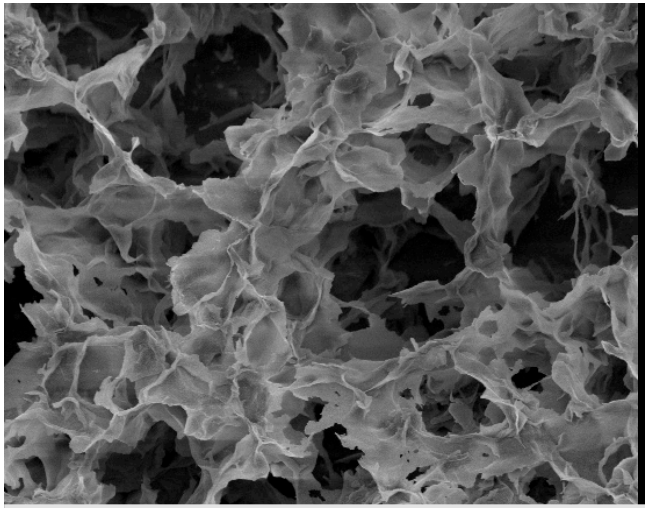
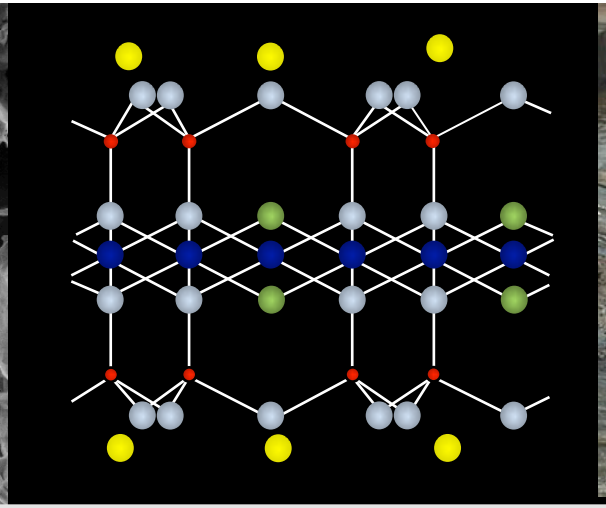




4th International Workshop on Modern Trends in Geomechanics, Assisi, May 2016

BEHAVIOR OF ULTRA SOFT CLAY-WATER SYSTEMS

Marika Santagata

LYLES SCHOOL OF CIVIL ENGINEERING

PURDUE UNIVERSITY

PURDUE ENGINEERING

SOFT OR ULTRASOFT?

"SOFT" used to refer to surfactants, liquid crystals, polymer melts, some biomaterials …. and colloids

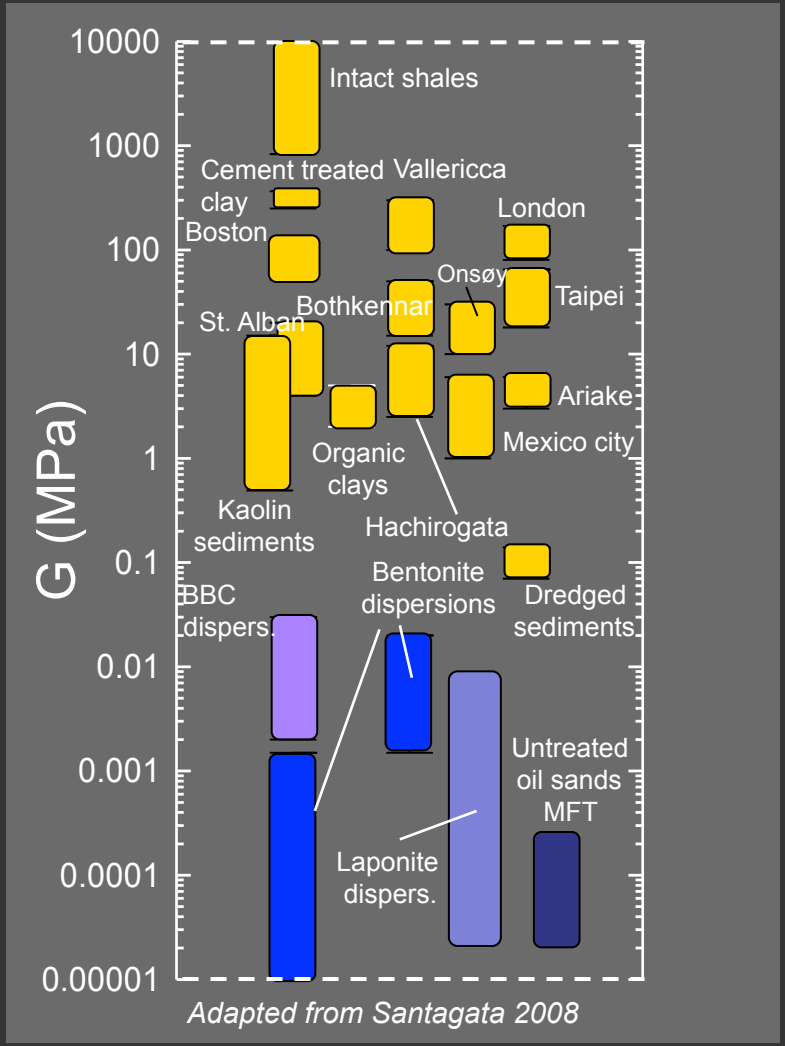
"*…ordering generally intermediate between that of a crystalline solid and that of a liquid*."

Hamley 2007

…... but term "SOFT CLAY" comes with a lot of baggage in geotechnical engineering

ULTRA SOFT CLAY-WATER SYSTEMS

HOW SOFT IS ULTRASOFT?



ULTRA SOFT CLAY-WATER SYSTEMS

RELEVANCE?

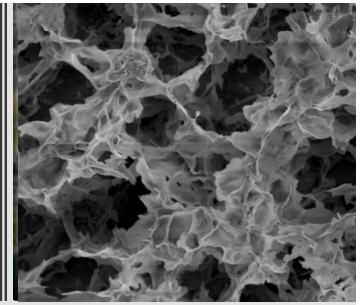
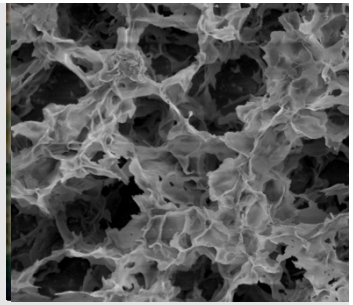


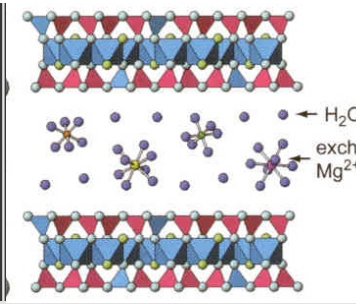
Image sources: trenchlessonline.com; W.G.Godden collection, NISEE-PEER, UC Berkeley; www.cosia.ca; hendersoninternational.wordpress.com, s3fluids.com, greatbay.org

NEXT…..



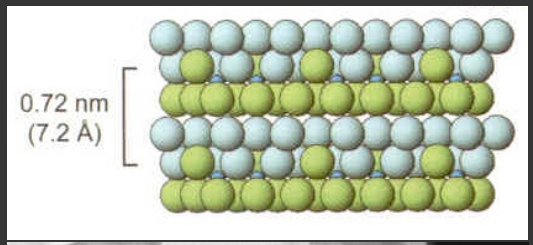
- **SELECT ASPECTS OF THE BEHAVIOR OF ULTRA SOFT CLAY-WATER SYSTEMS**
- **ENGINEERING THE BEHAVIOR OF CLAY-WATER SYSTEMS**
- **FINAL THOUGHTS**

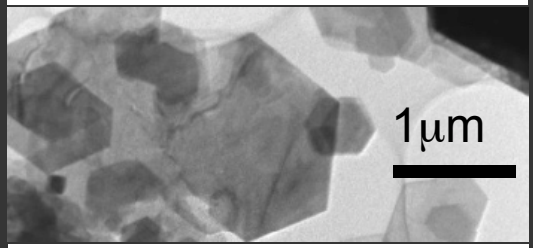
CLAY MINERALS



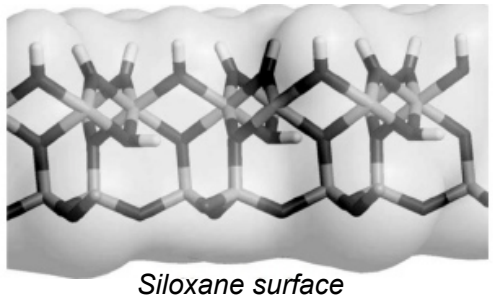
KEY CHARACTERISTICS

1. Layer structure with one dimension in the nanometer range
2. Anisotropy of the layers (and particles)
3. Existence of several types of (charged) surfaces
4. Ease with which the external (and internal) surfaces can be modified





