Lessons Learned for the Practicing Engineer: How & When Geosynthetic Clay Liners are Effective for Containment

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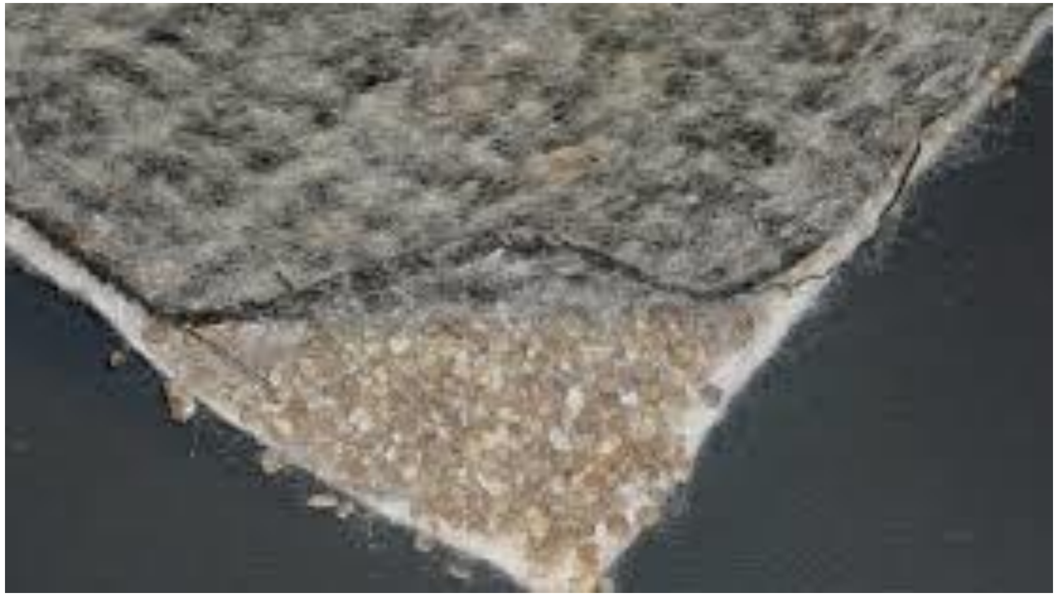
GEOANZ #1 ADVANCES IN GEOSYNTHETICS
7–9 JUNE 2022 | BRISBANE CONVENTION & EXHIBITION CENTRE

