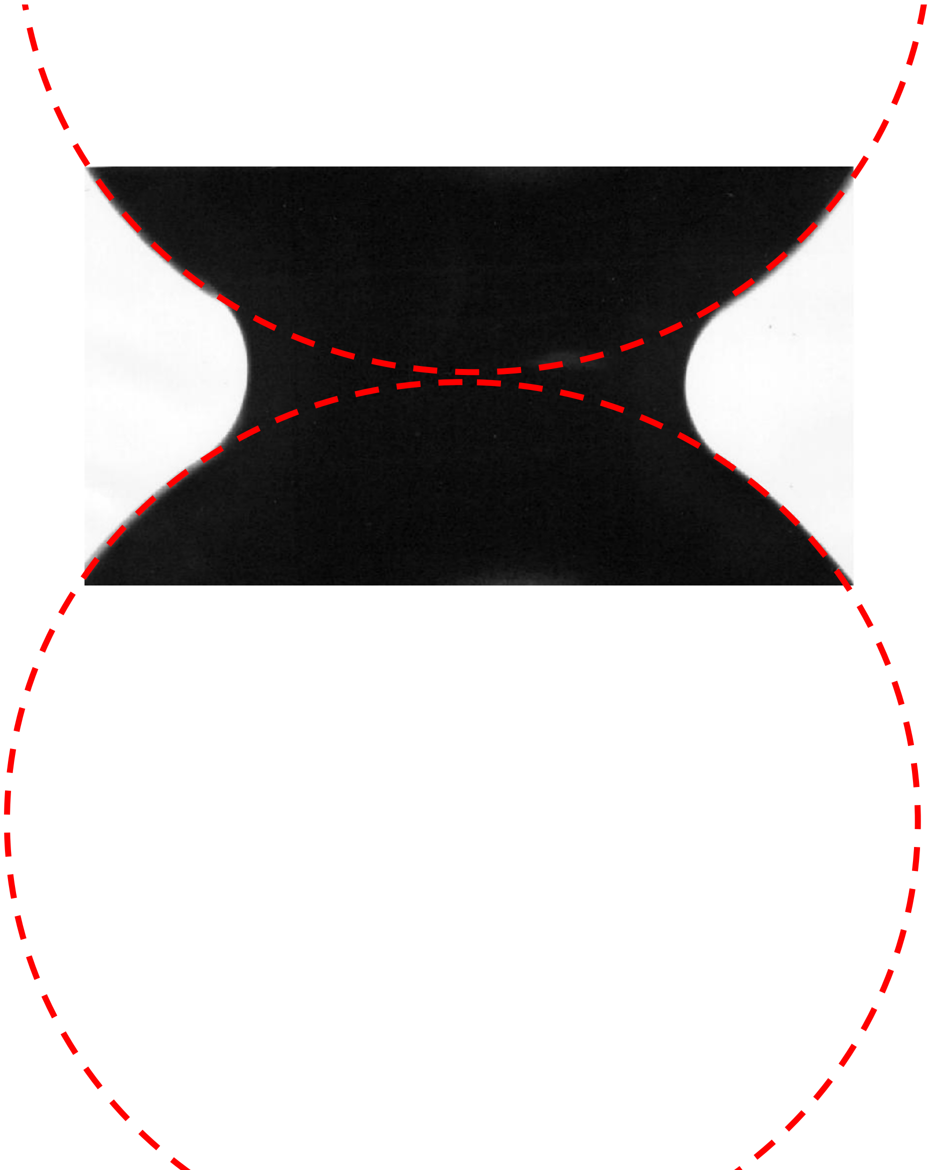
MDL / www.soils.wisc.edu/virtual_museum/index.html

Diffuse double layer

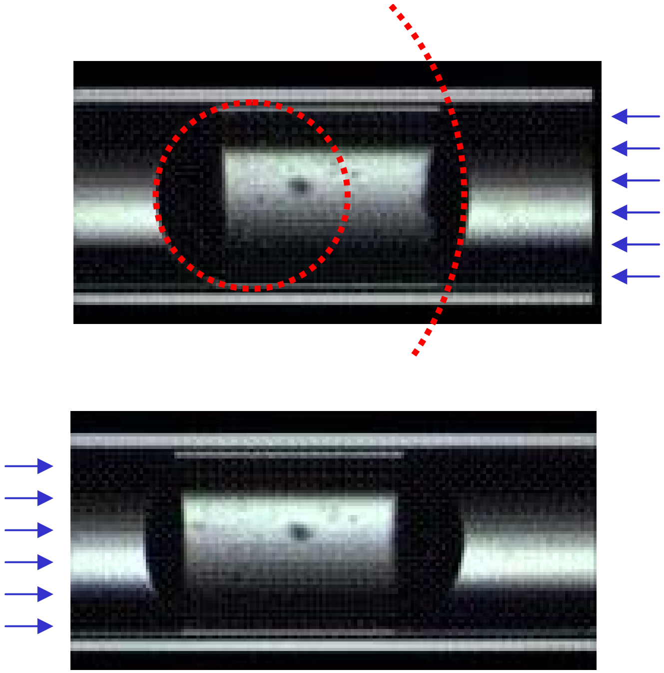


pH ionic concentration & valence

Mixed fluid phase



Interacting menisci:



θ non-constant

fluid

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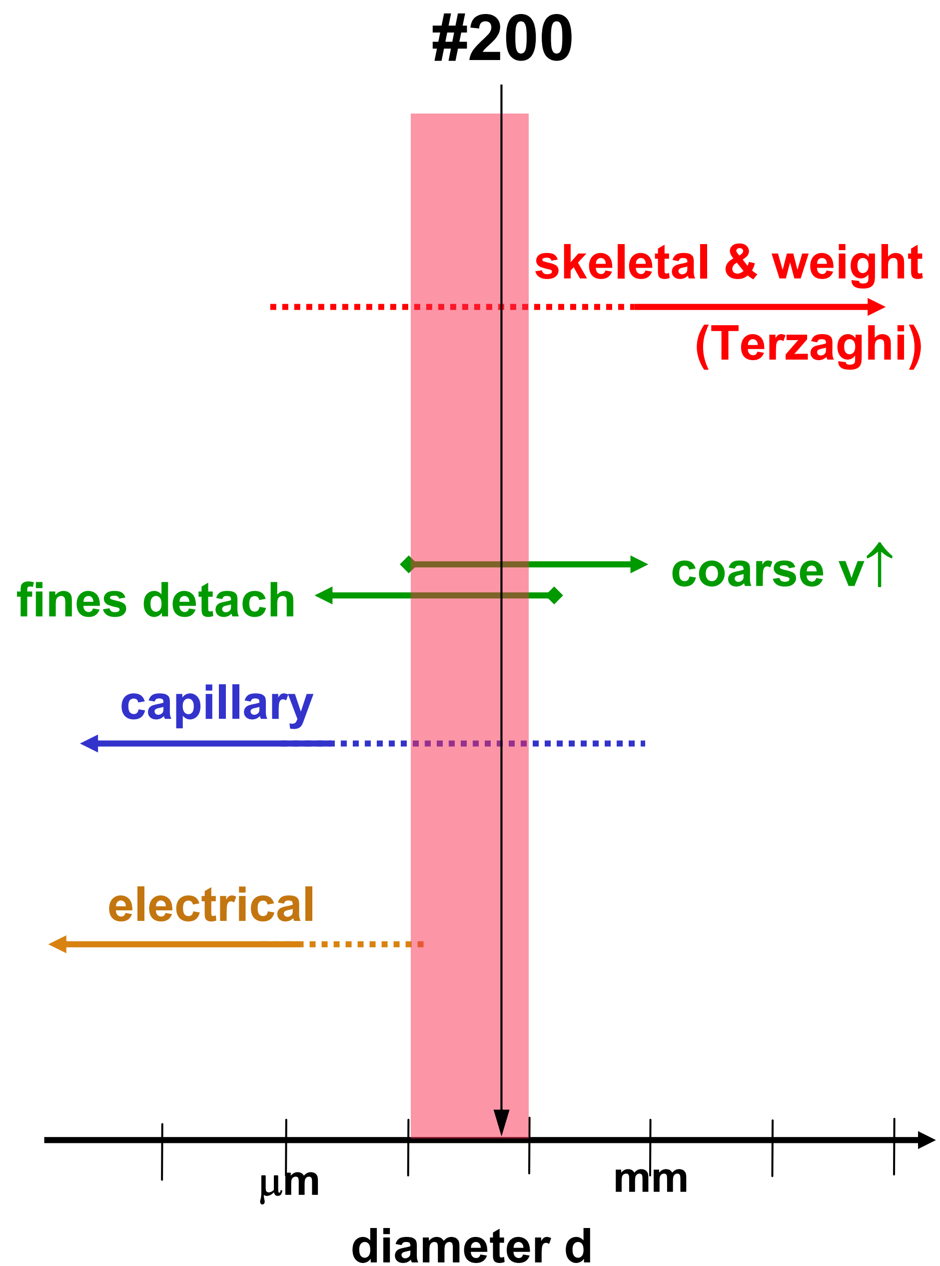
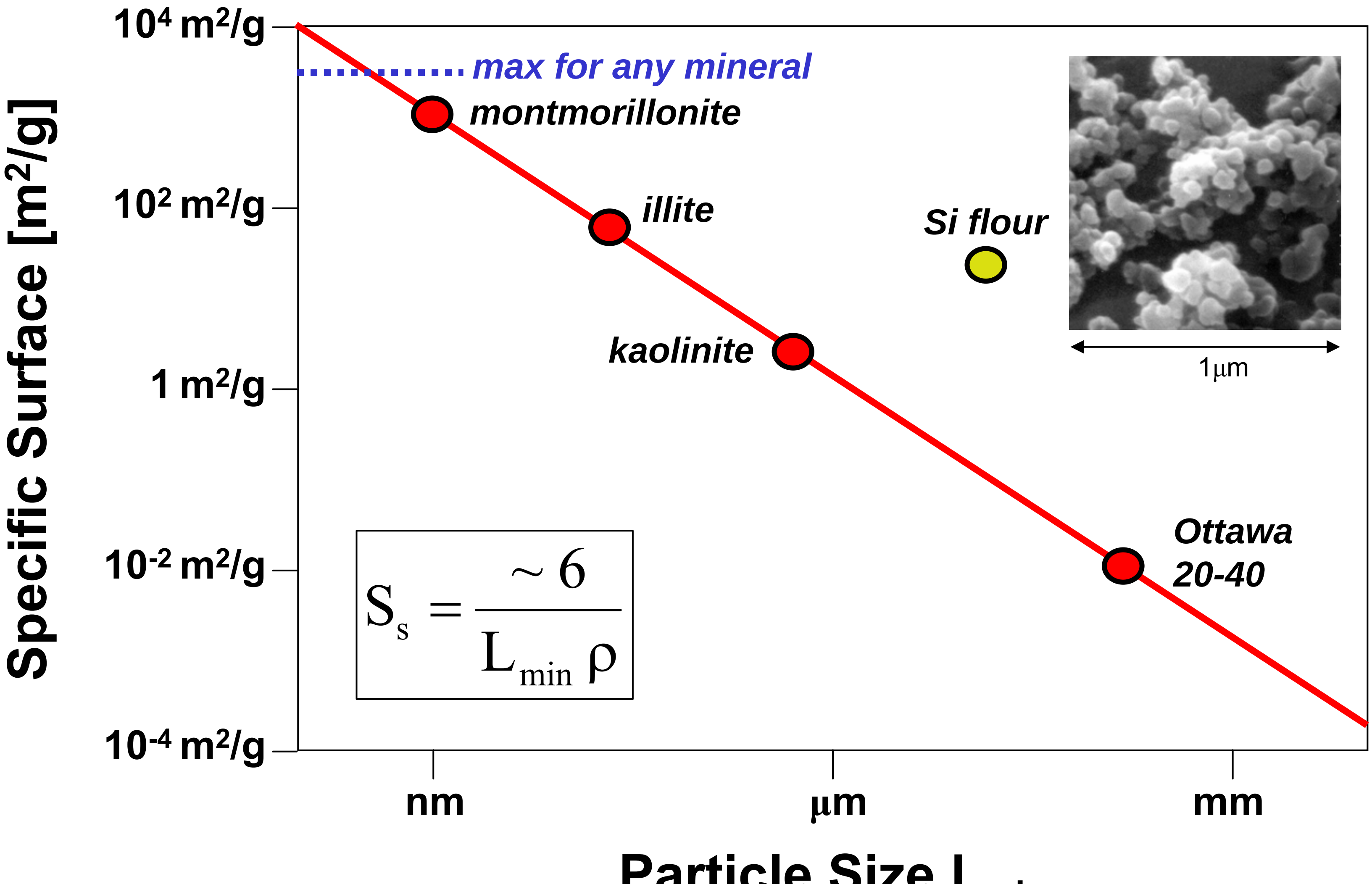
Particle Forces