Hydroxyl surface

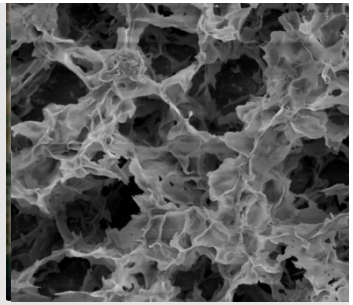


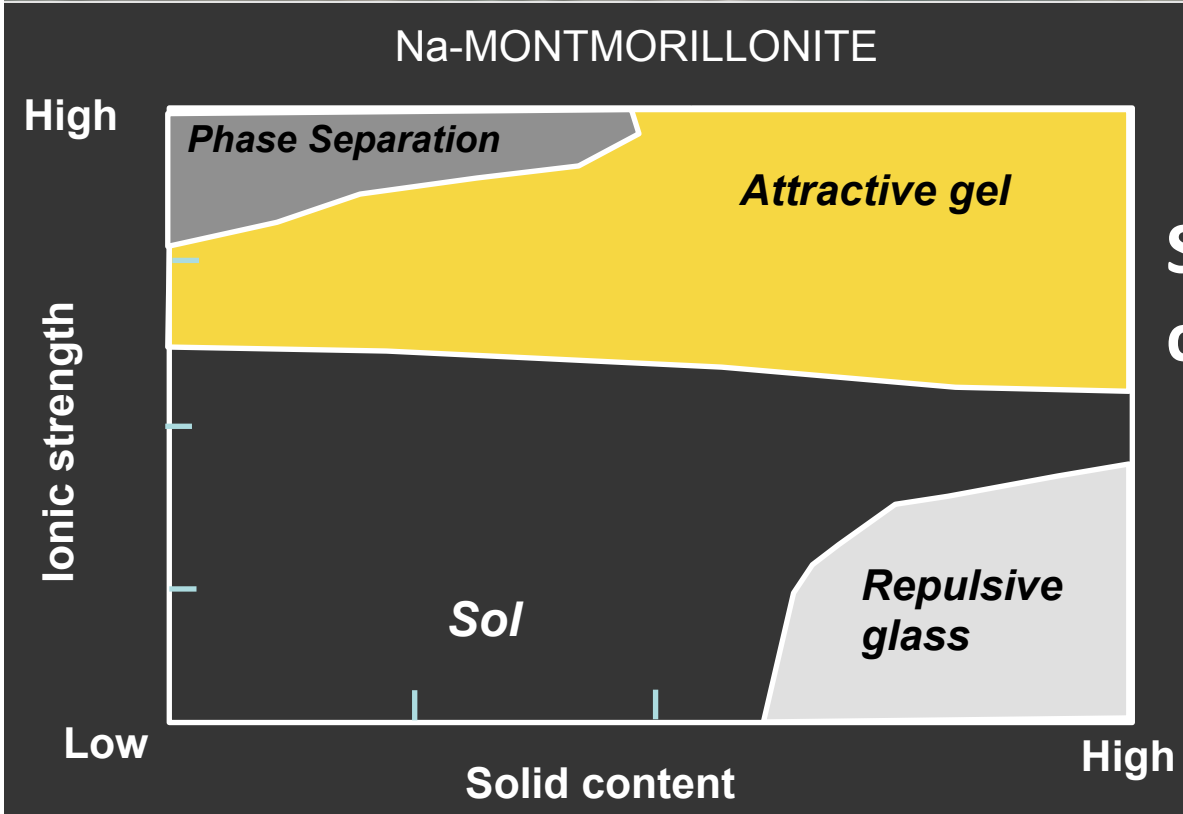
Siloxane surface

Adapted from Bergaya & Lagaly 2013

Images from Schulze 2002, Kogure et al 2010, Johnston 2015

STRUCTURE





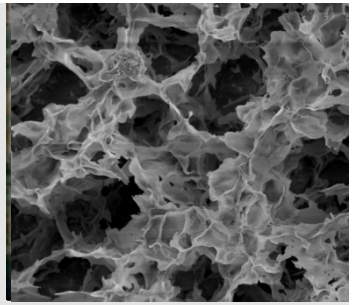
Structure product of colloidal interactions

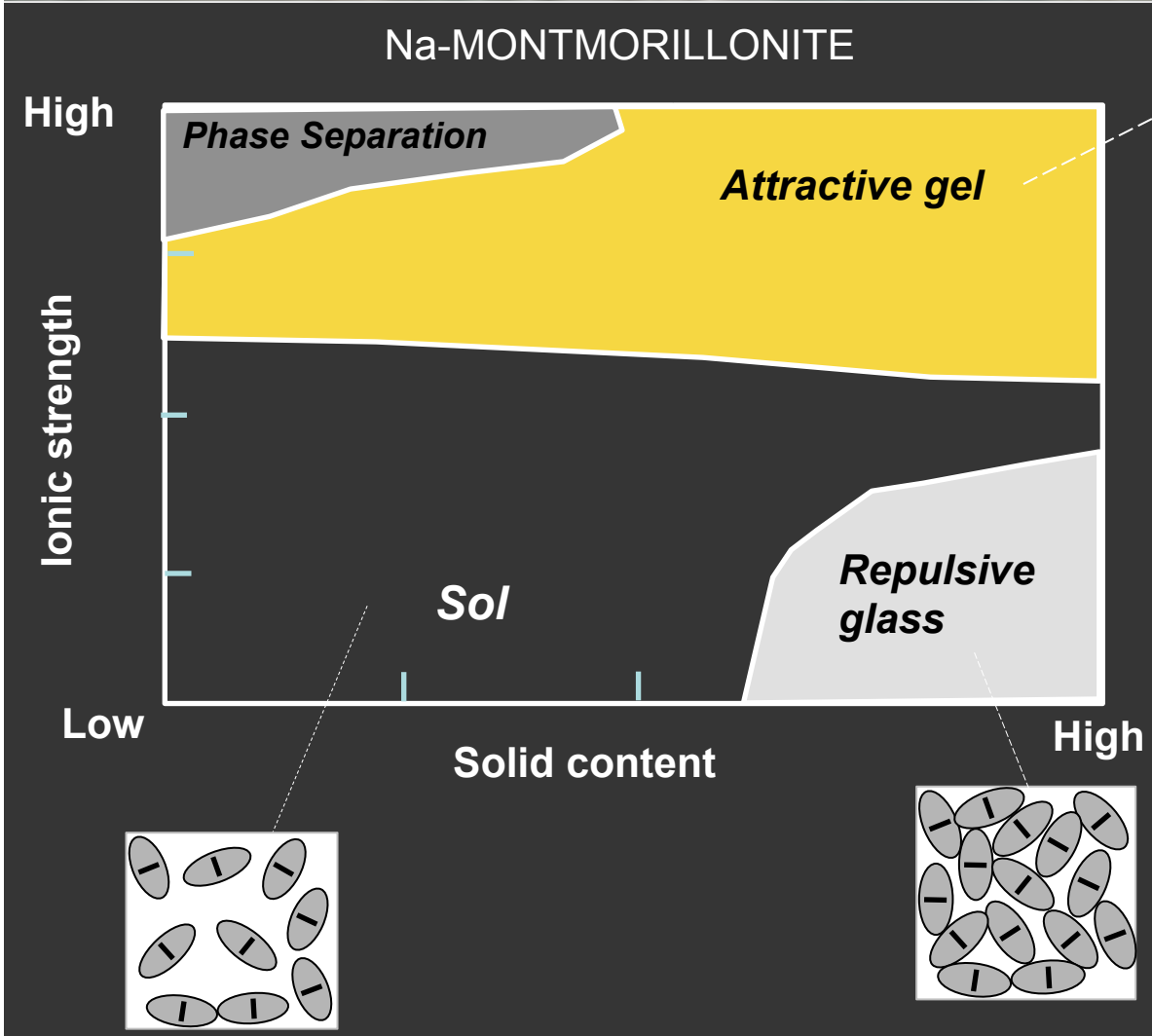
f(solid concentration & "environment")

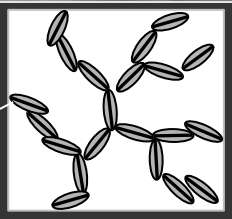
Based on *Abend and Lagaly (2000) & Huang (2013)*

ULTRA SOFT CLAY-WATER SYSTEMS

STRUCTURE







ATTRACTIVE GEL

- disordered state
- percolated network structure (← attractive interactions)
- characteristic length of network > colloidal particles
- solid response *Tanaka et al. 2004*

REPULSIVE GLASS

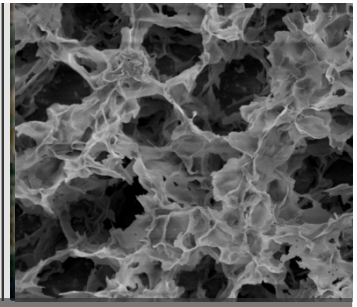
- disordered colloidal system
- elasticity originates from caging effects
- length scale ~ particle dist.
- long range electrostatic repulsion forces dominate