GCLs – Thin Factory-Manufactured Clay Liners

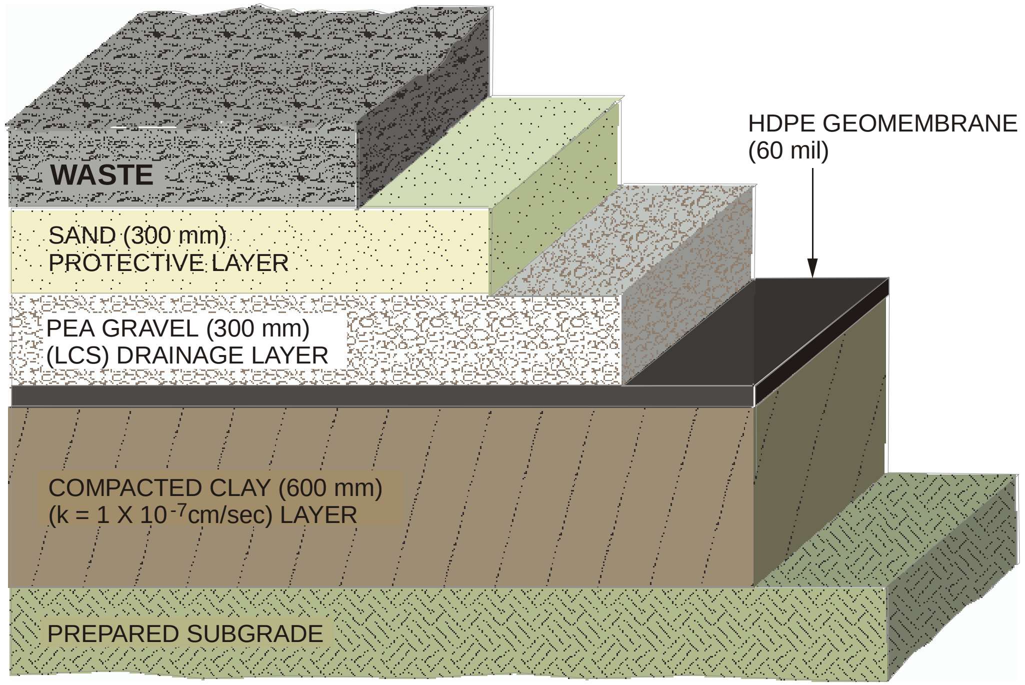


Geosynthetic Clay Liners: Remarkable Materials

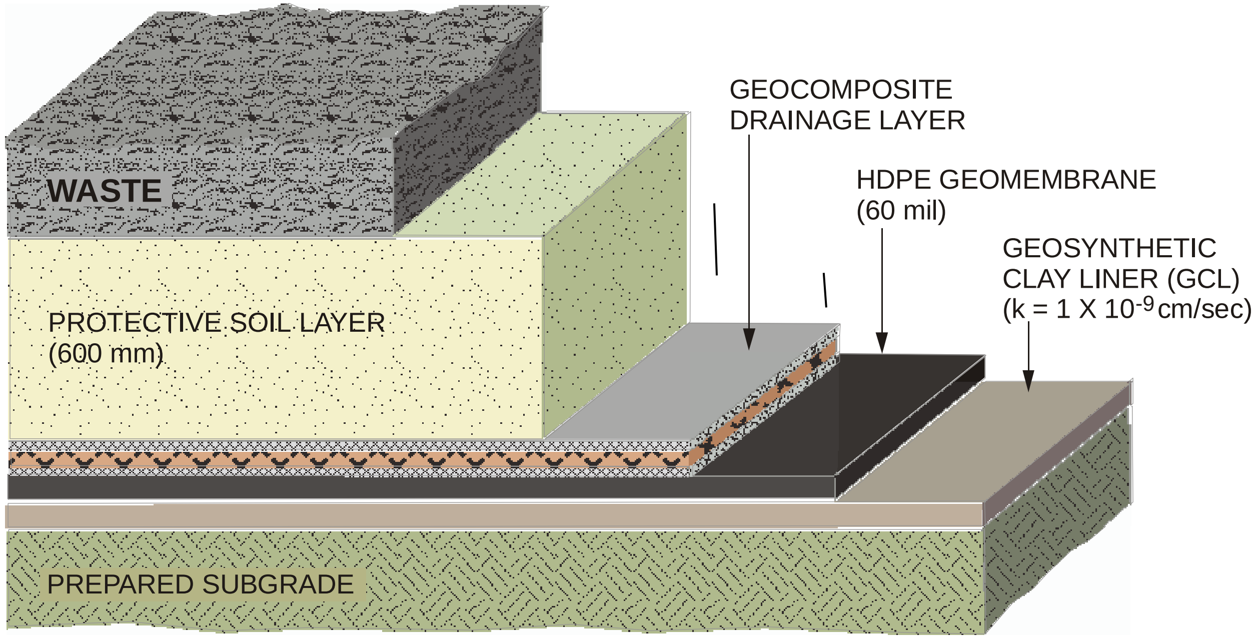
A relatively dry and thin sheet of granular or powdery material becomes an impervious barrier to flow as it hydrates on a subgrade.

Geosynthetic Clay Liners Expedite Design and Construction & Preserve Airspace

Conventional Liner System



Alternative Design with Geosynthetic Clay Liner (GCL)