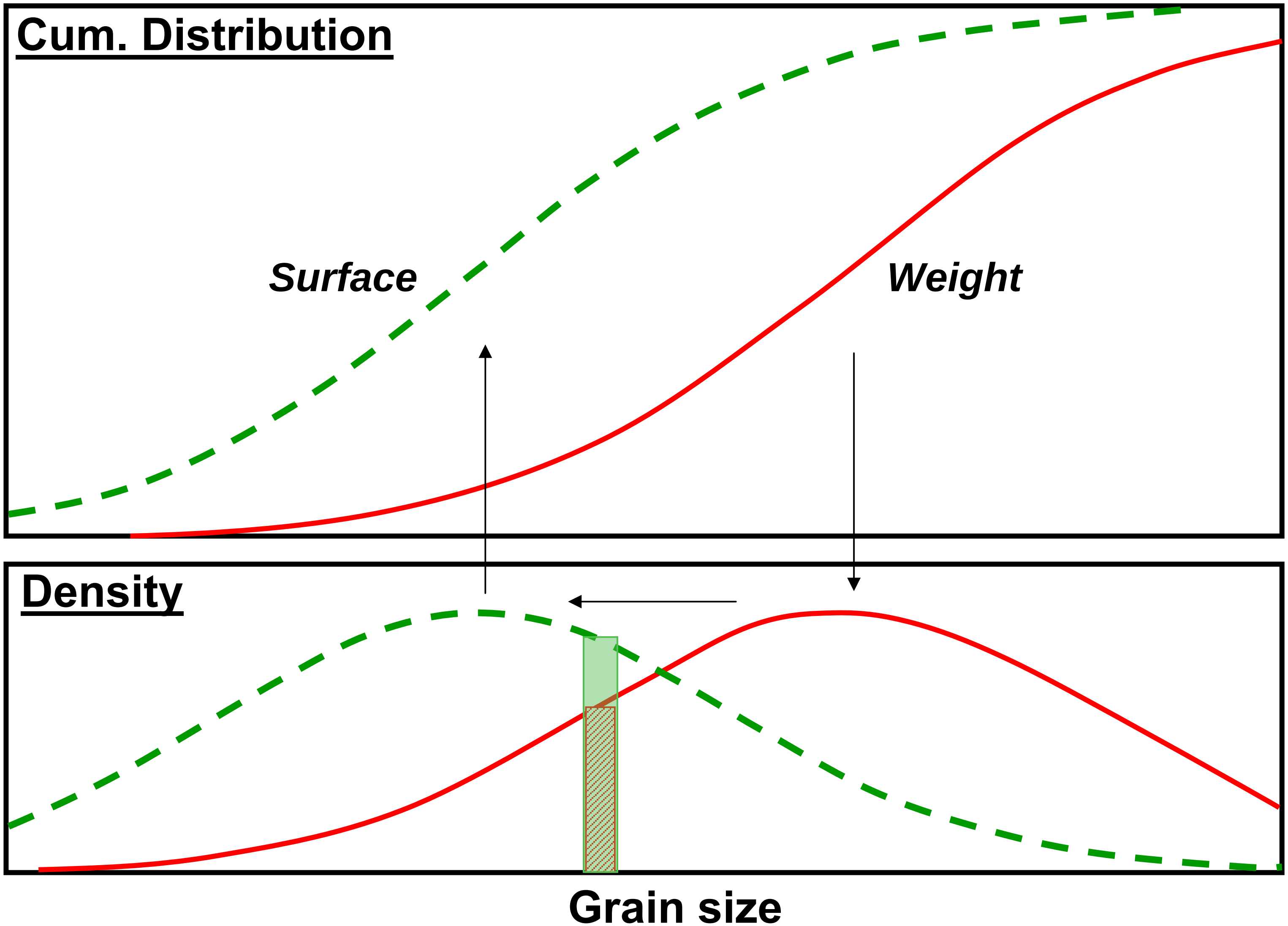
Skeletal	$\underline{N} = \sigma' d^2$
Weight	$W = (\pi G_s \gamma_w / 6) d^3$
Buoyant	$U = (\pi \ \gamma_w / 6) d^3$
Hydrodyn.	$F_{drag} = 3\pi \mu v d$
Capillary	$F_{cap} = \pi T_s d$
El. attraction	$Att = \dfrac{A_h}{24t^2} d$
El. repulsion	$Re\,p = \dfrac{24\sqrt{c_o}}{10000} e^{-10^8 t \sqrt{c_o}} d$
Cementation	$T = \pi \sigma_{ten} t d$