Based on *Abend and Lagaly (2000) & Huang (2013)*

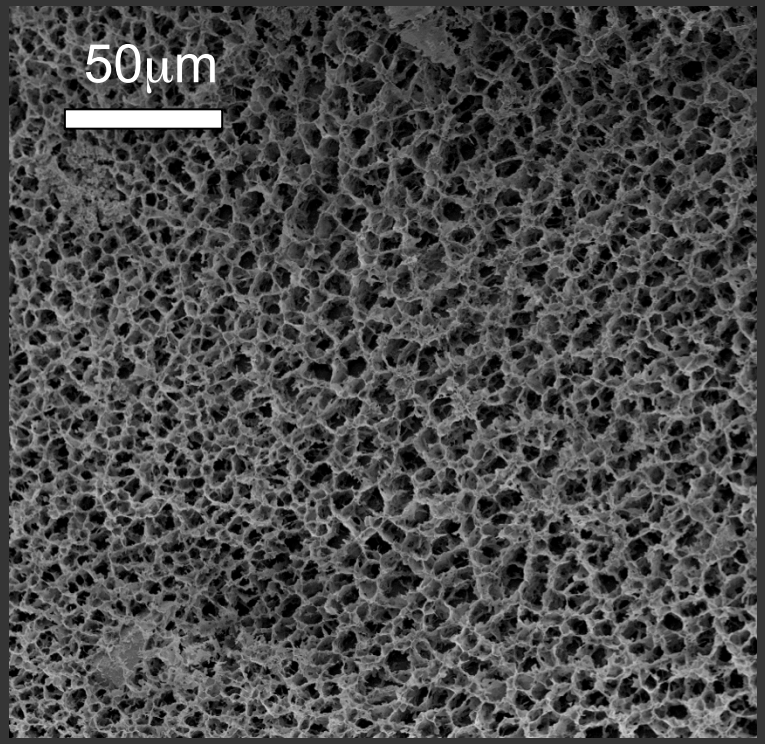
Tanaka et al. 2004

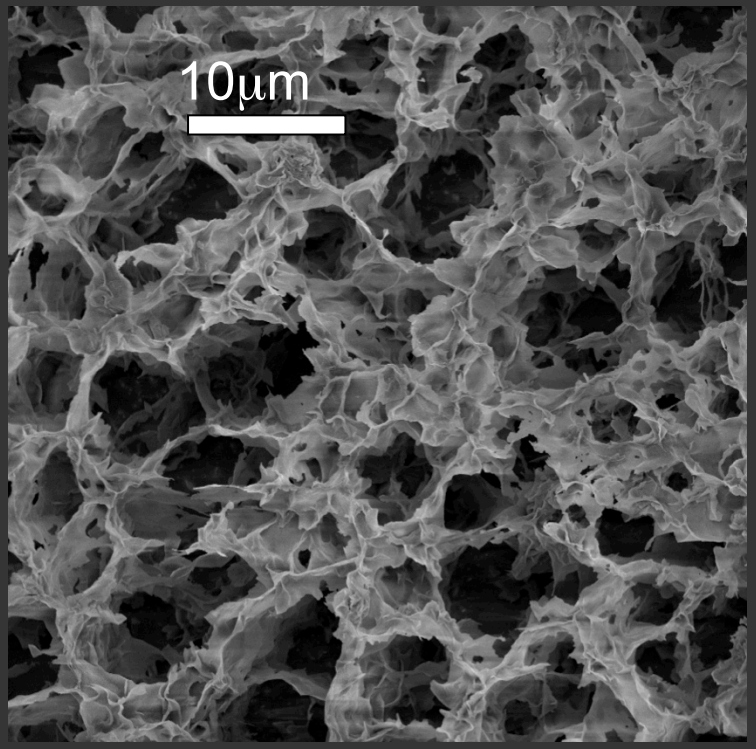
ULTRA SOFT CLAY-WATER SYSTEMS

STRUCTURE



DIRECT OBSERVATION OF ATTRACTIVE GEL





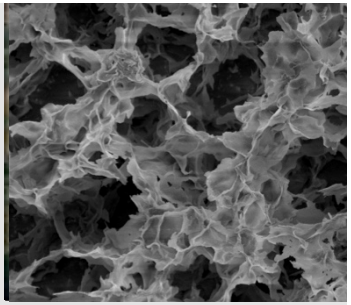
11% BENTONITE DISPERSION

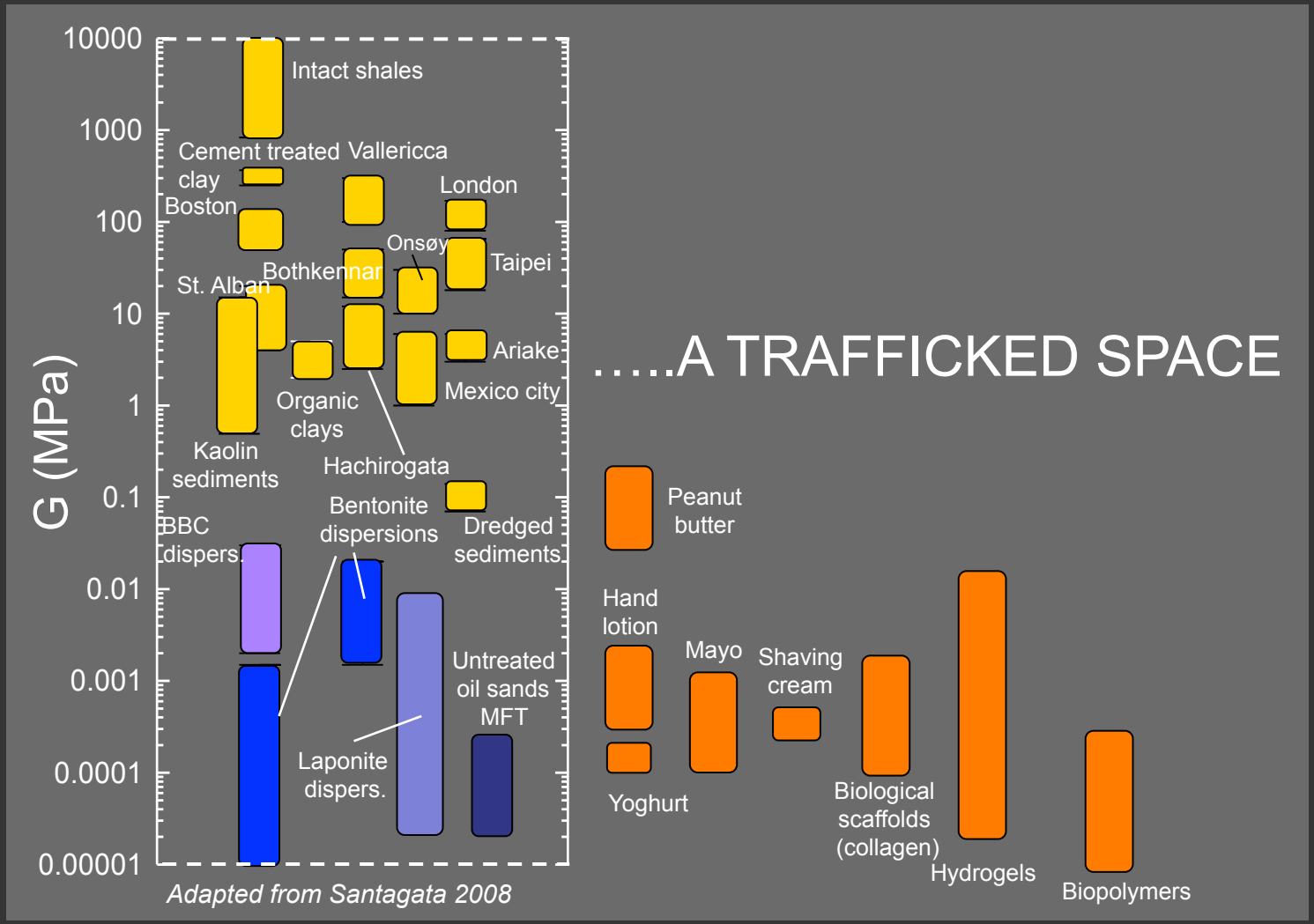
FEI NOVA CRYO-nanoSEM
Purdue Life Sciences Microscopy Facility

Huang (2013)

ULTRA SOFT CLAY-WATER SYSTEMS

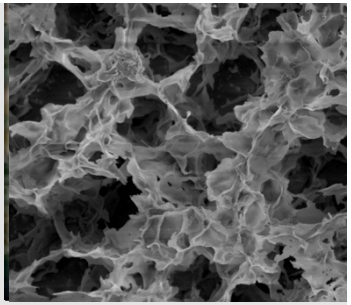
HOW TO INVESTIGATE?



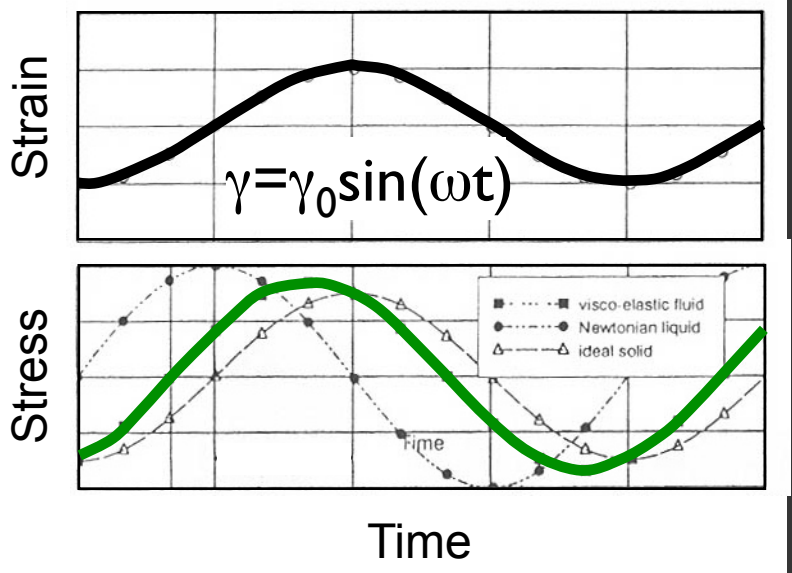


ULTRA SOFT CLAY-WATER SYSTEMS

RHEOLOGY OF CLAY-WATER DISPERSIONS



OSCILLATORY TESTS



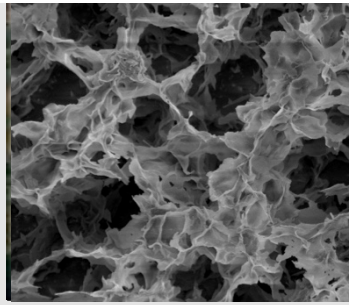
$$\tau = \gamma_0[G'\sin(\omega t) + G''\cos(\omega t)]$$

$$\tan\delta = G''/G'$$

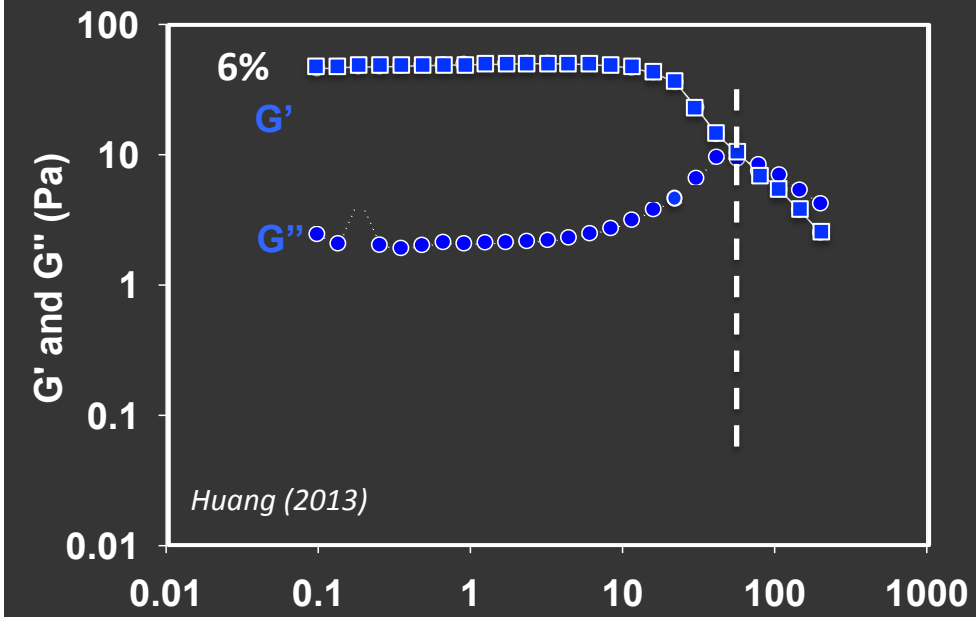
- **Fingerprint visco-elastic response as a function of strain (or frequency)**
- **Monitor structure build-up processes**