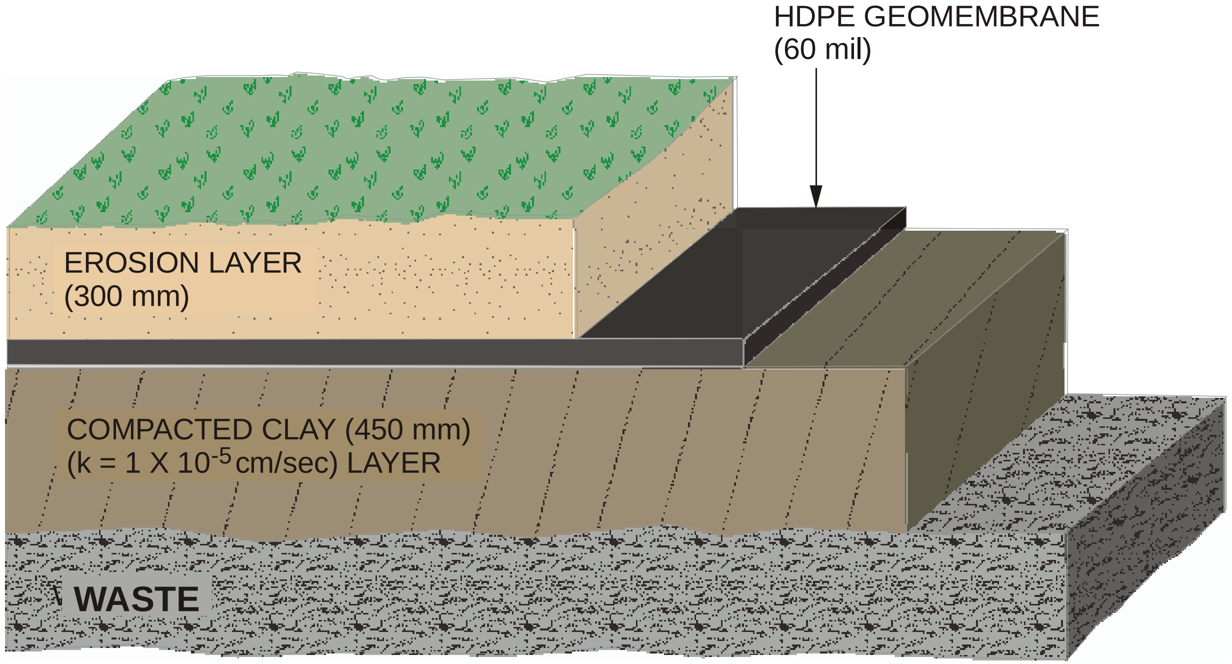


Figures courtesy M. Othman, Geosyntec Consultants

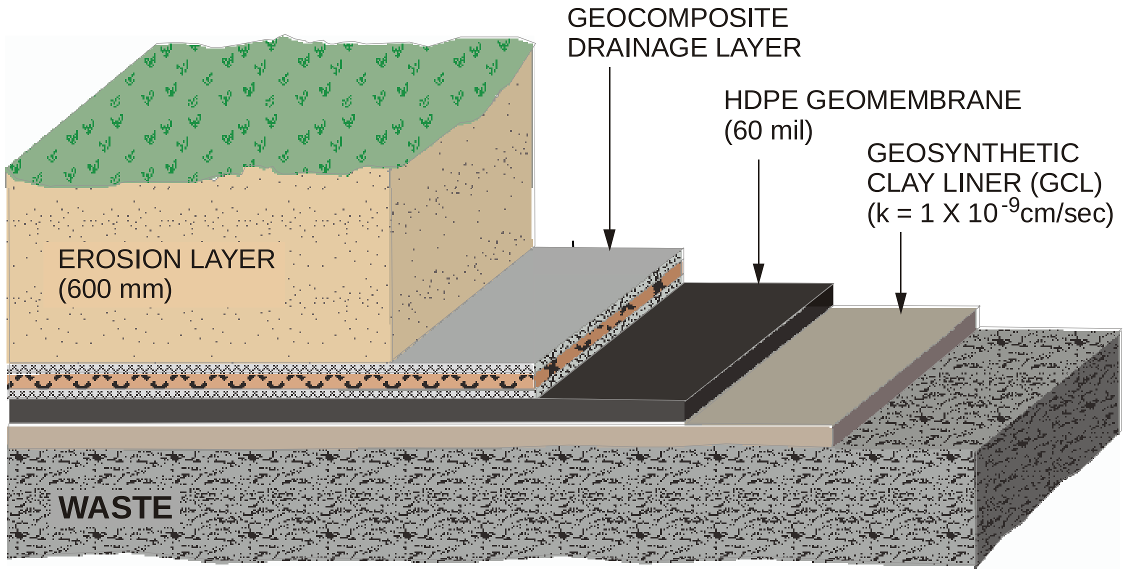
GCLs permit rapid and cost-effective construction, as well as savings in air space. Particularly advantageous in clay poor areas.

Using GCLs in Final Covers Improves Performance

Conventional Cover System



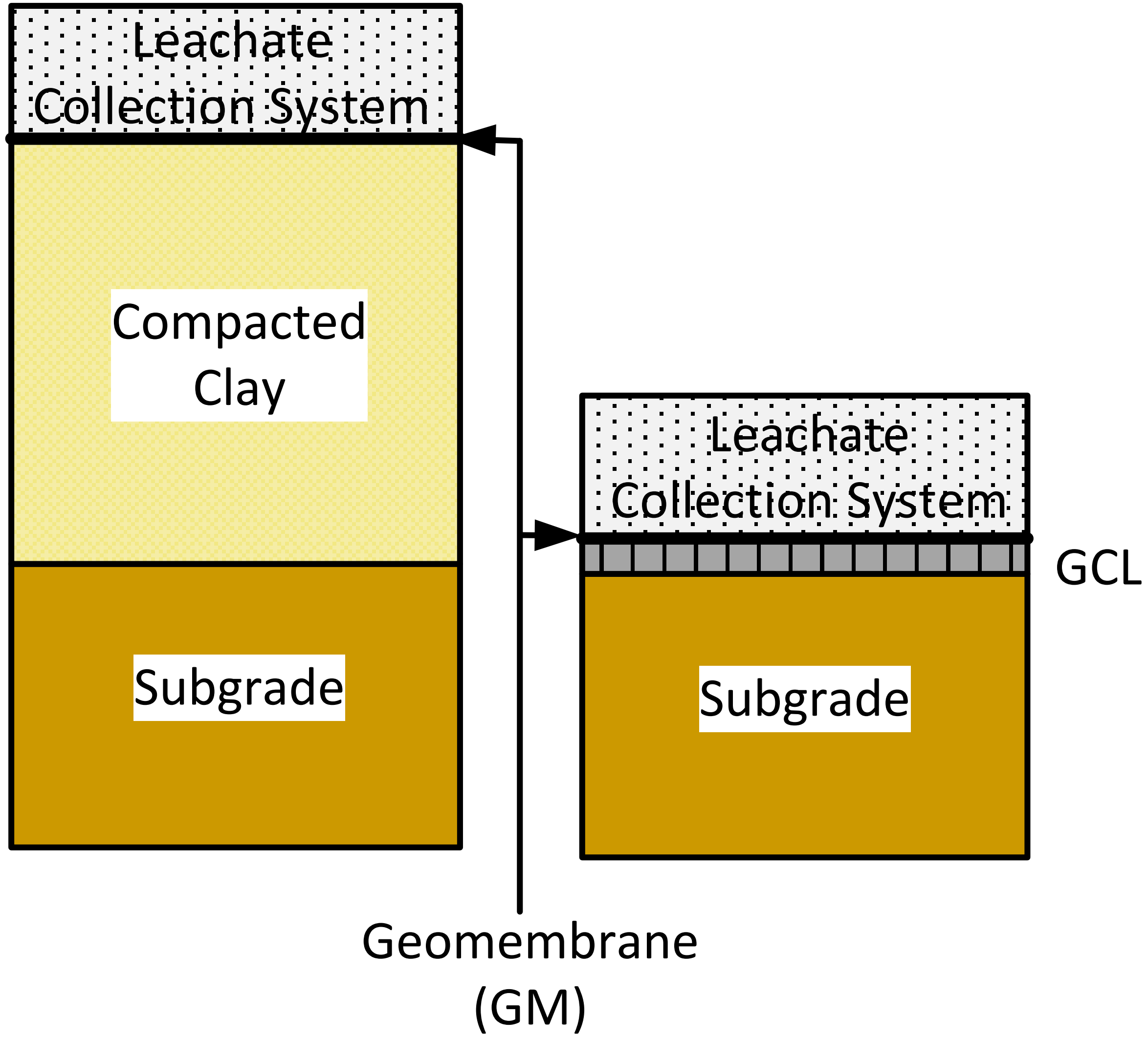
Alternative Design with Geosynthetic Clay Liner (GCL)