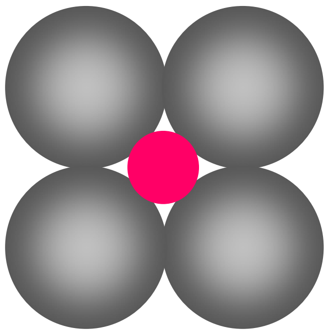
Size and Surface - Surface Phenomena



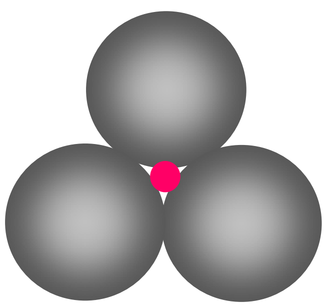
Size and Surface - Surface Phenomena



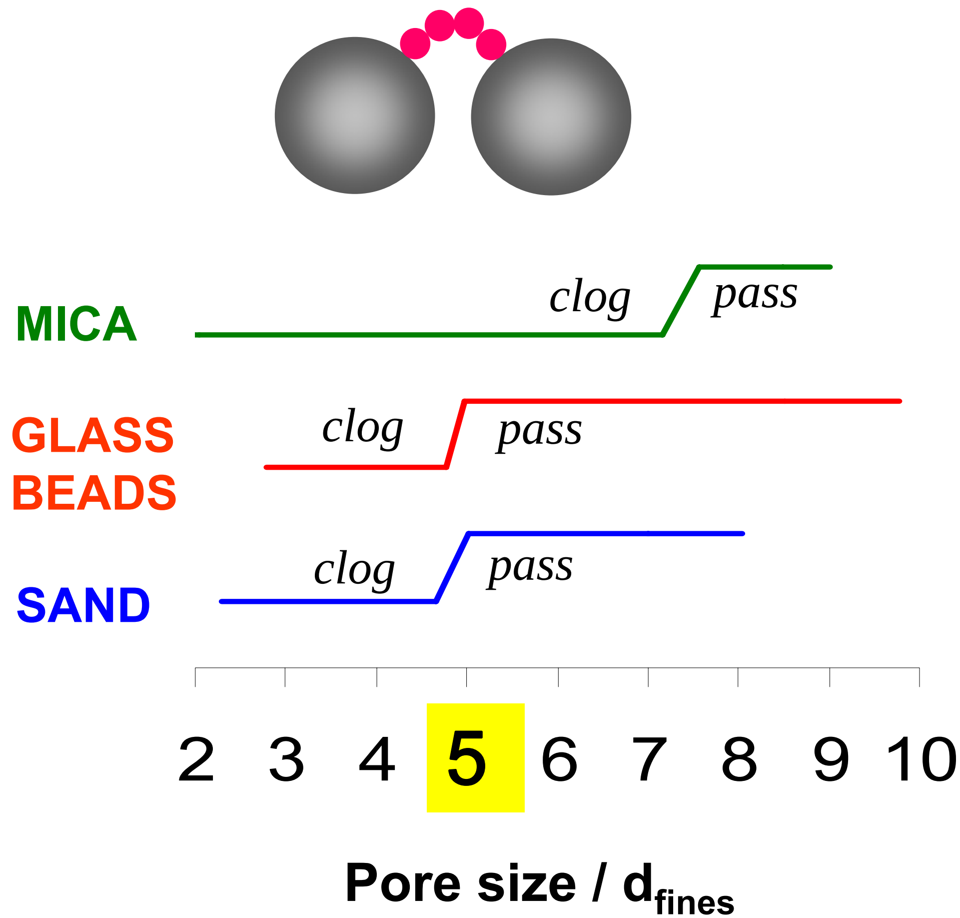
Fines migration and bridge formation



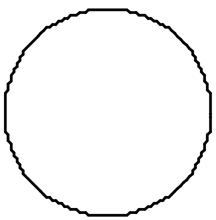
D/d=2.4



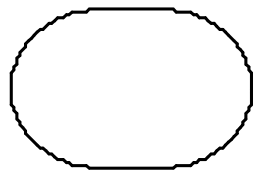
D/d=6.5



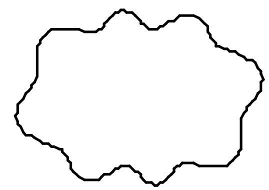
Particle Shape



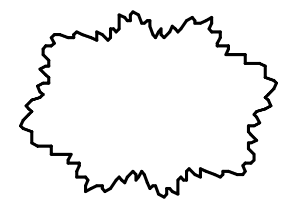
sphericity
vs. ellipticity..platiness

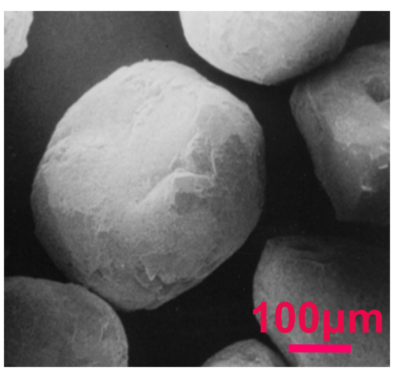


roundness
vs. angularity

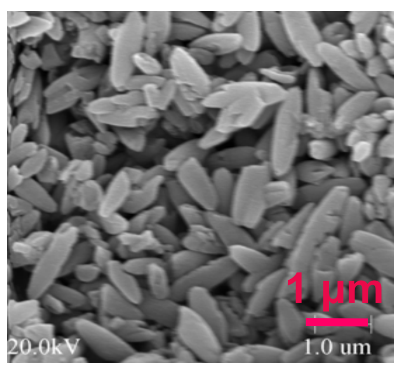


smoothness
vs. roughness

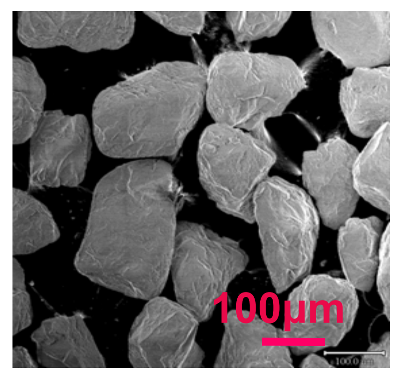




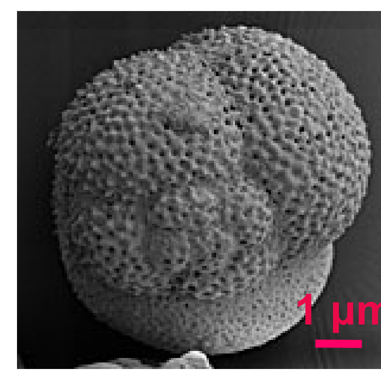
Ottawa



PCC



Nevada

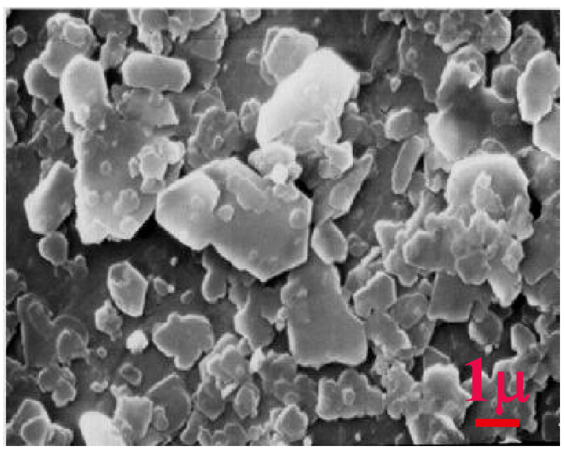


formineferan

Particle Shape

50 µm

chemically controlled | *mechanically controlled*



kaolinite

Margaret River

fluid

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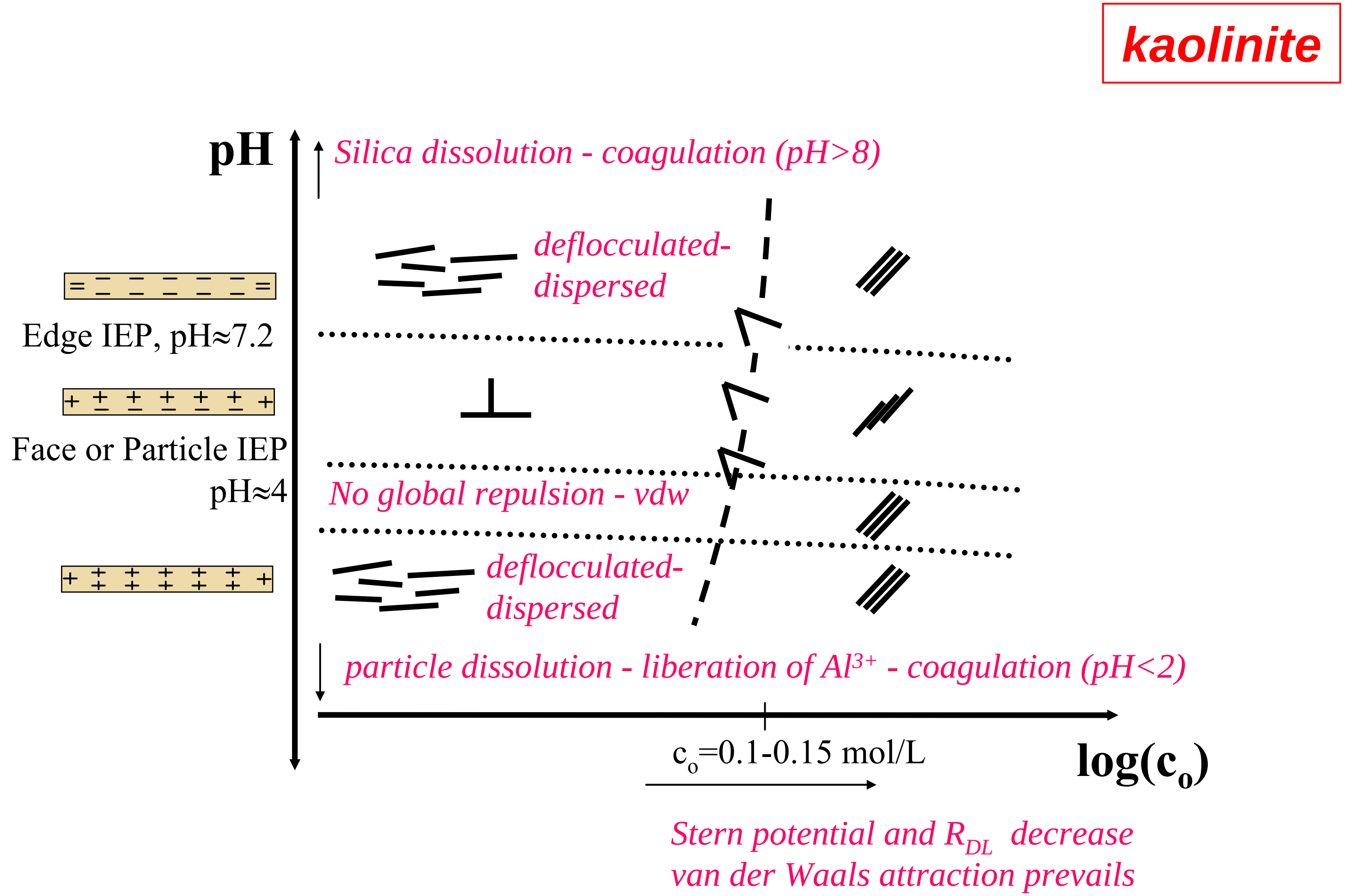
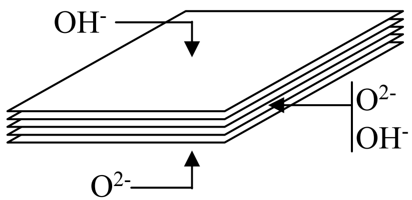
Fabric map



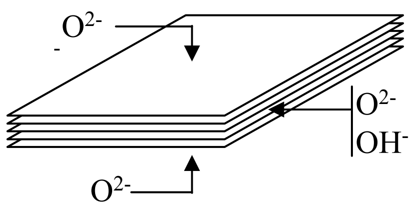
kaolinite
pH
Silica dissolution - coagulation (pH>8)
deflocculated-
dispersed
Edge IEP, pH≈7.2
Face or Particle IEP
pH≈4
No global repulsion - vdw
deflocculated-
dispersed
particle dissolution - liberation of Al^{3+} - coagulation (pH<2)
c_o=0.1-0.15 mol/L
log(c_o)
Stern potential and R_{DL} decrease
van der Waals attraction prevails

Clay minerals – Differences

1:1



2:1

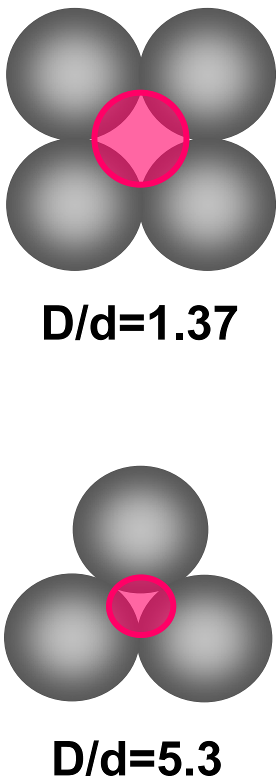


different faces
different from edge

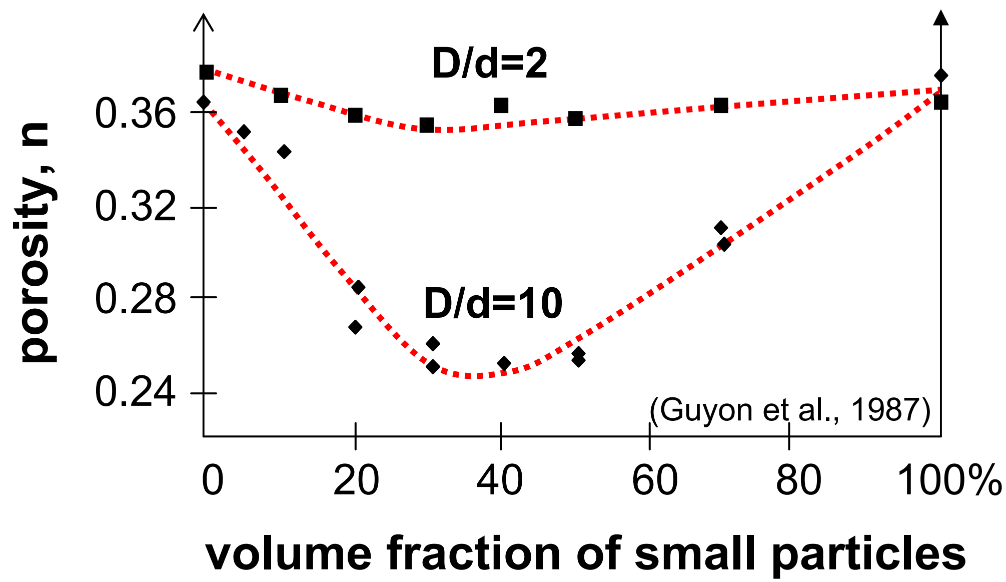
edge contribution
charge change

ζ / particle thickness
hiding edge DL

Coarse particles: relative size



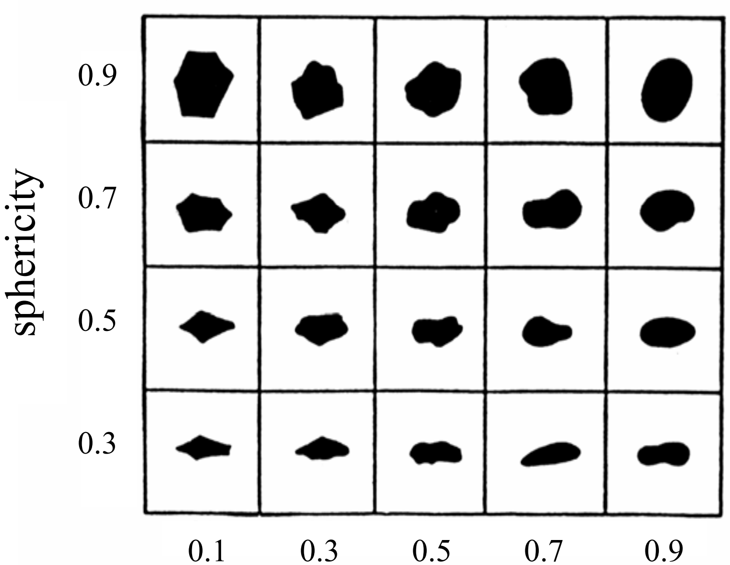
random packing:



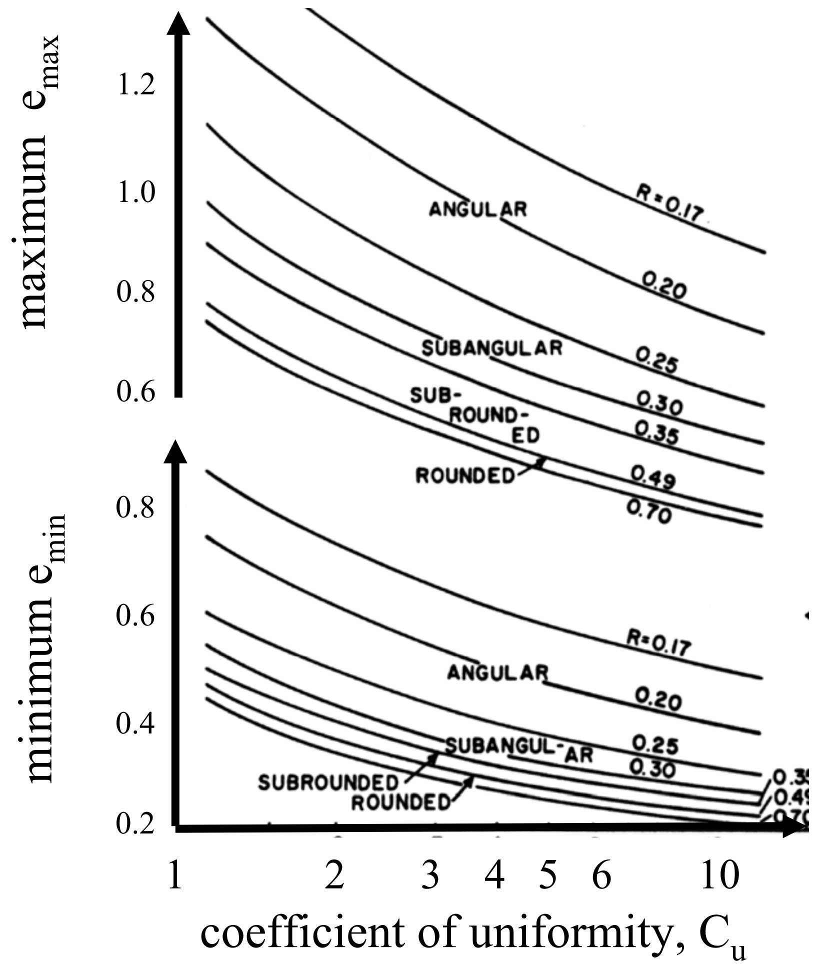
and…

Relative size and shape

(Krumbein and Sloss, 1963)