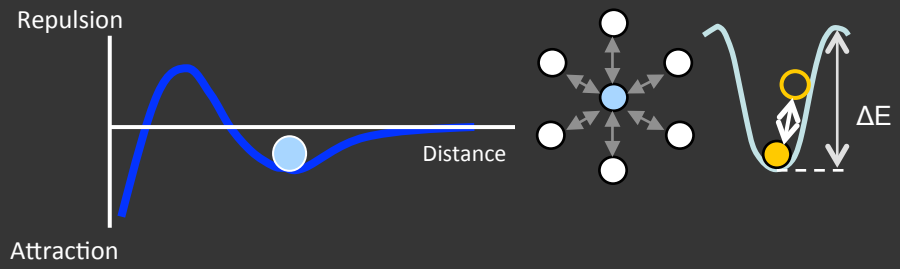
ULTRA SOFT CLAY-WATER SYSTEMS

RHEOLOGY OF CLAY-WATER DISPERSIONS

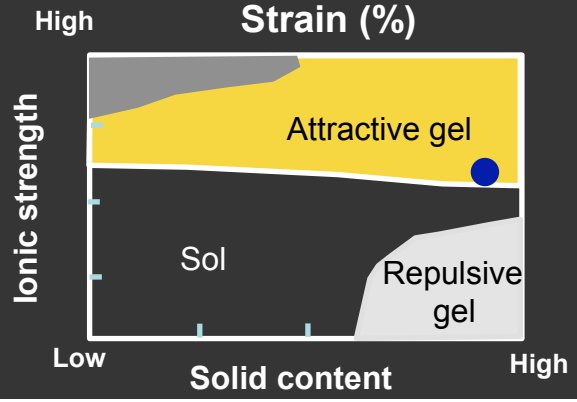


BENTONITE BASED DRILLING FLUID



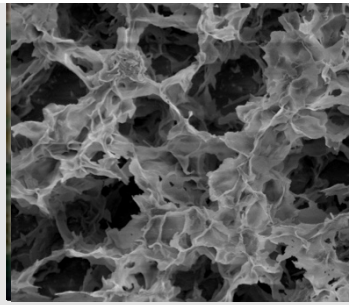


- Large linear threshold
- "Solid" like behavior up to large strains
- Relatively frequency independent at small strains
- Rapid rebuild-up following destructuring (thixotropy)

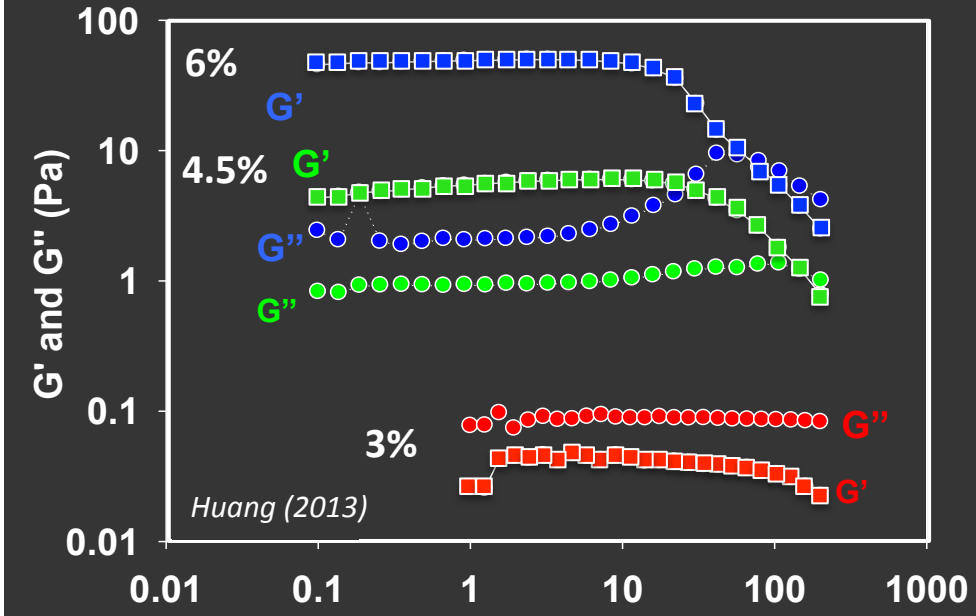


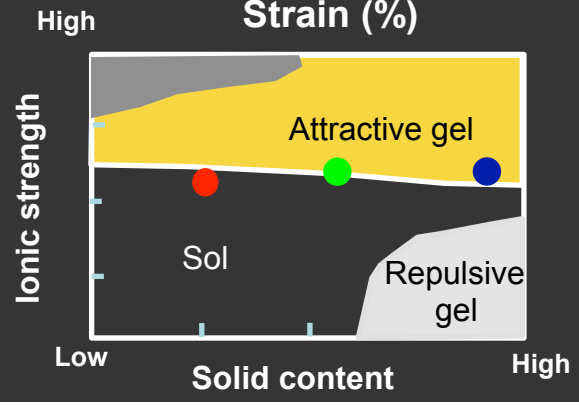
ULTRA SOFT CLAY-WATER SYSTEMS

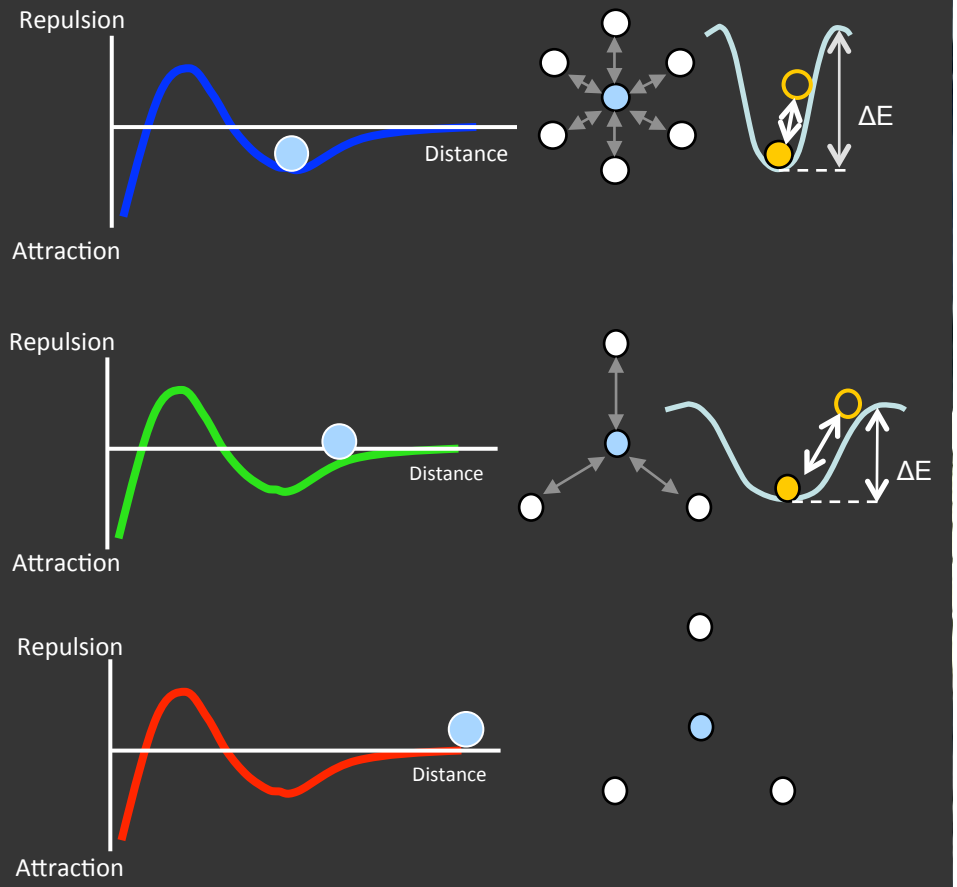
RHEOLOGY OF CLAY-WATER DISPERSIONS



BENTONITE BASED DRILLING FLUID



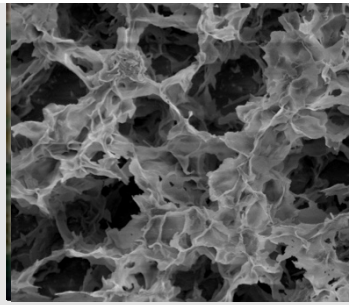


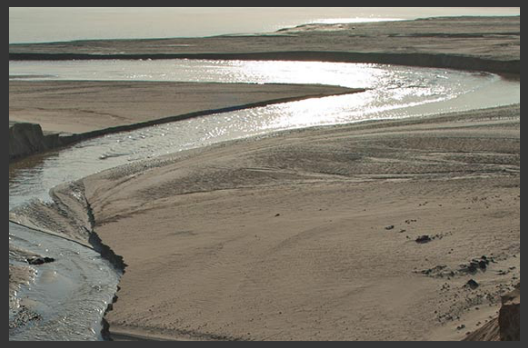


Based on Coussot (2005) and Huang (2013)

ULTRA SOFT CLAY-WATER SYSTEMS

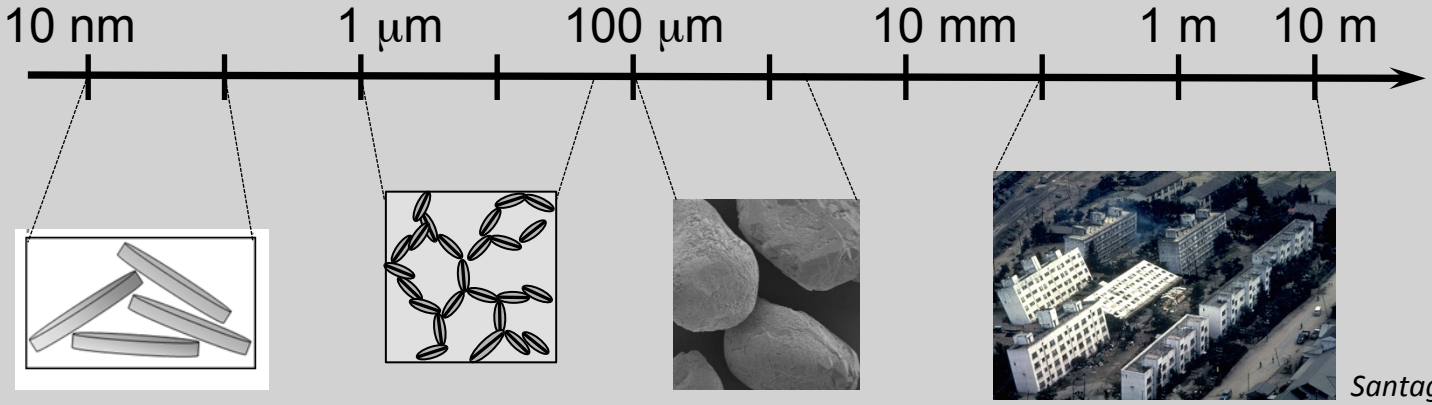
ENGINEERING THE RESPONSE OF CLAY-WATER SYSTEMS





PORE FLUID ENGINEERING FOR LIQUEFACTION MITIGATION

POLYMER FLOCCULATION OF CLAY-RICH TAILINGS



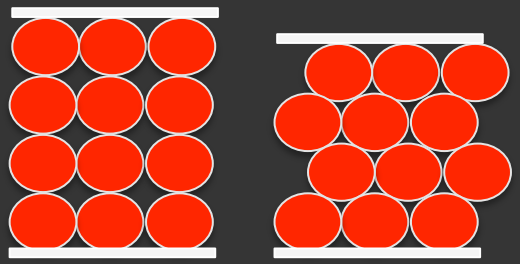
Santagata et al.(2014)