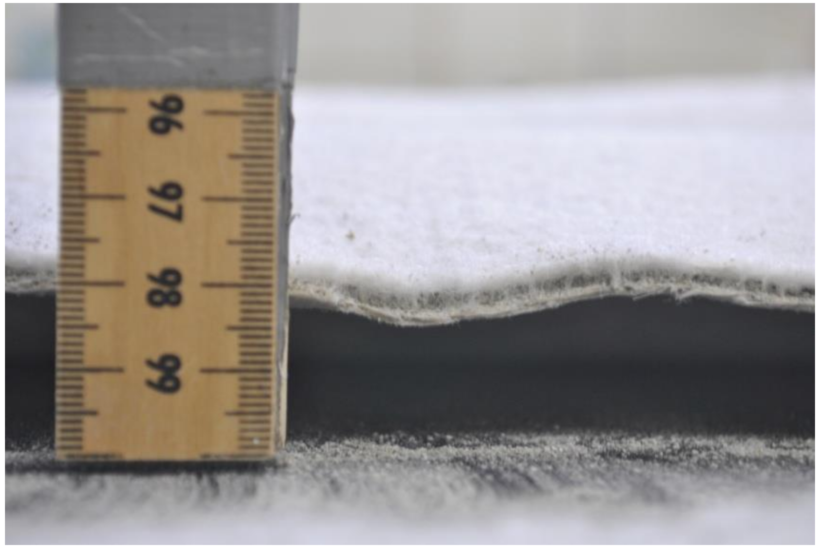


Figures courtesy M. Othman, Geosyntec Consultants

GCLs can be more readily and rapidly deployed over a softer and more compressible foundation. GCLs can be more resilient too (freeze-thaw, distortion)