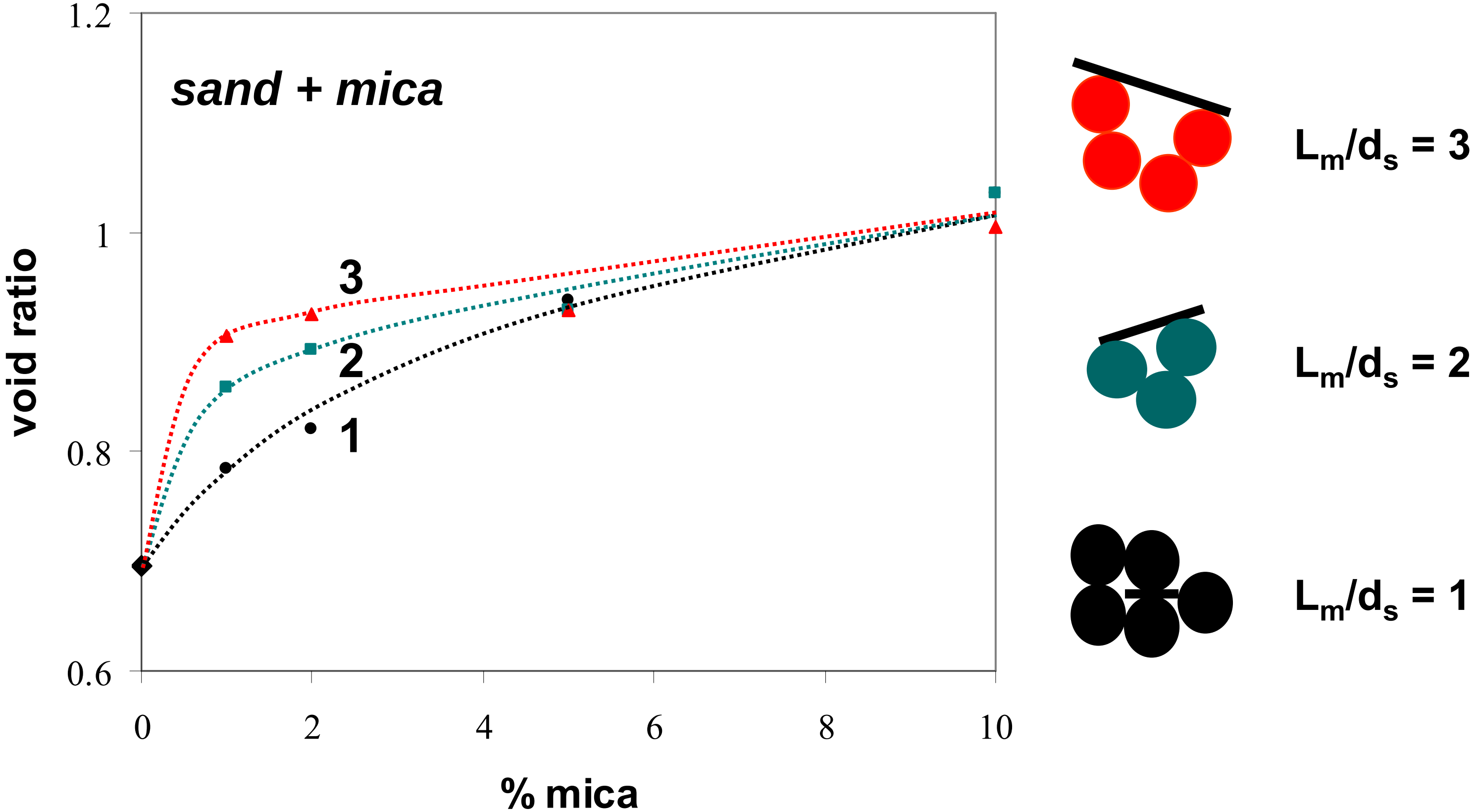


$$\text{roundness} = \frac{\sum r_i / N}{r_{max}}$$



(Youd, 1973; see also Maeda, 2001)

Platy particles: bridging



fluid **particles** **microorganisms**

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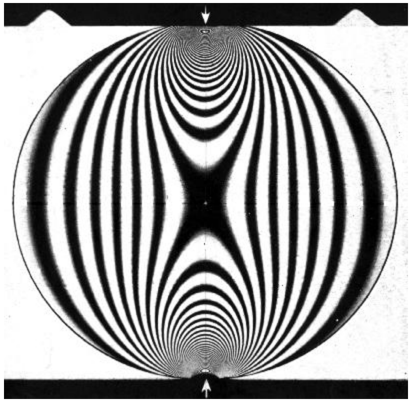
Small-strain stiffness: Contact-controlled

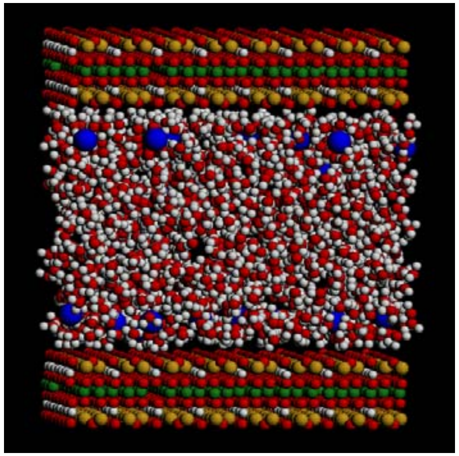
coarse grains



(Frocht, 1941)

$$V_S = \alpha \left(\frac{\sigma'}{kP_a} \right)^{\beta = \frac{1}{6}}$$

fine grains

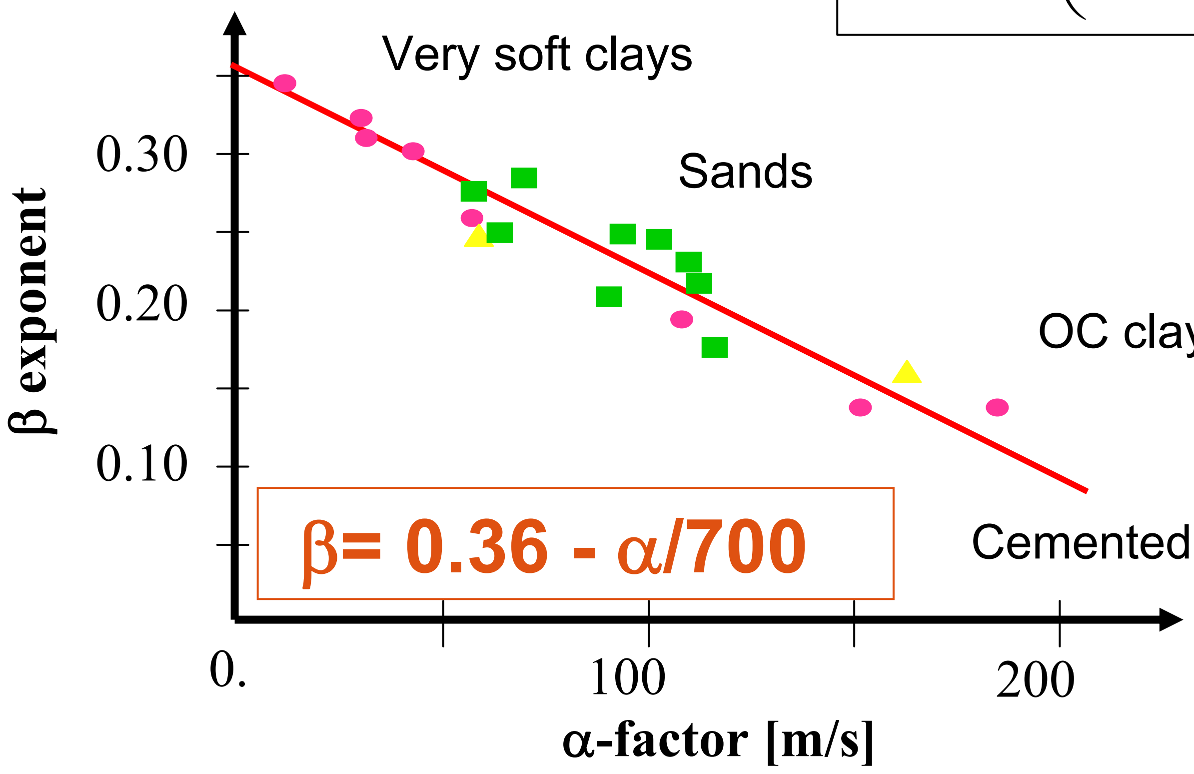


(N. Skipper – UCL 2002)

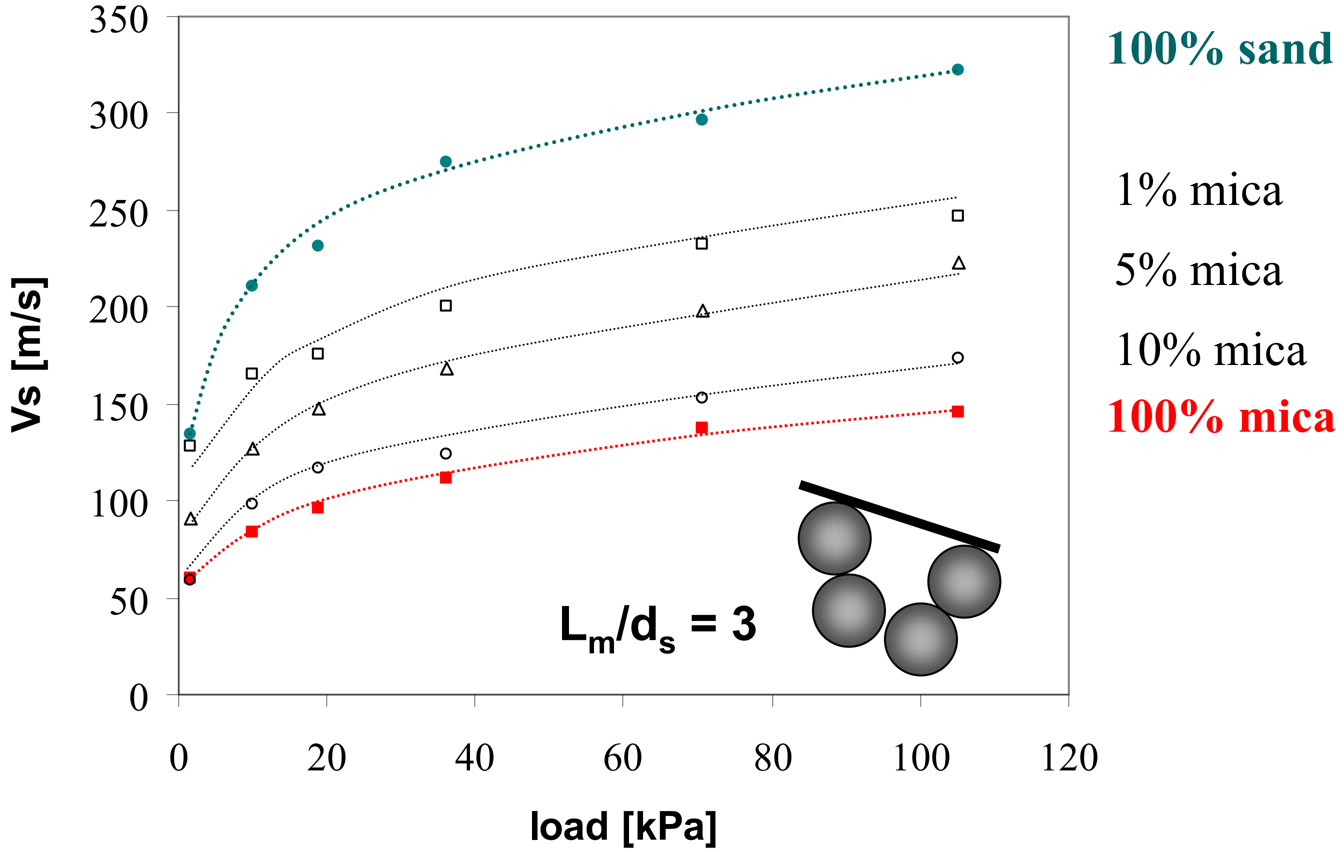
$$V_S = \alpha \left(\frac{\sigma'}{kP_a} \right)^{\beta < \frac{3}{4}}$$