ULTRA SOFT CLAY-WATER SYSTEMS

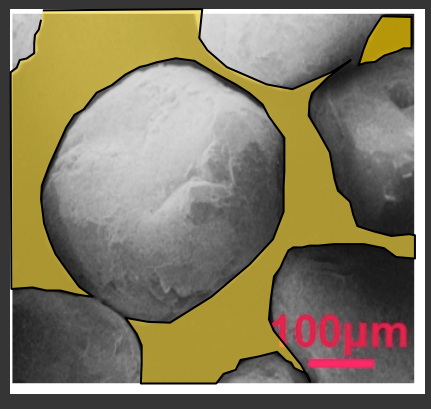
ENGINEERING THE RESPONSE OF CLAY-WATER SYSTEMS

PORE FLUID ENGINEERING FOR LIQUEFACTION MITIGATION

<u>GOAL</u>: RESTRICT GRAIN MOVEMENT DURING SHAKING THROUGH FORMATION OF CLAY-BASED PORE FLUID WITH SOLID LIKE RESPONSE

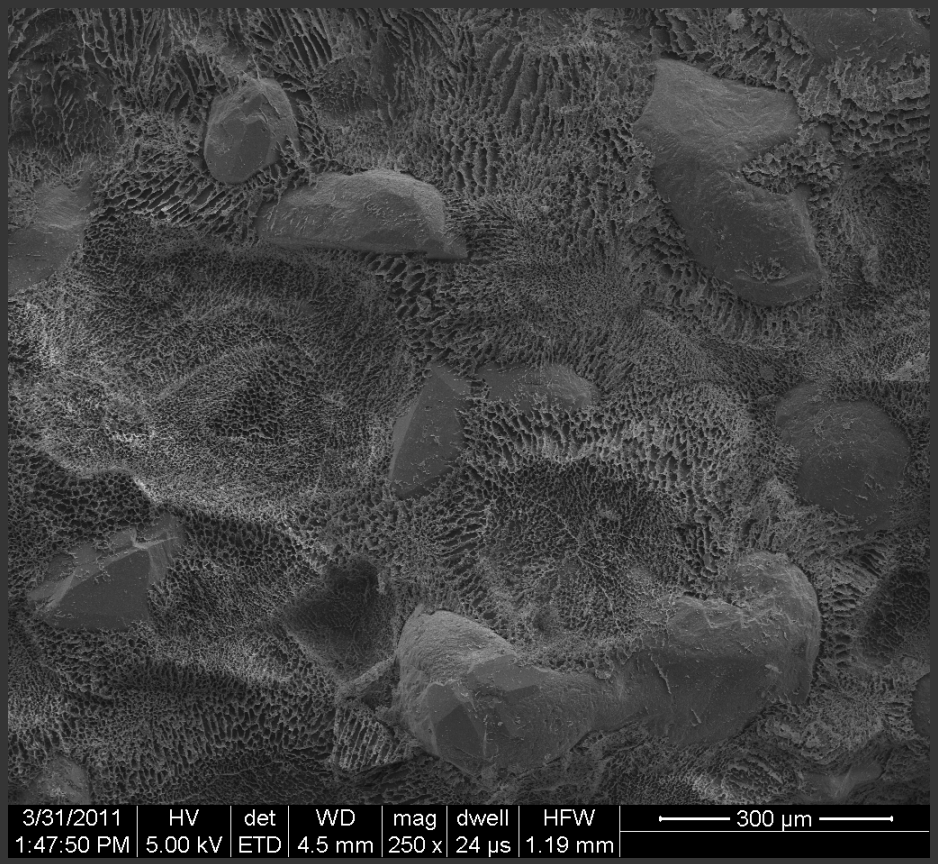


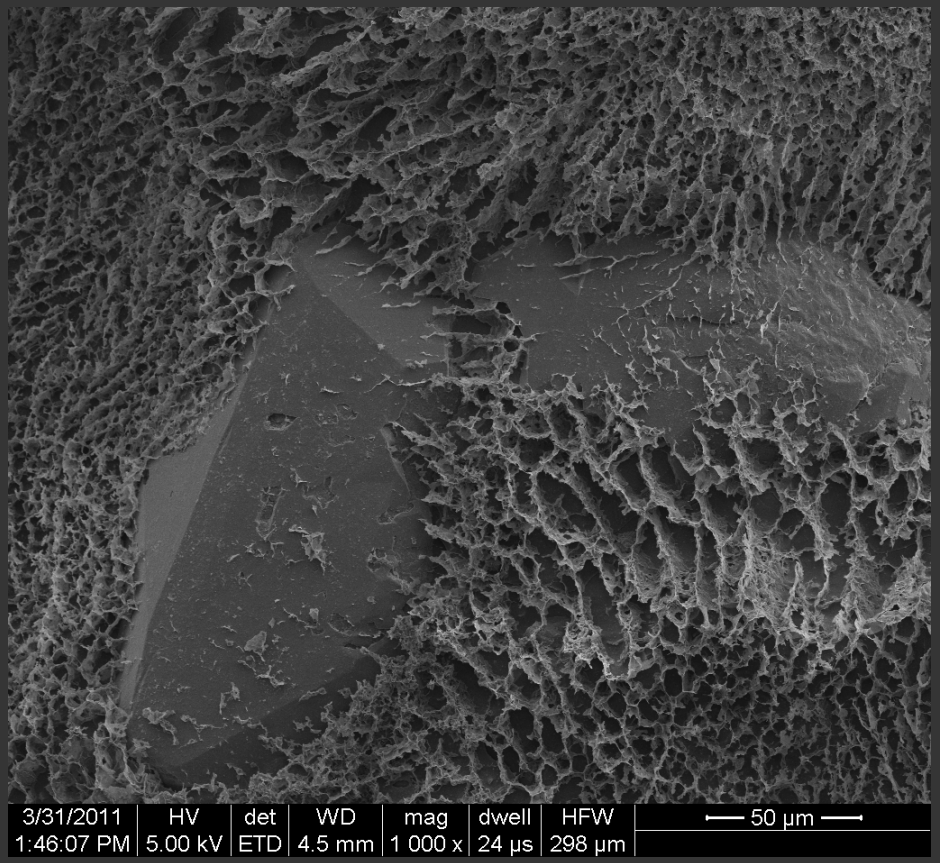
Work with BENTONITE and LAPONITE



ULTRA SOFT CLAY-WATER SYSTEMS

PORE FLUID ENGINEERING FOR LIQUEFACTION MITIGATION





El Howayek et al. 2014

ULTRA SOFT CLAY-WATER SYSTEMS

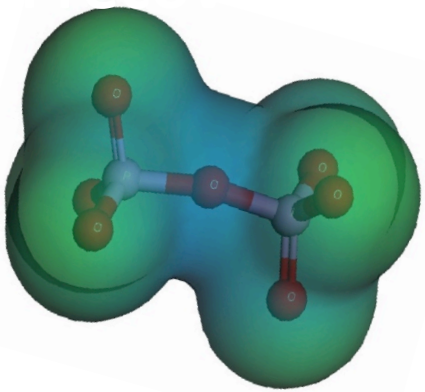
PORE FLUID ENGINEERING FOR LIQUEFACTION MITIGATION

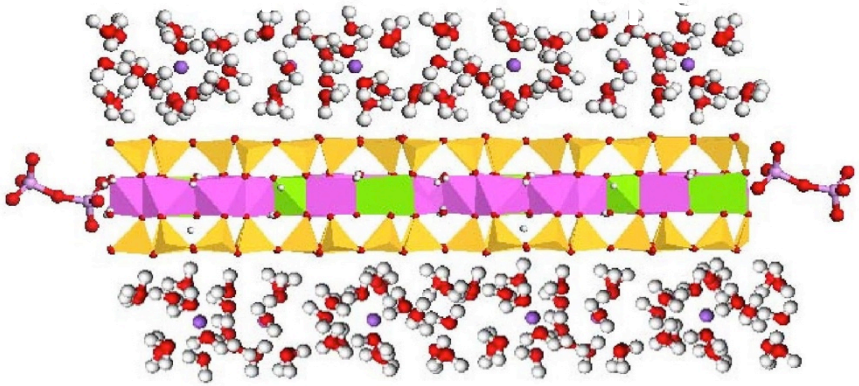
<u>CHALLENGE</u>: DELIVERING CLAY IN PORE SPACE AND ENSURING SUBSEQUENT GEL FORMATION

"TODAY" A SOL ..... "TOMORROW" A GEL

Geochemical control using SODIUM PYROPHOSPHATE (SPP):