Geosynthetic Clay Liners Preserve Airspace



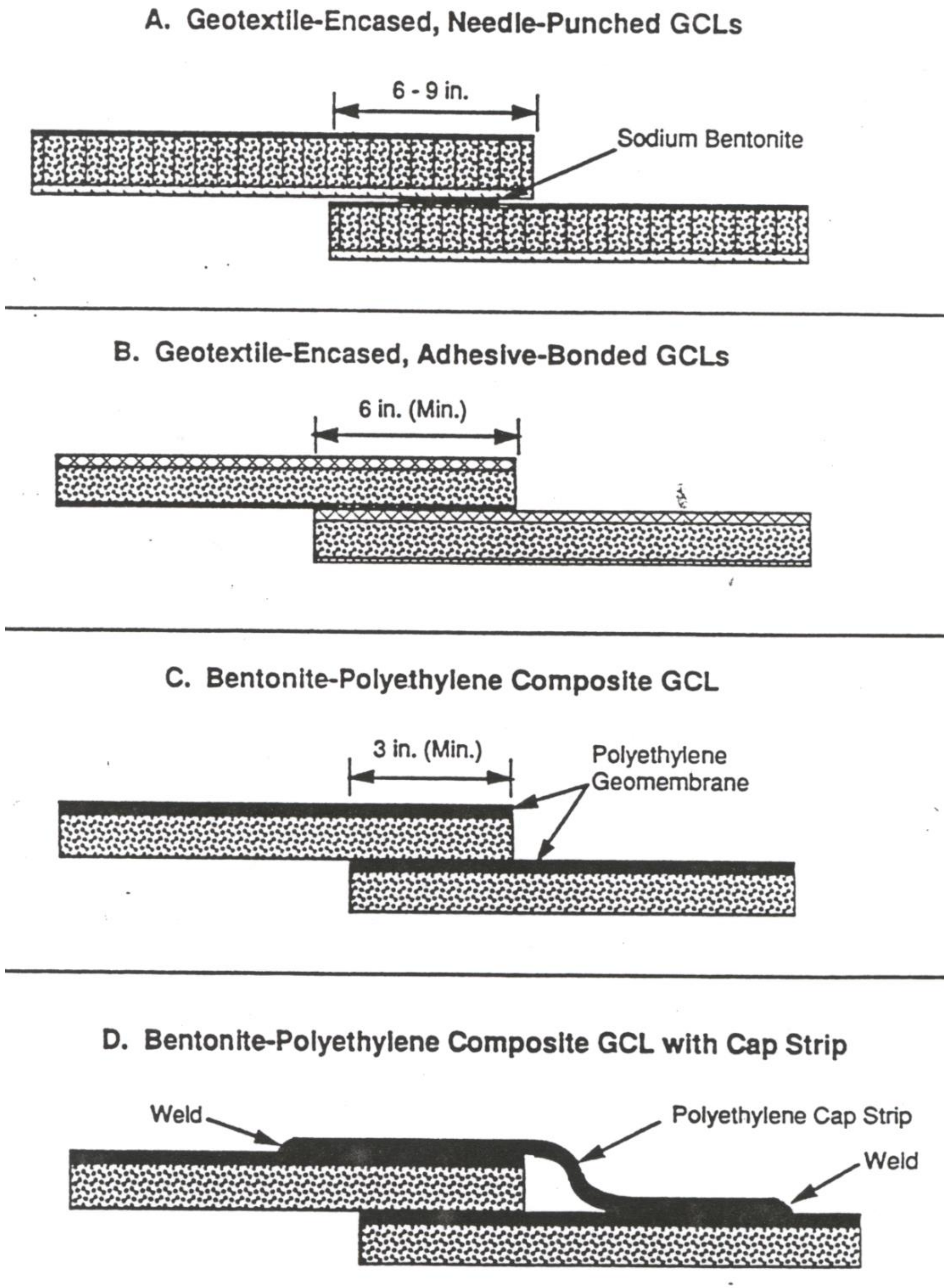


Joining Panels

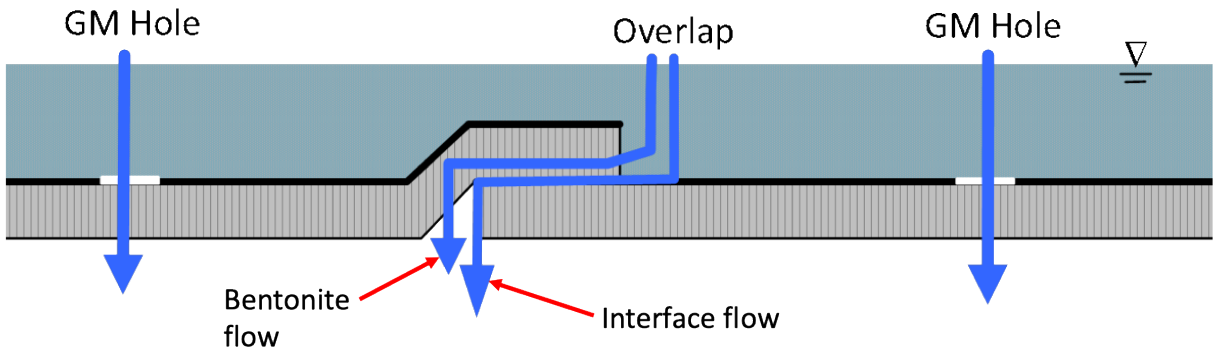
Overlap adjacent panels 150-300 mm (300 mm preferred).

Some manufacturers recommend adding dry bentonite in overlap (~1.5 kg/m) – my recommendation too.

Overlapped panels can be effective as intact panels (except laminated GCLs).