Stiffness-Stress: *contact behavior & fabric changes*

$$V_S = \alpha \left(\frac{\sigma'_x + \sigma'_y}{2\,kP_a} \right)^{\beta}$$



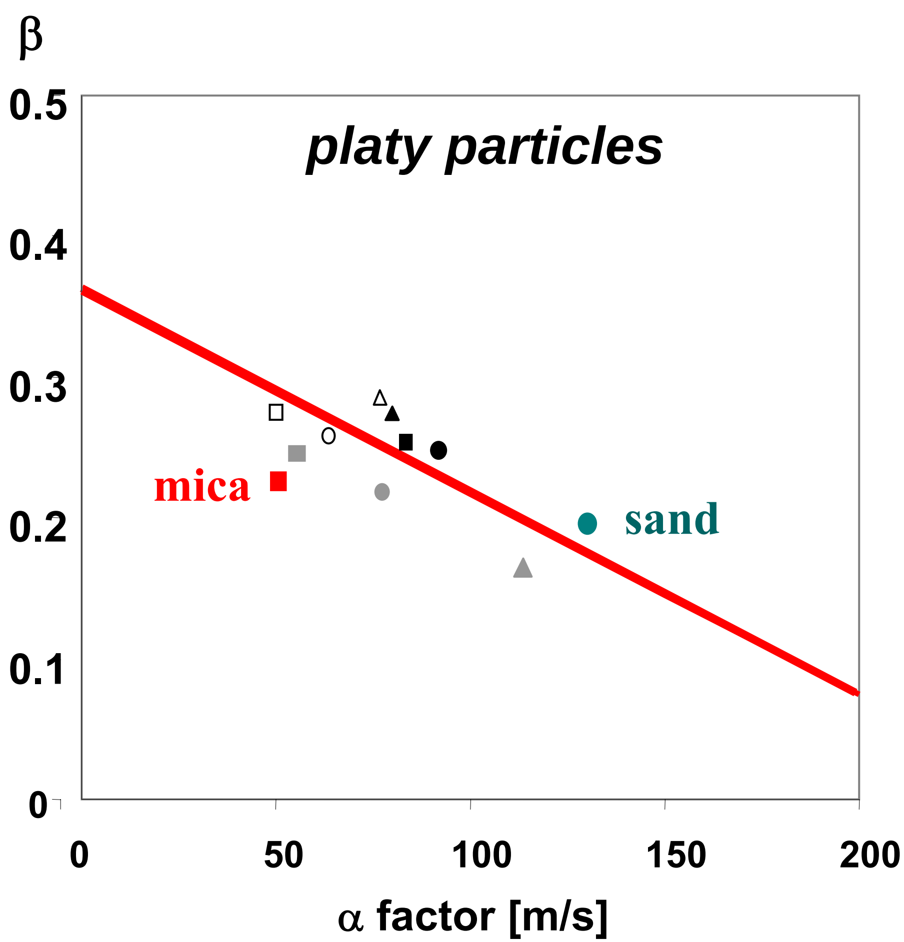
Stiffness: platy particles

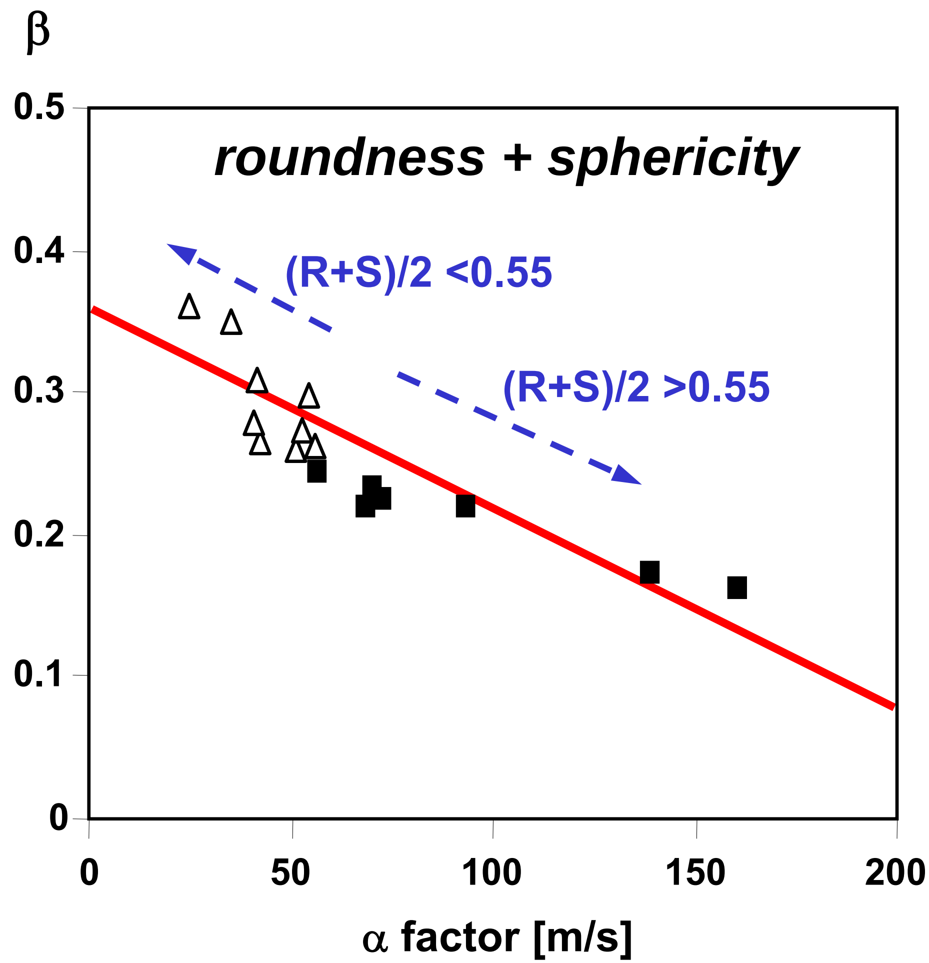


Particle shape effects

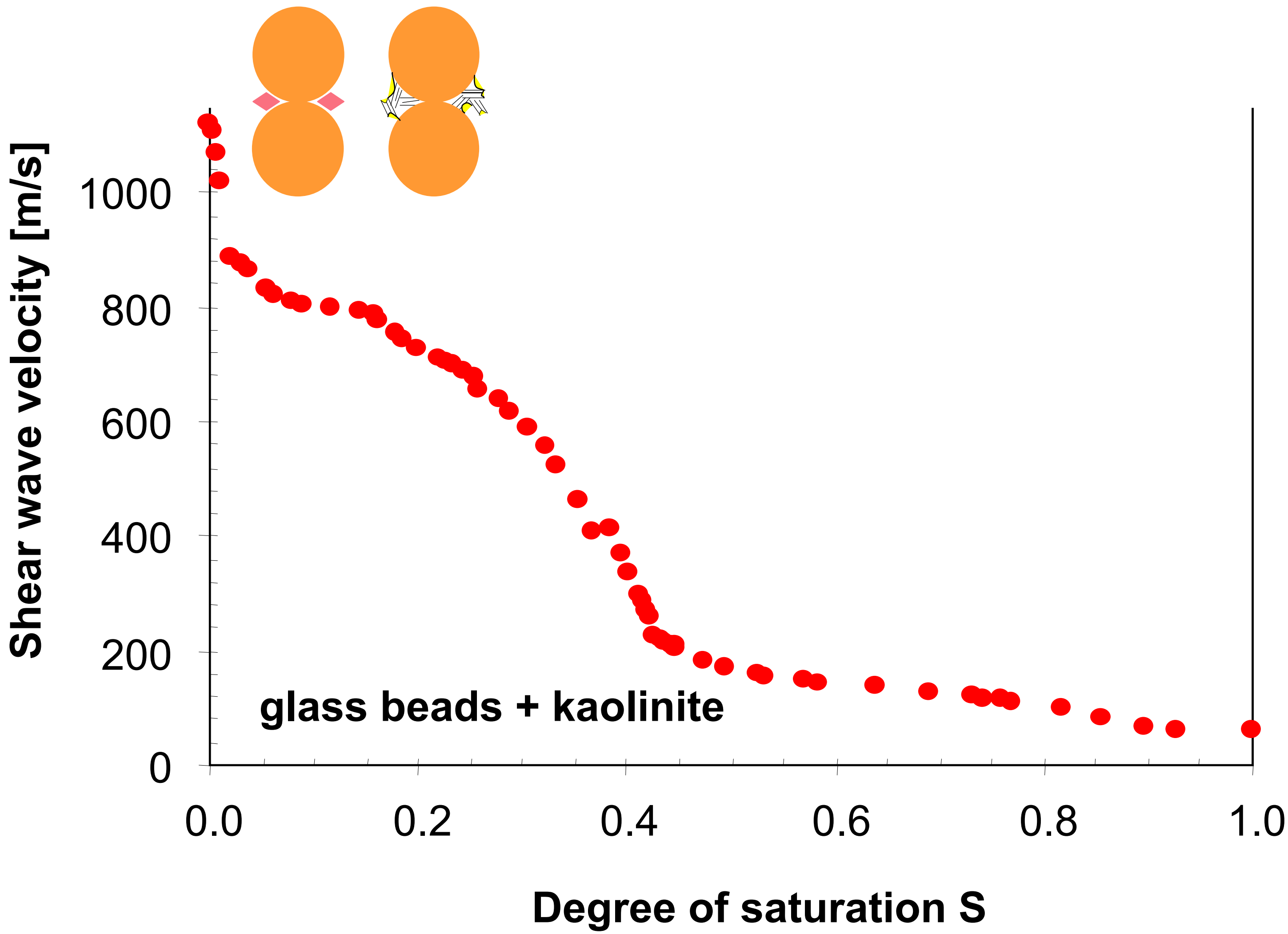
$$V_S = \alpha \left(\frac{\sigma'_x + \sigma'_y}{2\,kP_a} \right)^{\beta}$$