- **Inhibits gel formation at early ages**



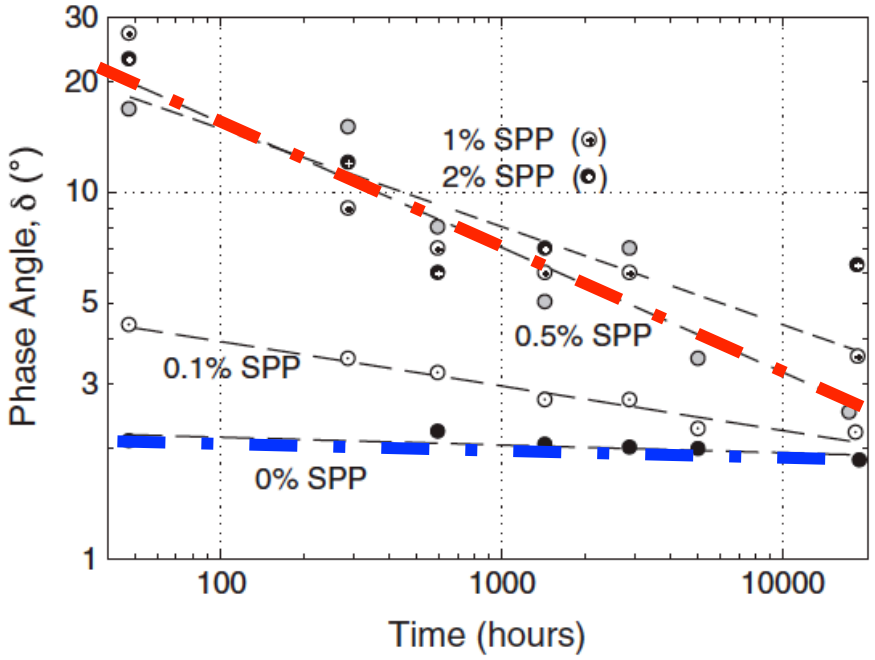


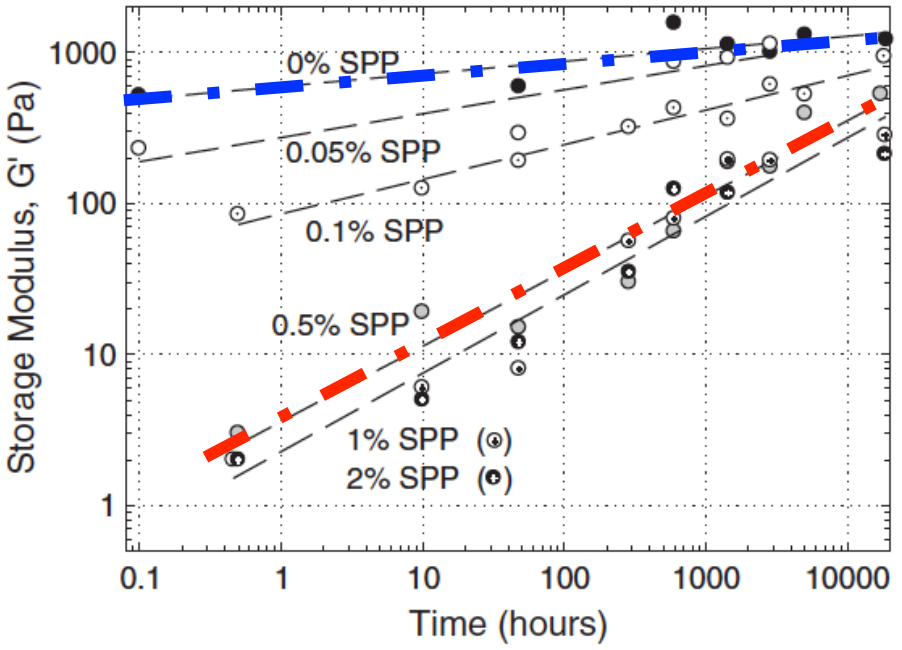
ULTRA SOFT CLAY-WATER SYSTEMS

PORE FLUID ENGINEERING FOR LIQUEFACTION MITIGATION

10% BENTONITE + SPP

- **Gradual recovery of gel structure and solid properties as well as thixotropy and frequency independent response**





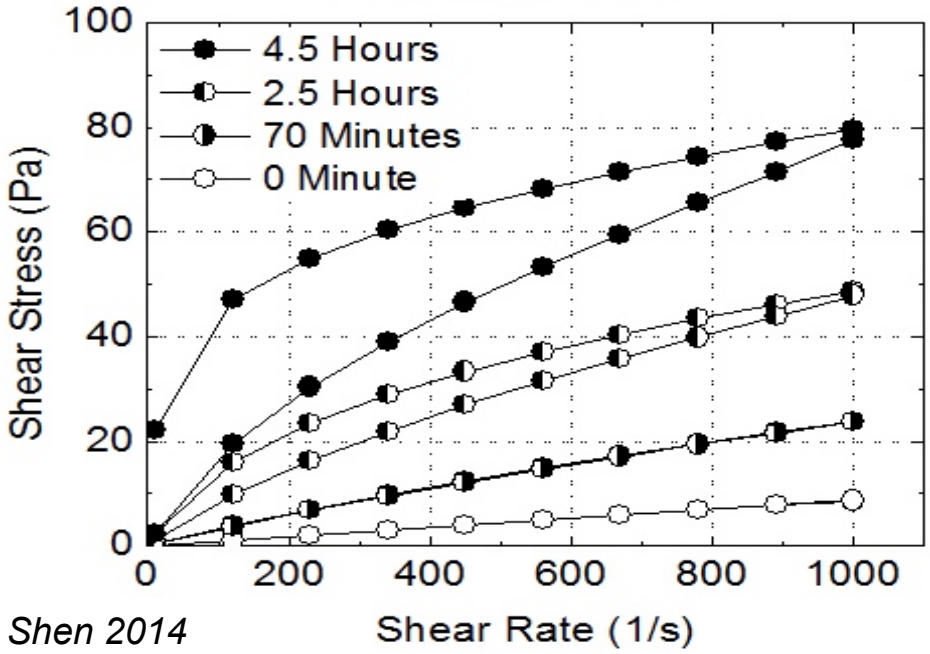
Santagata et al. 2014, Clarke 2008

ULTRA SOFT CLAY-WATER SYSTEMS

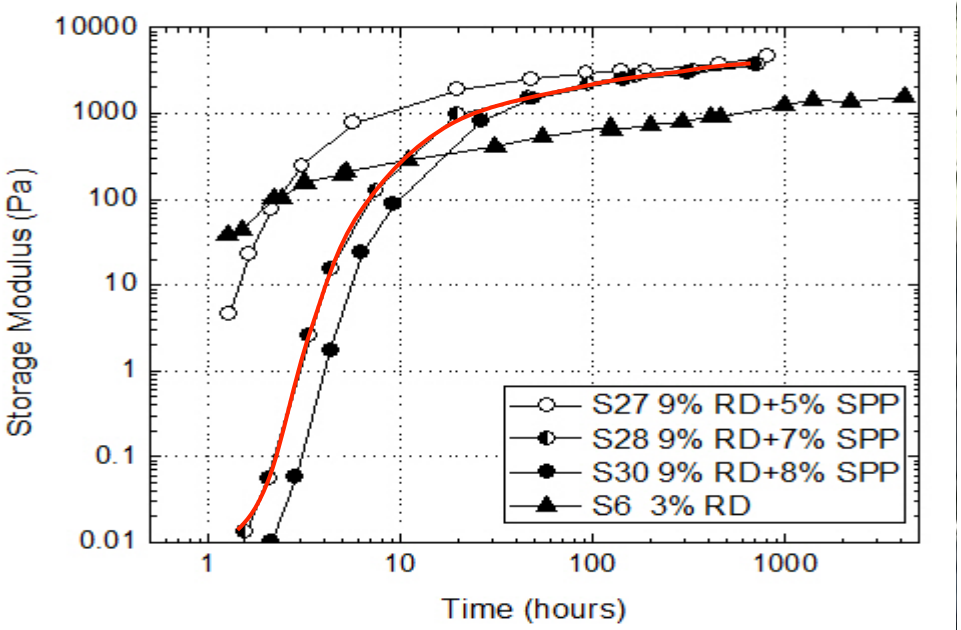
PORE FLUID ENGINEERING FOR LIQUEFACTION MITIGATION

SPP able to "tune" rheology of highly concentrated laponite dispersions

9% LAPONITE + 7%SPP

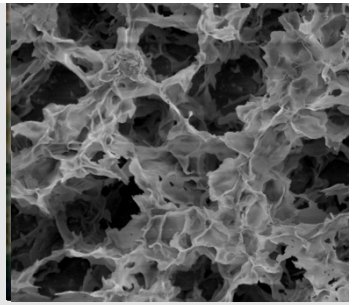


Shen 2014



ULTRA SOFT CLAY-WATER SYSTEMS

ENGINEERING THE RESPONSE OF CLAY-WATER SYSTEMS



PORE FLUID ENGINEERING FOR LIQUEFACTION MITIGATION

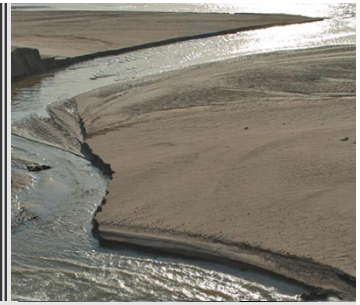
- Clays as a means to improve problem soils
- "Clean" materials - controlled conditions for modification
- Geo-chemical control
- #1 Challenge: Time dependent reversible behavior

POLYMER FLOCCULATION OF CLAY-RICH TAILINGS

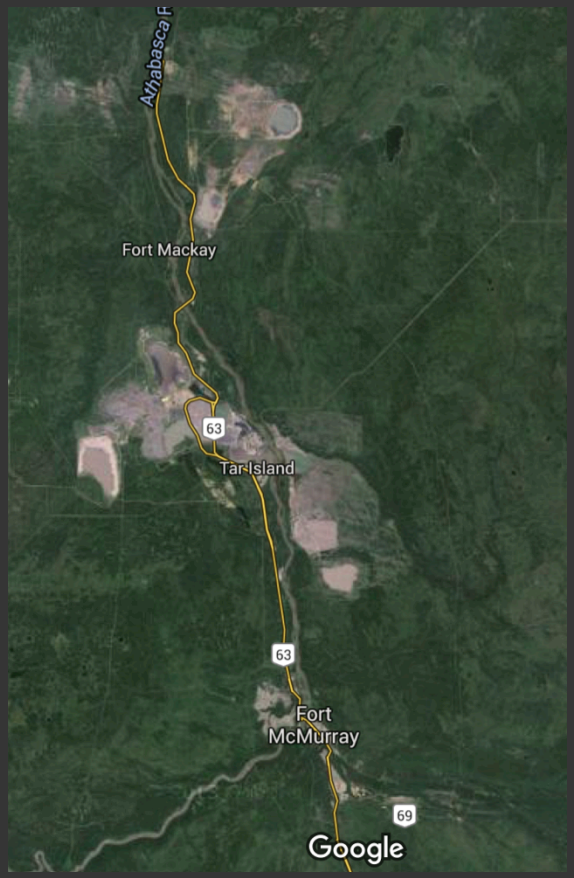
- Clay = problem
- Complex multi-phase material
- Polymer treatment
- #1 Challenge: Large scale and material variability