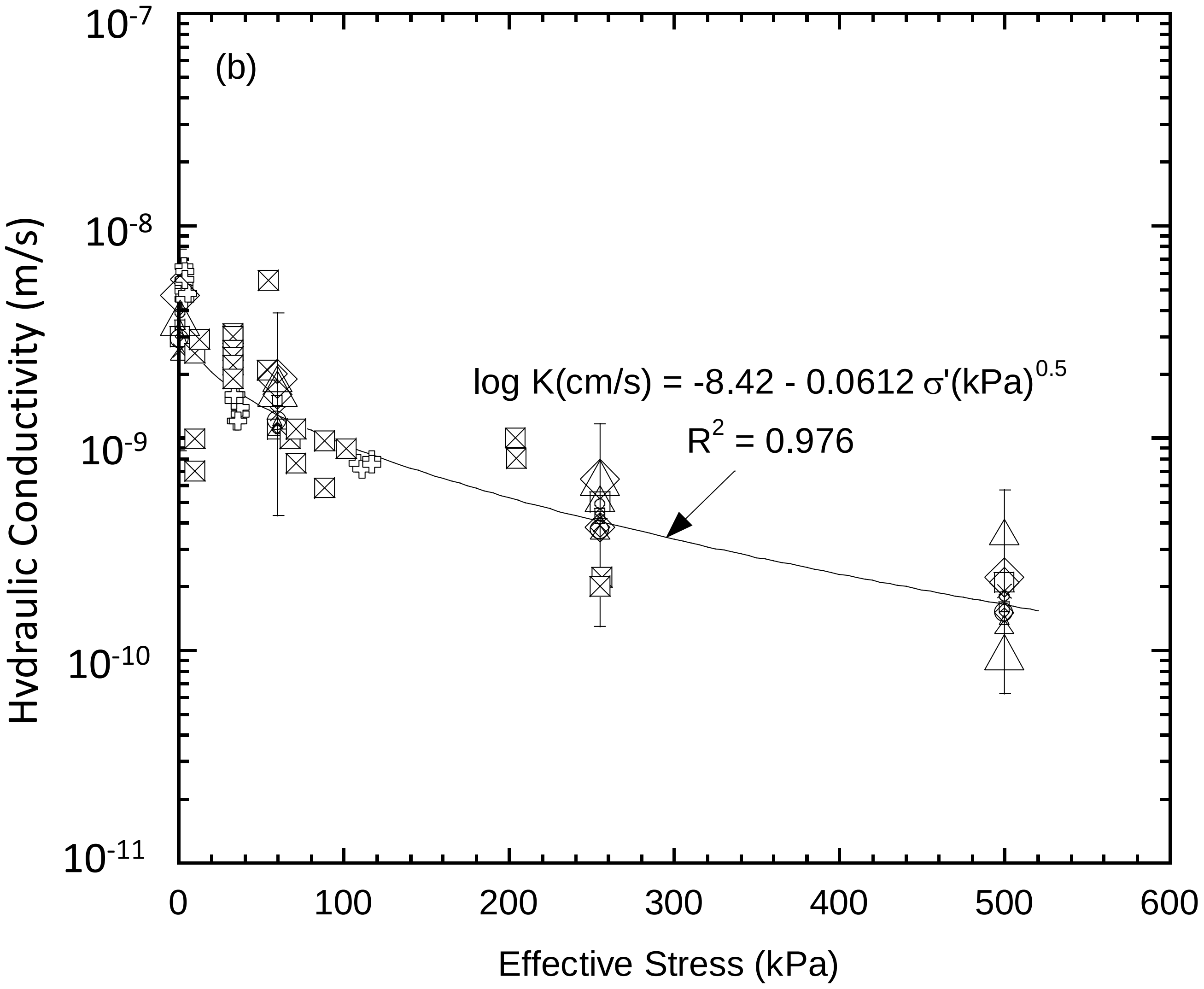


Geomembrane-GCL Composites(aka Laminated GCLs)



- Normally overlap seams, but can include a cap strip on overlap for greater flow reduction.
- Dry bentonite in overlap at 1.5 kg/m.
- Interface strength at GM-GCL can be a concern. Ensure stability criteria met (see follow on section).

Factory Manufactured: Highly Reproducible Properties



- Hydraulic conductivity to a given liquid typically varies ~ 2x..
- Products differ – **GCLs not interchangeable.**
- Bentonite source & quality, bentonite granule size & gradation, bonding technique influence hydraulic conductivity for given engineering application.
- Needlepunching fiber density can strongly affect hydraulic conductivity, all other factors being equal.

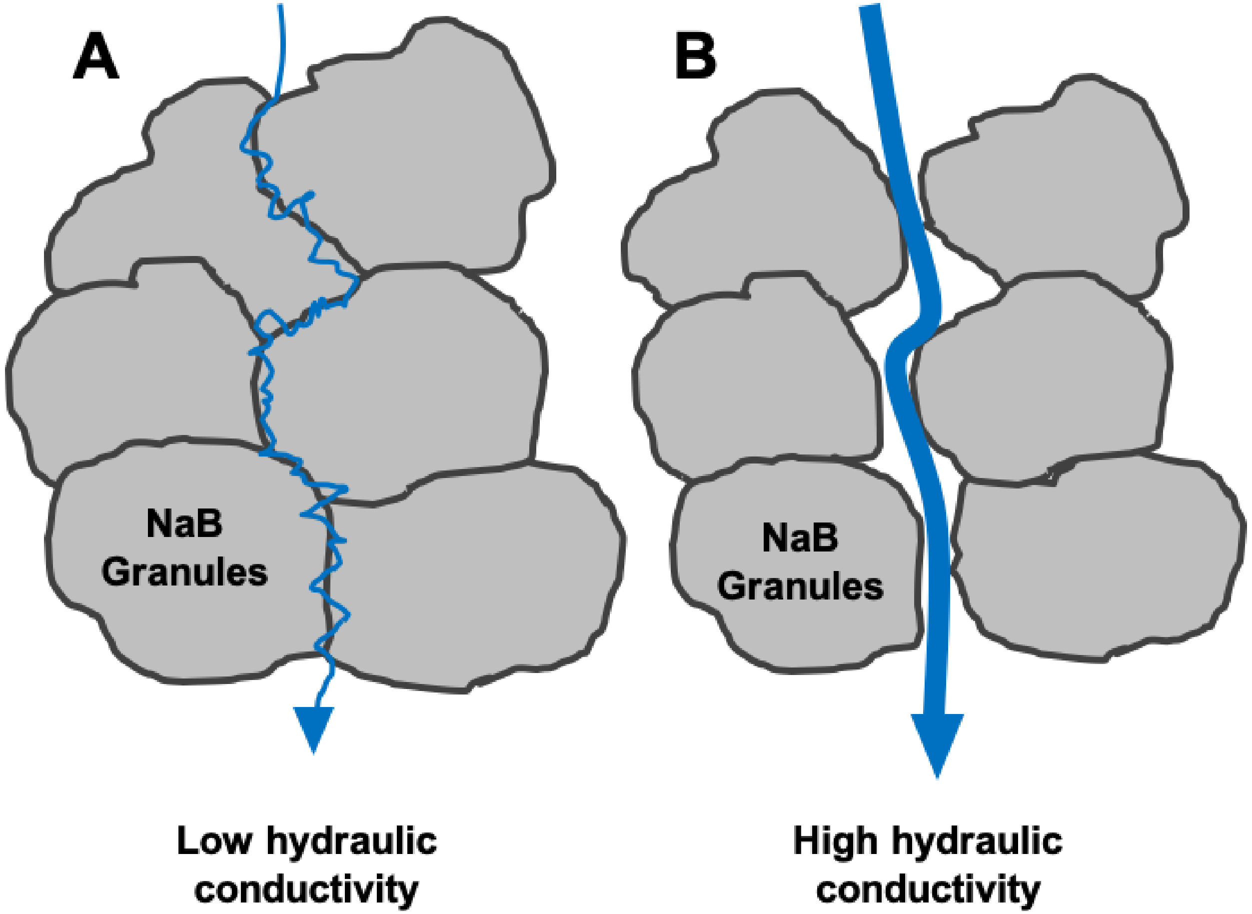
What makes a GCL Impervious?