$$\beta = 0.36 - \alpha/700$$



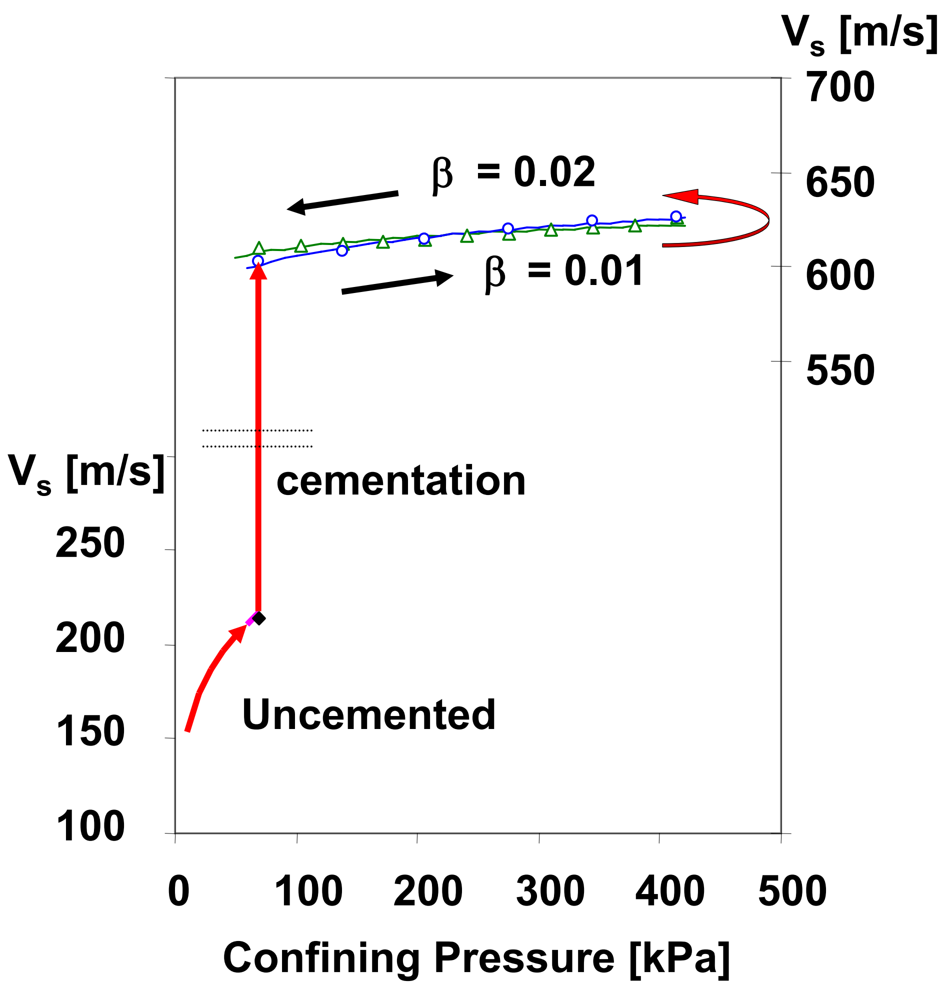


Drying – Unsaturated media

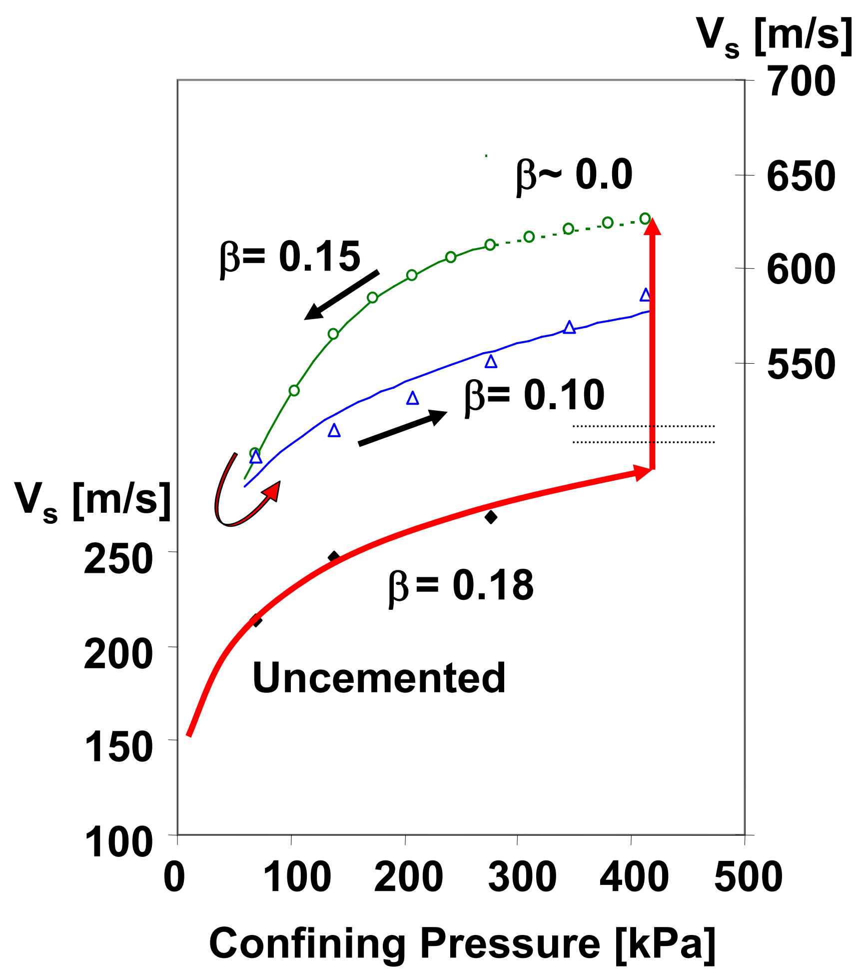


Stress change and cementation

Load (no unloading)



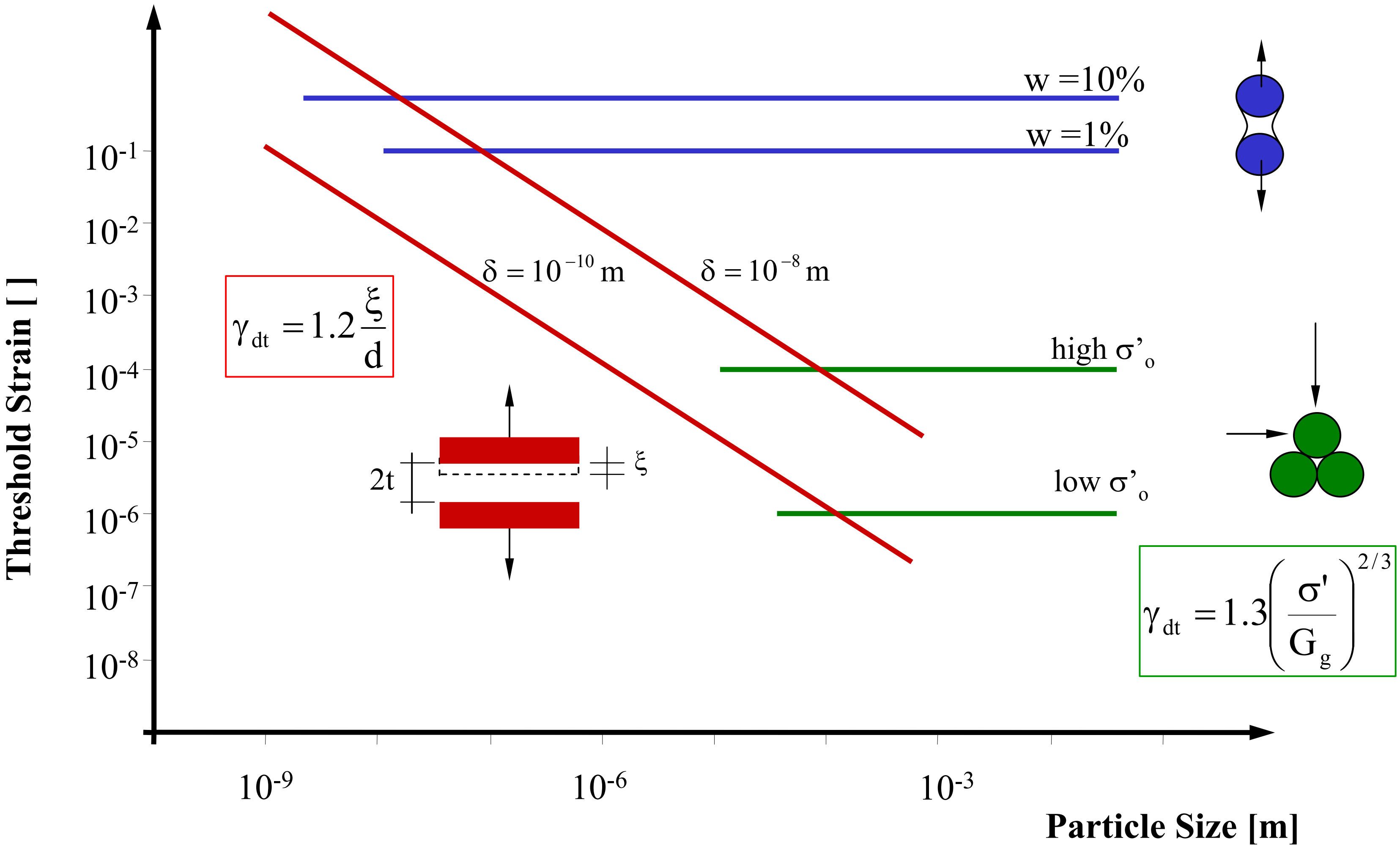
Unload and reload



Strain regimes

	Small Strain	*Large Strain*
Deformation	at contacts	fabric changes
Stiffness	maximum	decreases
Losses	very low	large - frictional
Volume Change	minimal	potentially large
Diagenetic effects	potentially high	small in drained shear
Fabric	constant	changes towards CS

Threshold strains - Ranges



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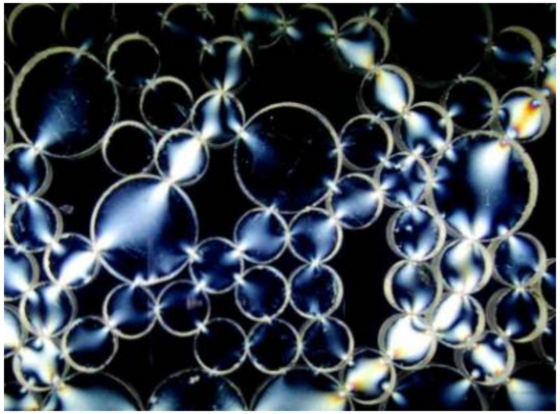
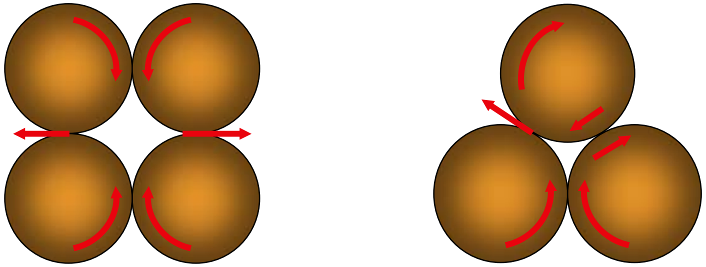
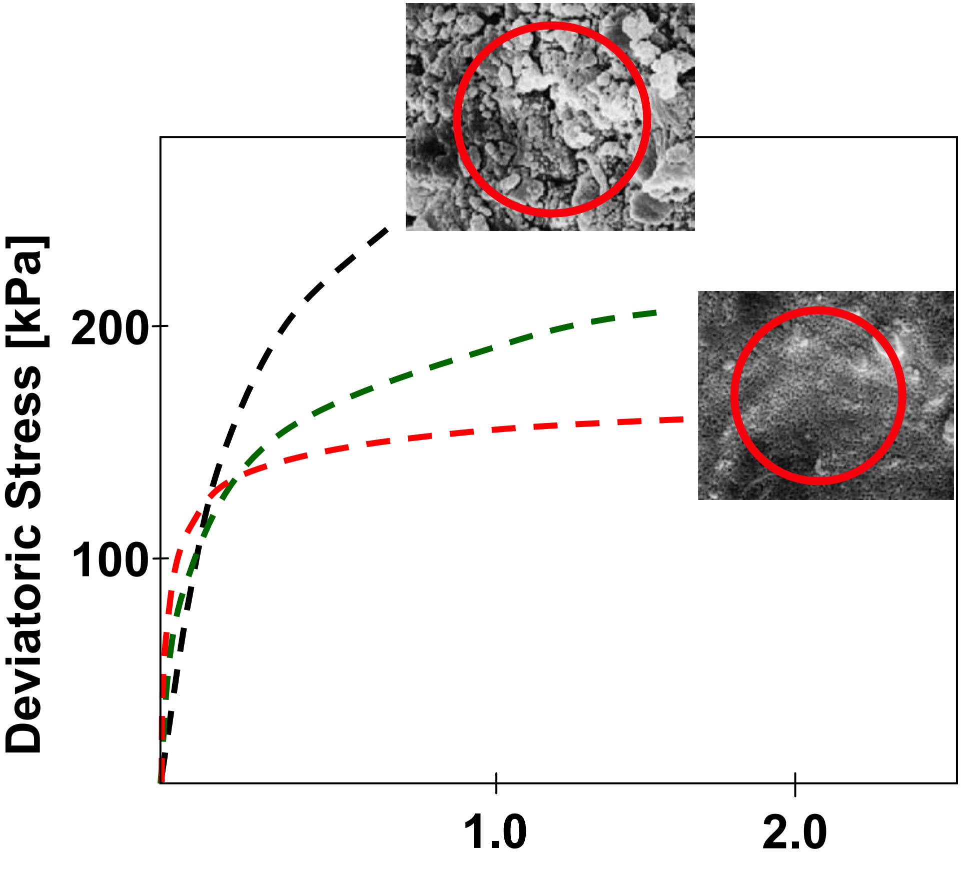
Stress-dependent strength and ε_{vol}