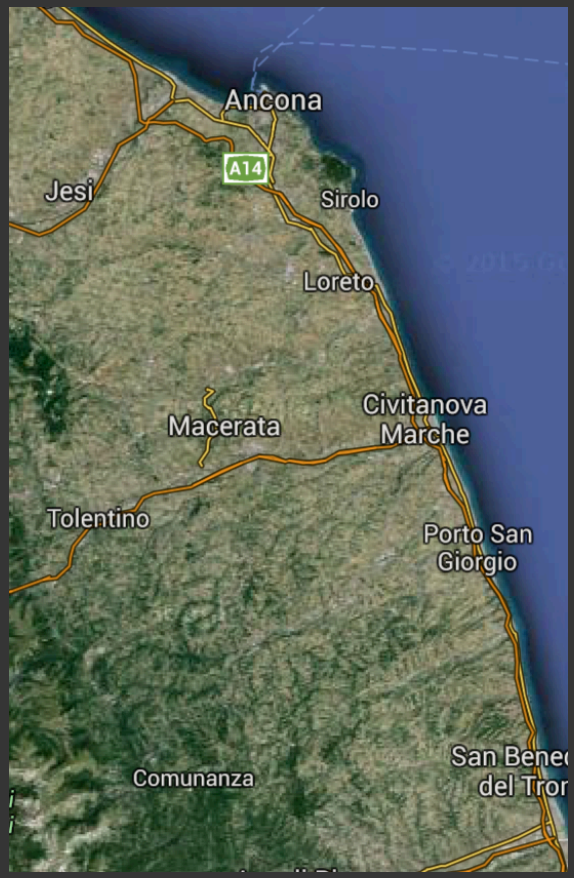
ULTRA SOFT CLAY-WATER SYSTEMS

ENGINEERING THE RESPONSE OF CLAY-WATER SYSTEMS



POLYMER FLOCCULATION OF CLAY-RICH TAILINGS





ULTRA SOFT CLAY-WATER SYSTEMS

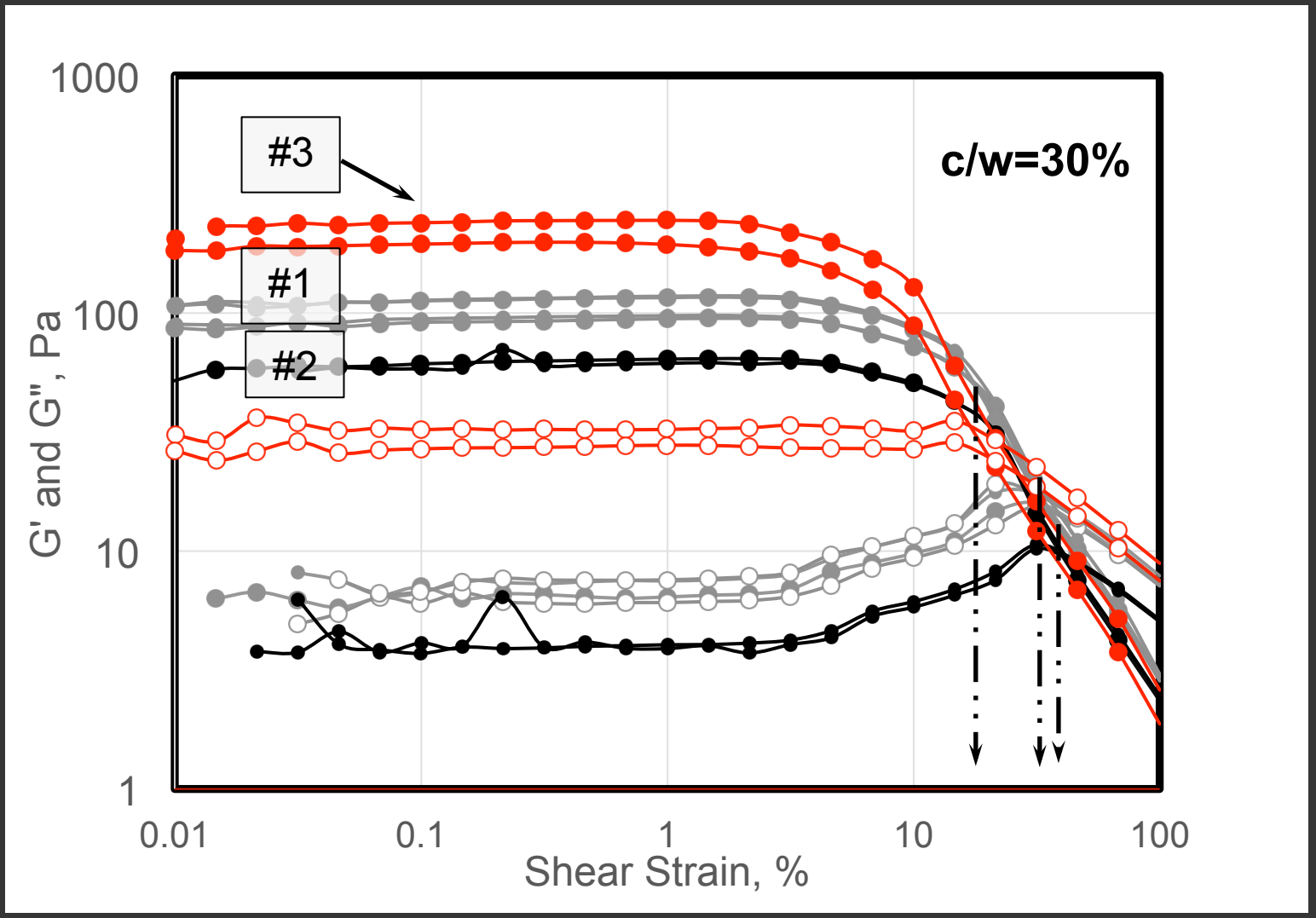
POLYMER FLOCCULATION OF CLAY-RICH TAILINGS

"How the Clay Particle Beat the 10^5 tph process"

(Hollander 2005)

ULTRA SOFT CLAY-WATER SYSTEMS

POLYMER FLOCCULATION OF CLAY-RICH TAILINGS

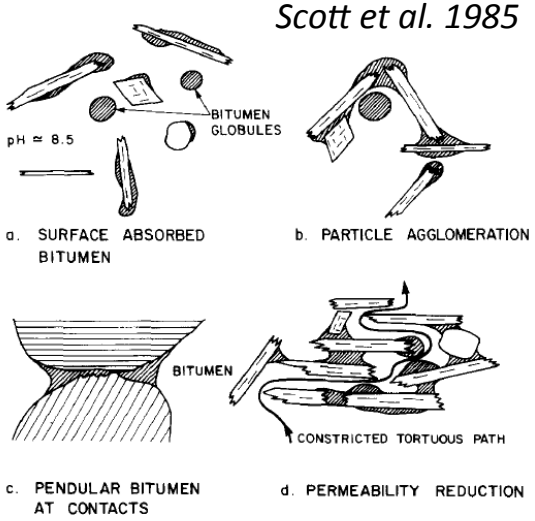


ULTRA SOFT CLAY-WATER SYSTEMS

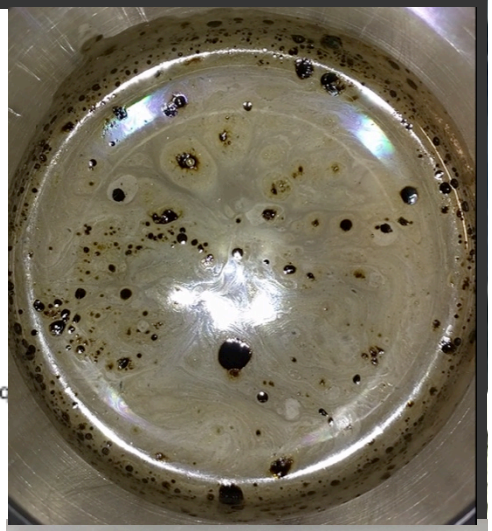
POLYMER FLOCCULATION OF CLAY-RICH TAILINGS