- For low hydraulic conductivity, **sodium (Na) bentonite** granules swell to from a gel (paste).
- Gel must be maintained to retain **low hydraulic (~ 10^{-11} m/s) conductivity**.
- ***If granules do not swell*** and form gel, **higher hydraulic conductivity (>10^{-7} m/s)**.

GCL bentonite before hydration

GCL bentonite after hydration with NaCl solution.

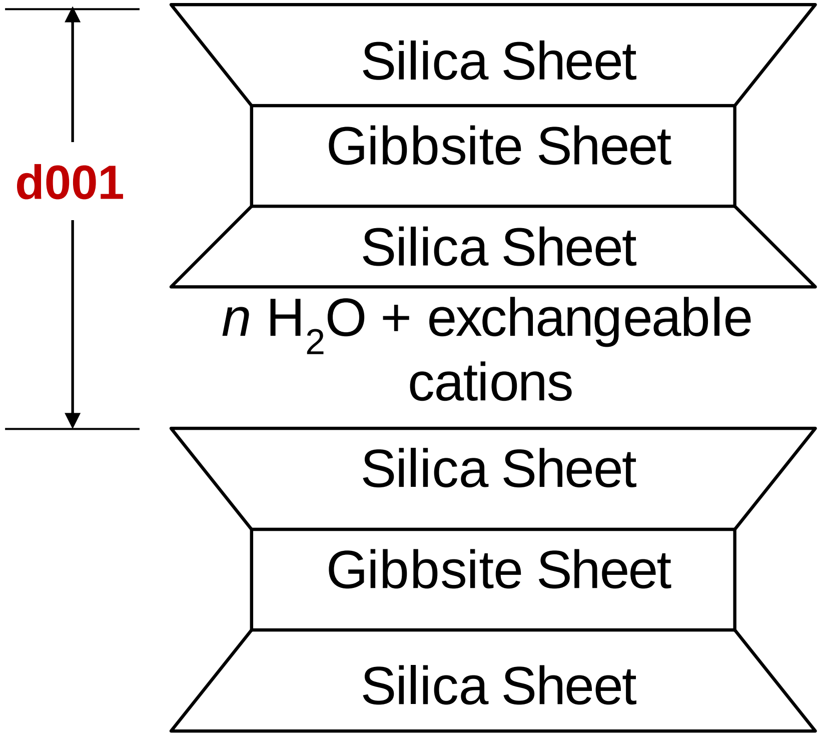
Mechanisms Controlling Hydraulic Conductivity of Bentonite



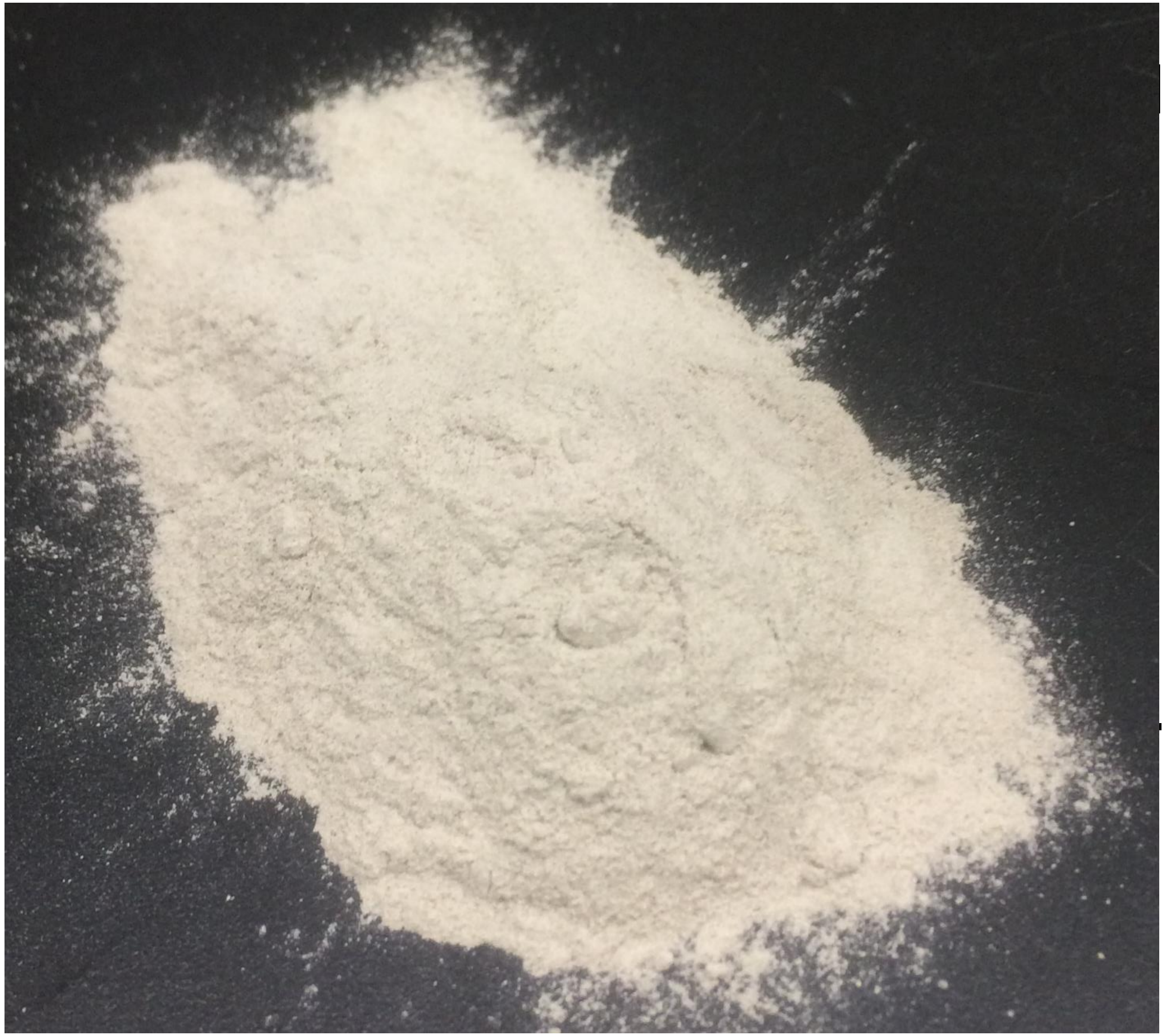
- When bentonite swells sufficiently, intergranular pores swell shut & hydraulic conductivity low, flow occurs through nanoscale pores (< 100 nm).
- When swell constrained, & intergranular pores remain open, hydraulic conductivity higher as flow through macro and microscale pores.
- Sensitive to size of granules.
- **Must seal needlepunching fibers too.**