Chain buckling: coordination↑

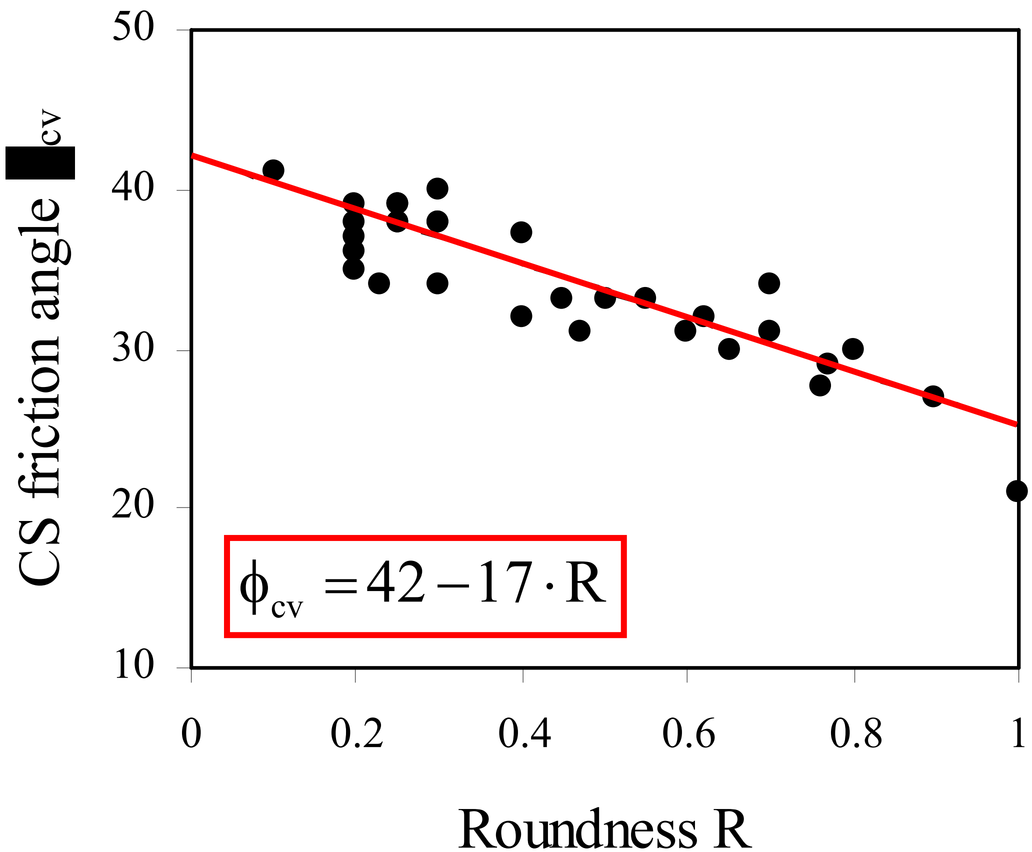


Rotational frustration: coordination↓

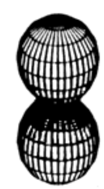




Effect of roundness on Φ_{cv}

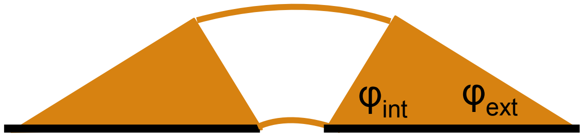


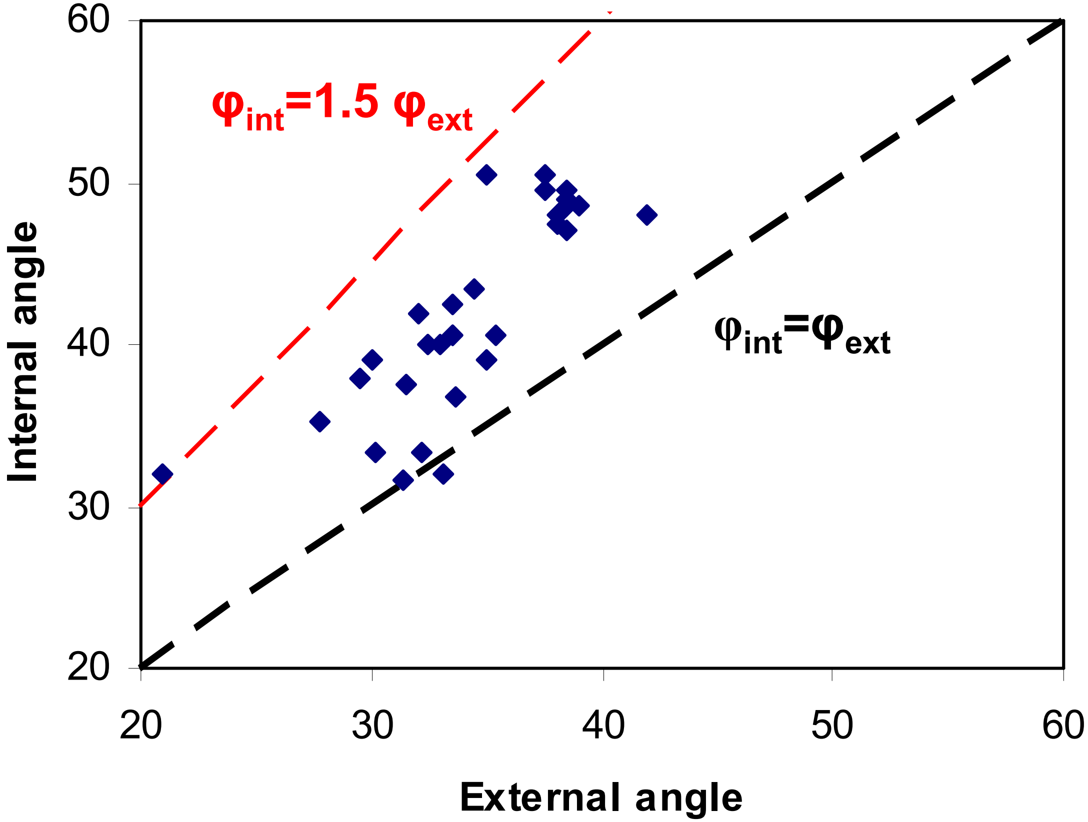
Evolution of internal micro-scale – 3D

	Isotropic confine.	At peak dev. load	
		AC (b=0)	AE (b=1)
Contact normals			
$\underline{N}(\theta)$			
$\underline{T}(\theta)$ (magnified x5)			

Chantawarangul, 1993

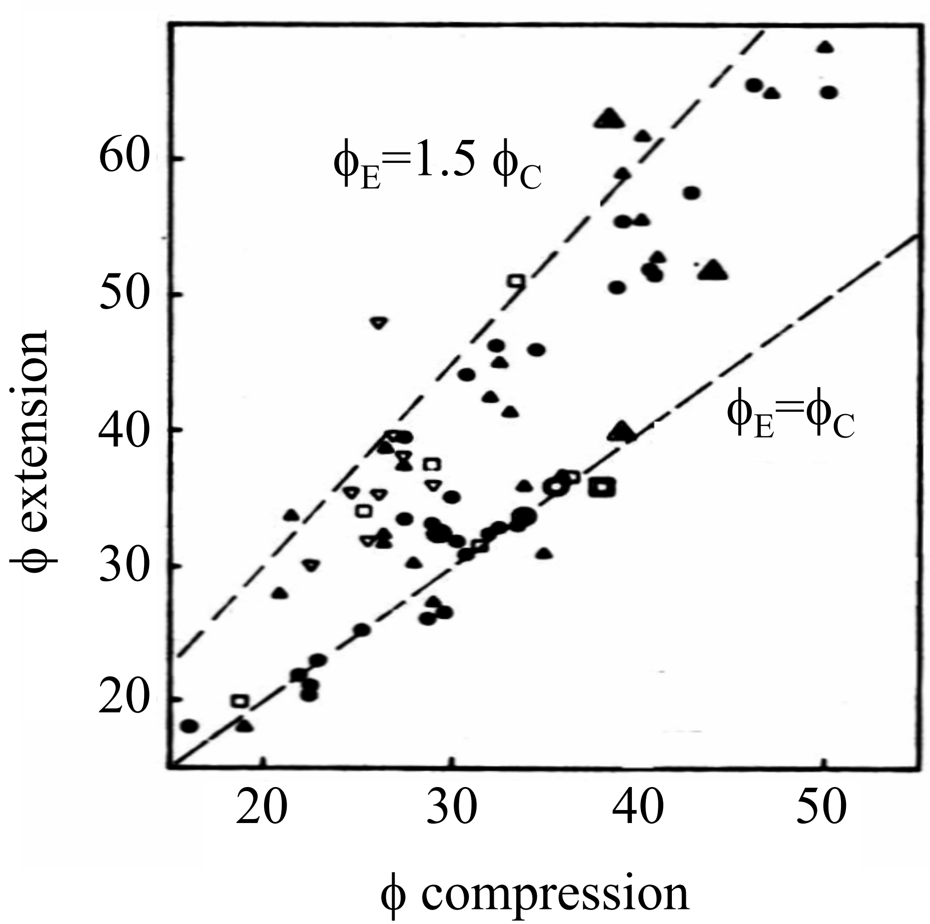
Constant angle of repose?





Narsilio, Dodds, Fugle, Trott, Kim, Yun

Anisotropy in ϕ - Clays

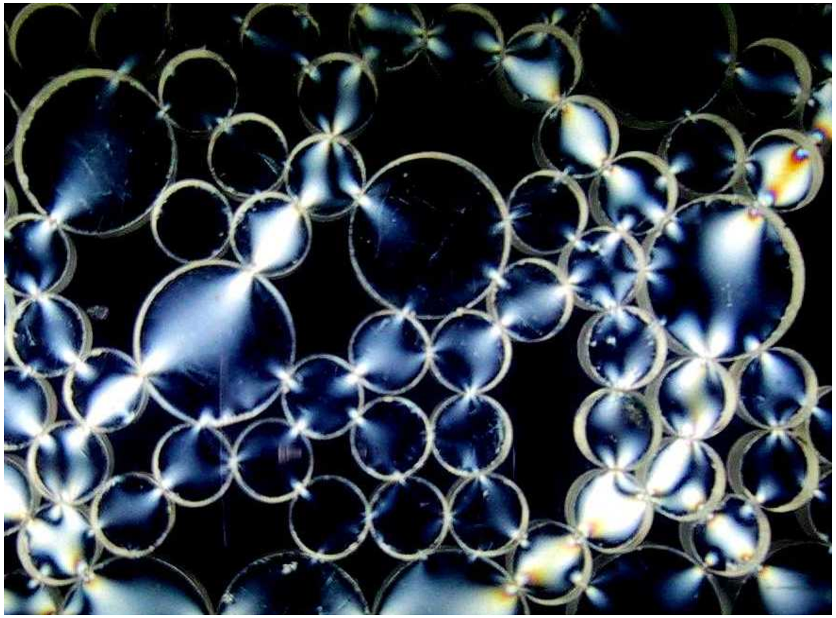


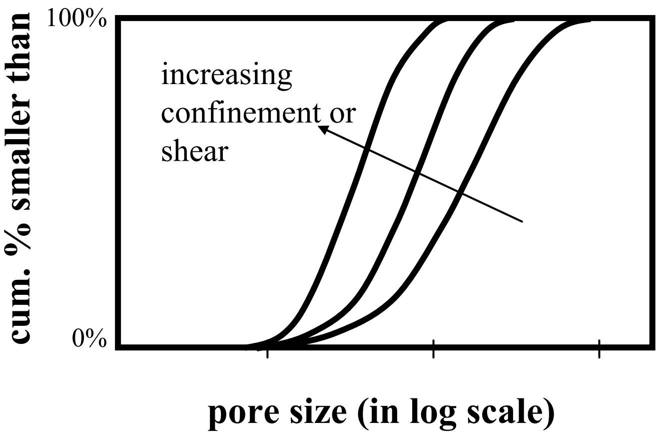
Mayne & Holtz 1985

Undrained strength anisotropy

Controlled by the generation of pore pressure

- ***chain buckling and skeletal stiffness***
- ***spatial variability of e***





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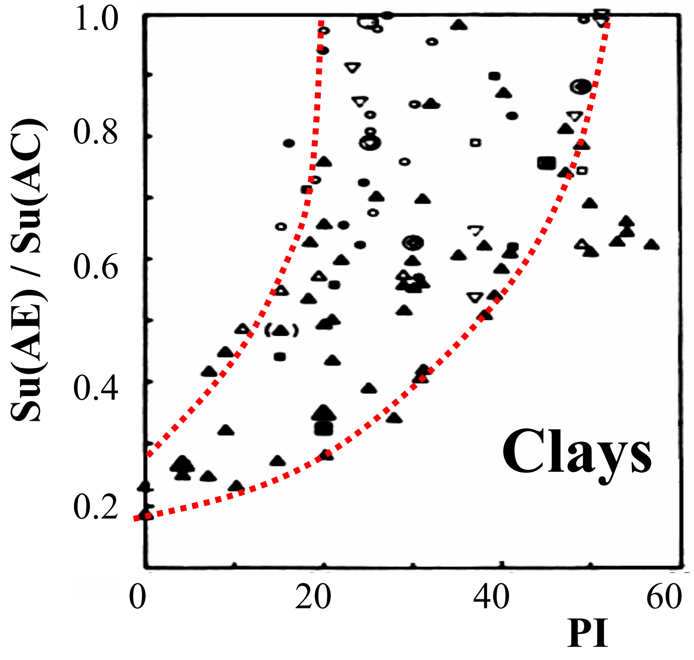
- ***spatial variability of e***
- ***threshold strain***