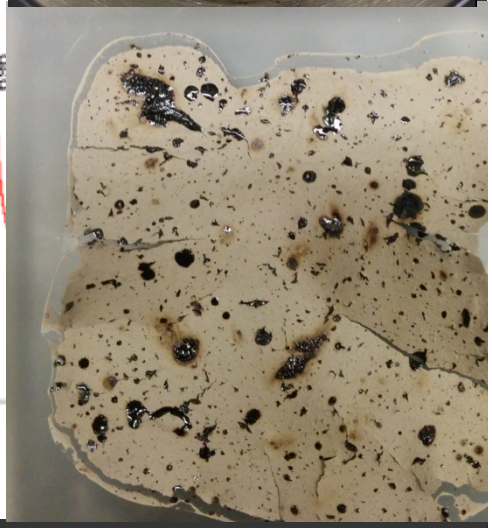
FTIR Spectroscopy

Scott et al. 1985



Johnston et al. 2016

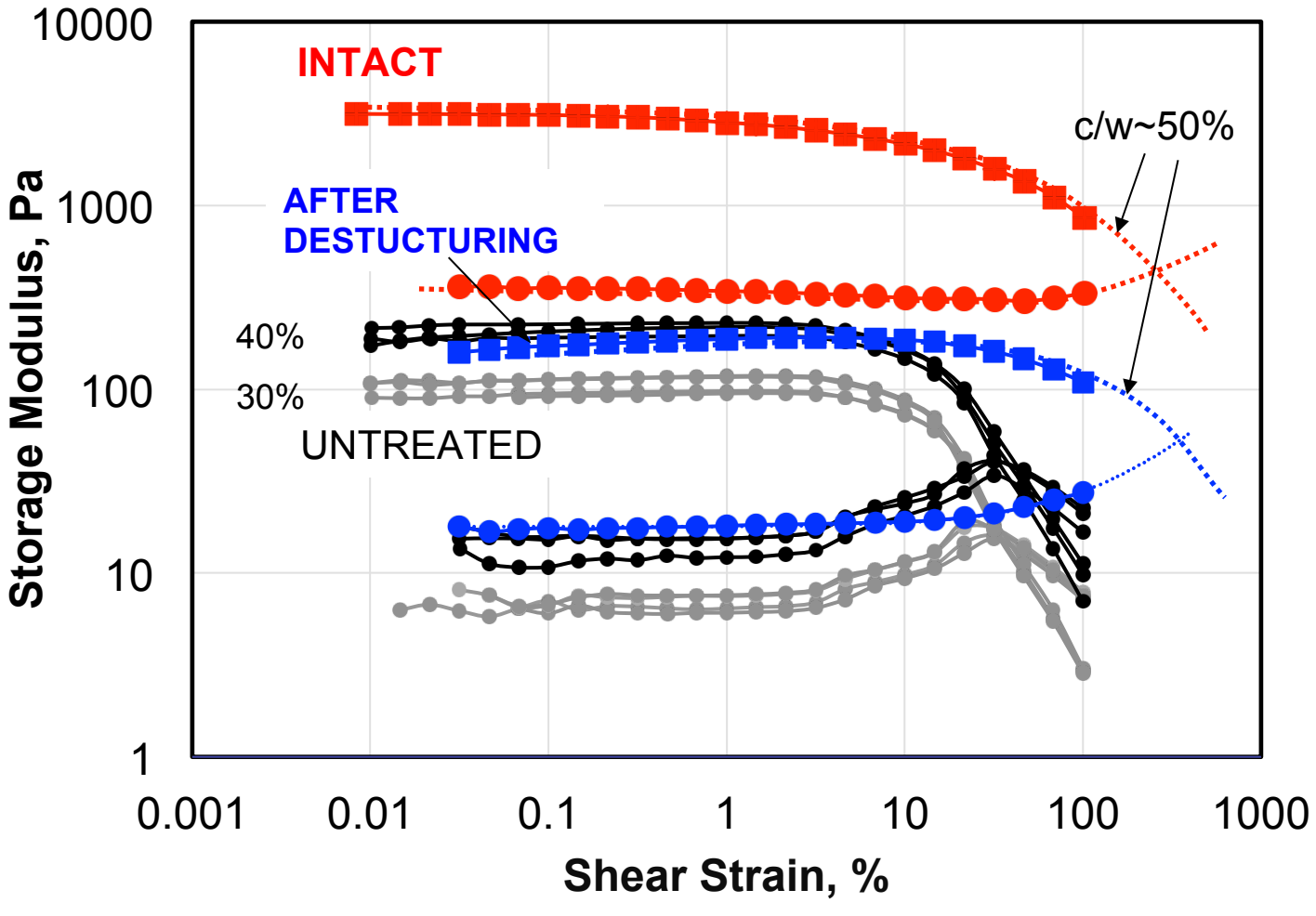




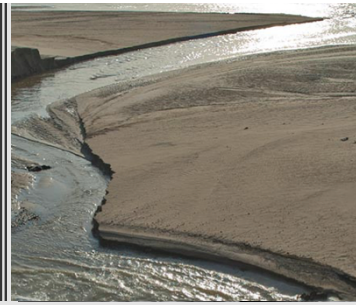
ULTRA SOFT CLAY-WATER SYSTEMS

POLYMER FLOCCULATION ON CLAY-RICH TAILINGS

RHEOLOGY OF TREATED MFT



FINAL THOUGHTS

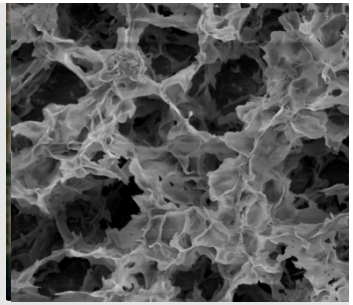


- *"**Clays and clay minerals**, either as such or after modification, will be recognized as the **materials of the 21st century** because they are abundant, inexpensive, and environment friendly."*

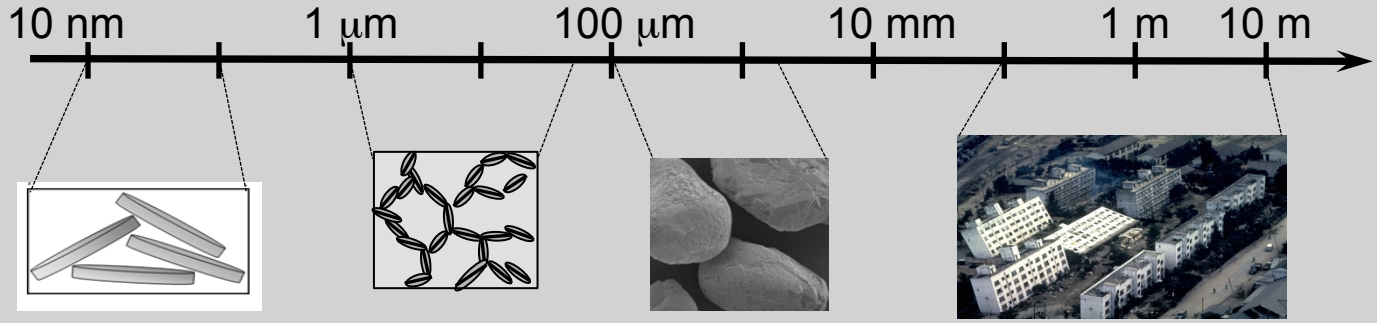
Bergaya & Lagaly 2006

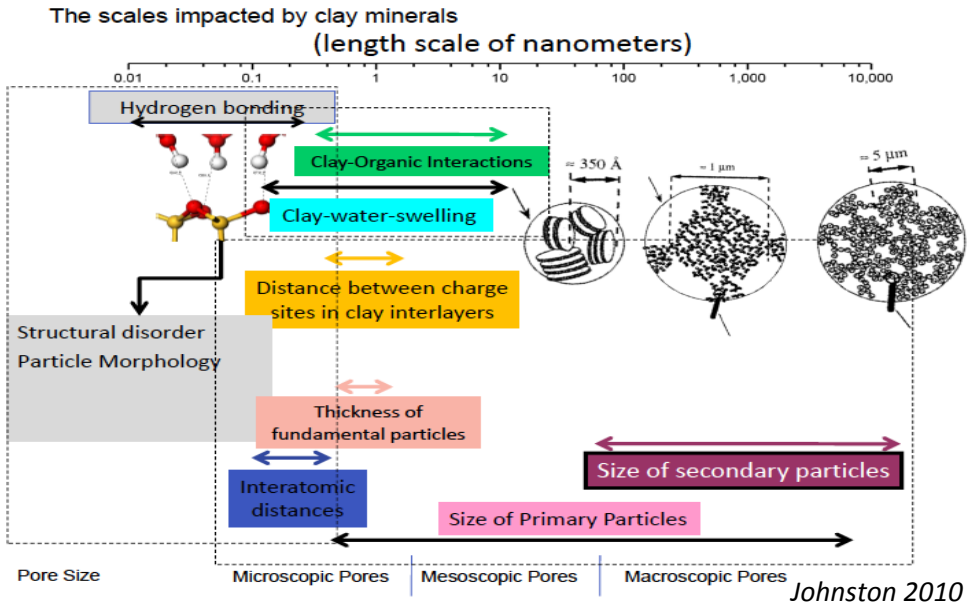
- **GREAT OPPORTUNITIES ON THE SOFTER SIDE OF SOIL MECHANICS**
  - **TAILORING RESPONSE THROUGH GEOCHEMICAL CONTROLS**
  - **CHALLENGING CLASS OF MATERIALS TO CHARACTERIZE AND MODEL**

FINAL THOUGHTS

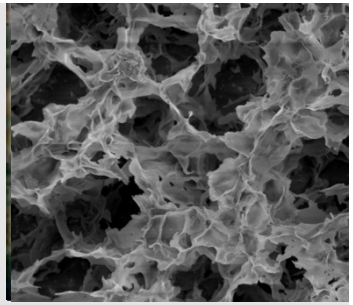


- **ENGINEERING ACROSS SCALES**



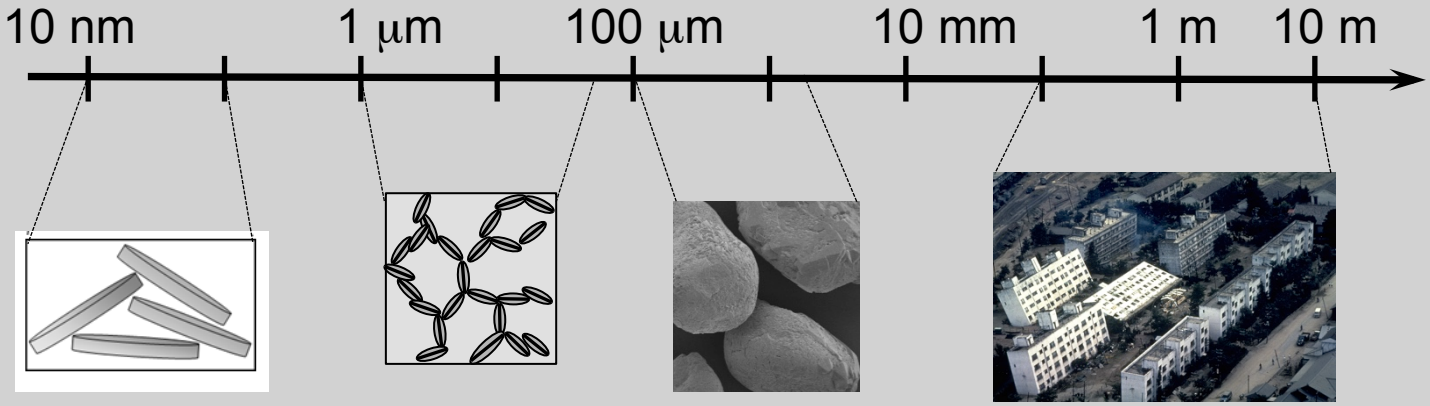


Johnston 2010

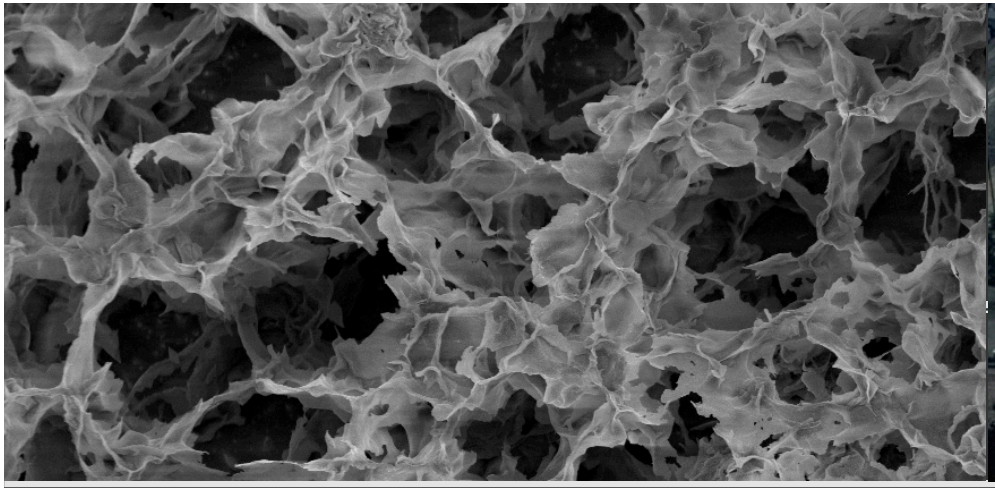


FINAL THOUGHTS

- **ENGINEERING ACROSS SCALES**



- Not only rheology: in many cases understanding of **SURFACE CHEMISTRY** is critical



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