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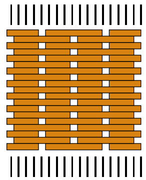
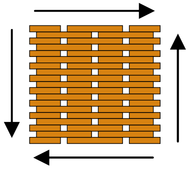
Undrained strength anisotropy

Controlled by the generation of pore pressure

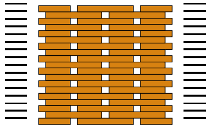
- ***chain buckling and skeletal stiffness***
- ***spatial variability of e***
- ***threshold strain***
- ***fabric anisotropy***



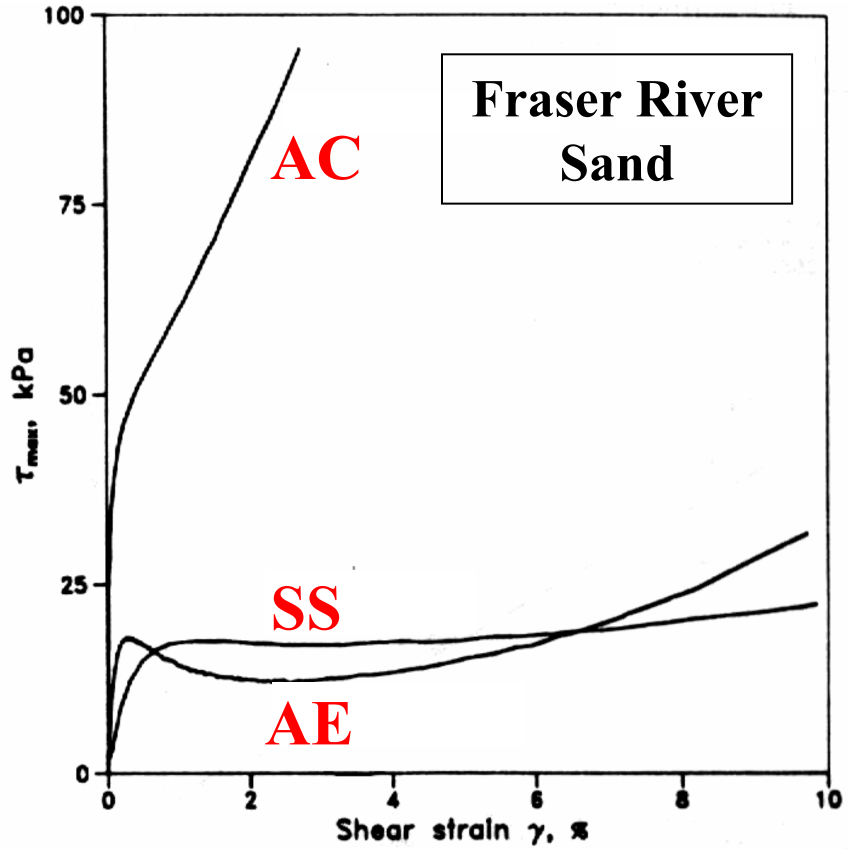
AC: b=0 α=0



SS: b>0 α>0



AE: b=1 α=90



Vaid and Sivathayalan 1996

Scales

temporal		*spatial*

$$\frac{t_{load}}{L^2 / c_v}$$

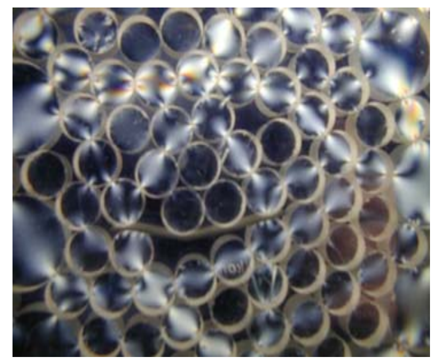
drained or undrained

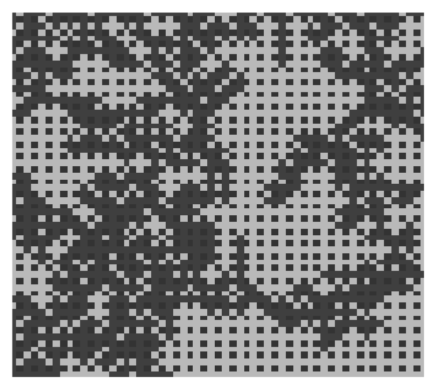
$$\frac{f}{f_{res}}$$

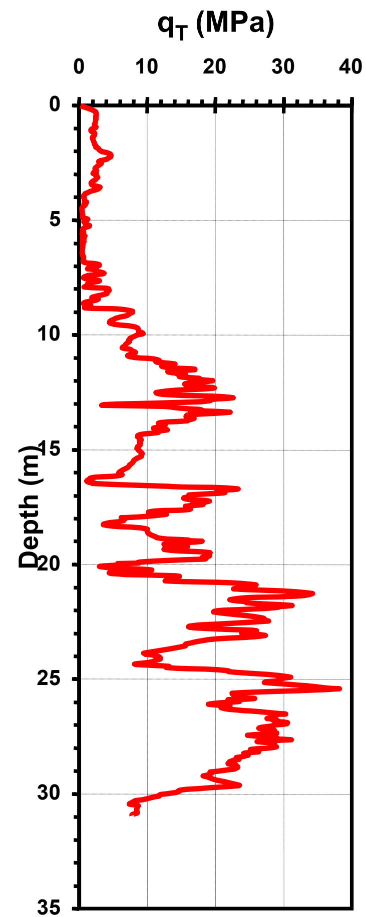
quasi-static or dynamic

$$\frac{L / ki}{L^2 / c_v}$$

seepage or consolidation







fluid

particles

microorganisms

mineral

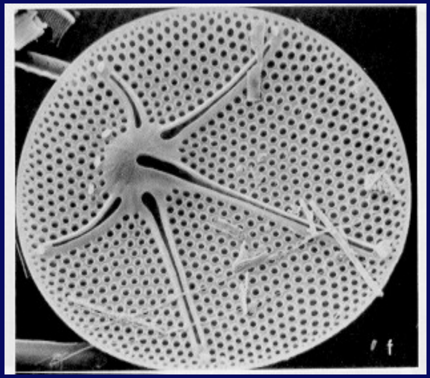
surface charge
double layers
capillarity

size

forces
specific surface
relative size

shape

sphericity
roundness
smoothness



soil

fine-grained soil fabric
coarse-grained soil packing
platy particles

conduction
diffusion
energy coupling

stiffness
threshold strain

strength
(scales)

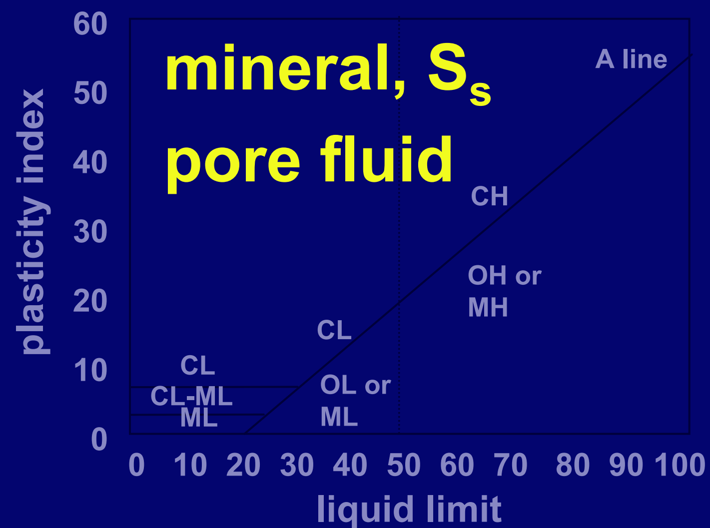
rheology
diagenesis

COARSE > 50% retained sieve #200	Gravel: > 50% retained sieve #4	< 5% fines	$C_u>4$, $1 \le C_c \le 3$	GW
			else …	GP
		> 12% fines	Below 'A' line	GM
			Above 'A' line	GC
	Sand: < 50% retained sieve #4	< 5% fines	$C_u>6$, $1 \le C_c \le 3$	SW
			else …	SP
		> 12% fines	Below 'A' line	SM
			Above 'A' line	SC
FINE < 50% retained sieve #200	LL<50			ML
				CL
				OL
	LL>50			MH
				CH
				OH

relative size

filled porosity

50-100 μm



mineral, S_s

pore fluid

pore fluid (explicitly)

degree of saturation

particle shape - coarse

specific surface - fines (explicitly)

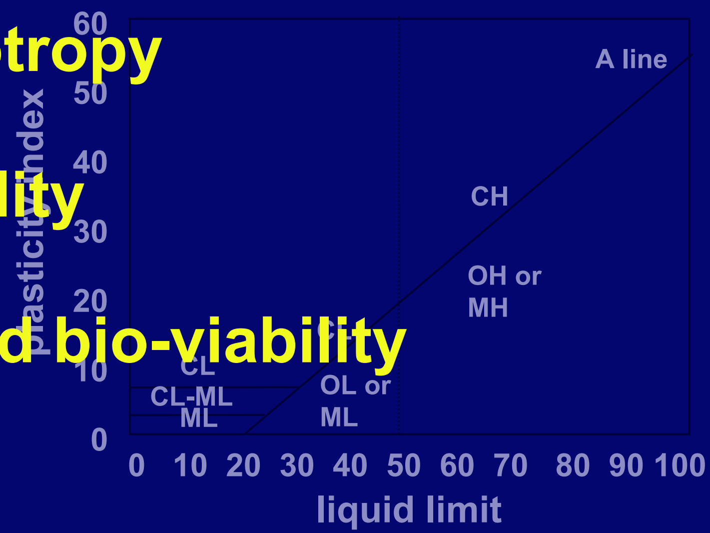
extent of diagenesis

inherent anisotropy

spatial variability

bio-activity and bio-viability

…

COARSE > 50% retained sieve #200	Gravel: > 50% retained sieve #4	< 5% fines	$C_u>4$, $1\leq C_c\leq 3$	GW
			else …	GP
		> 12% fines	Below 'A' line	GM
			Above 'A' line	GC
	Sand: < 50% retained sieve #4	< 5% fines	$C_u>6$, $1\leq C_c\leq 3$	SW
			else …	SP
		> 12% fines	Below 'A' line	SM
			Above 'A' line	SC
FINE < 50% retained sieve #200	LL<50			ML
				CL
				OL
	LL>50			MH
				CH
				OH