Bentonite is Primarily Montmorillonite, a Special Clay

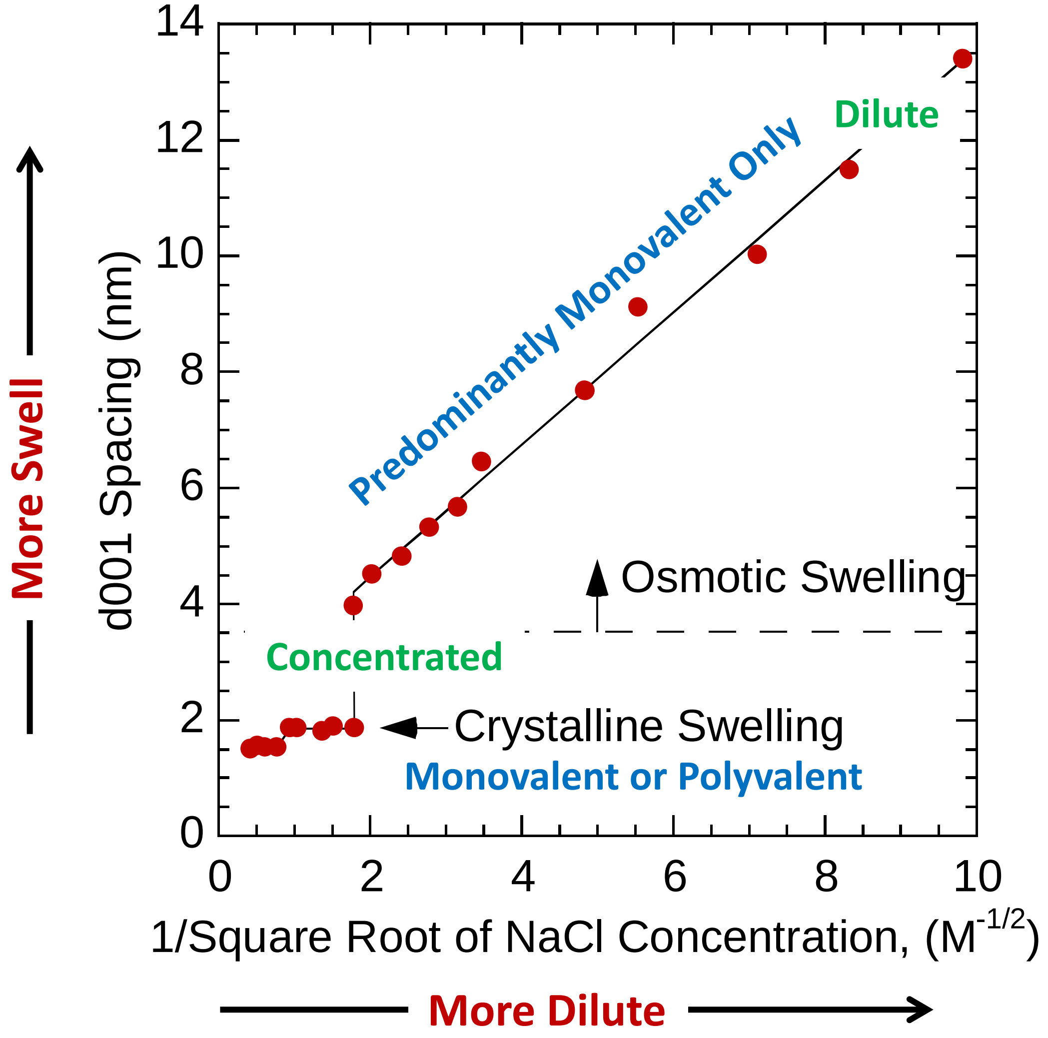
d001 indicative of swell



Exchangeable cations include Na^+, K^+, Ca^{2+}, Mg^{2+}, and other cations in the solution being contained.



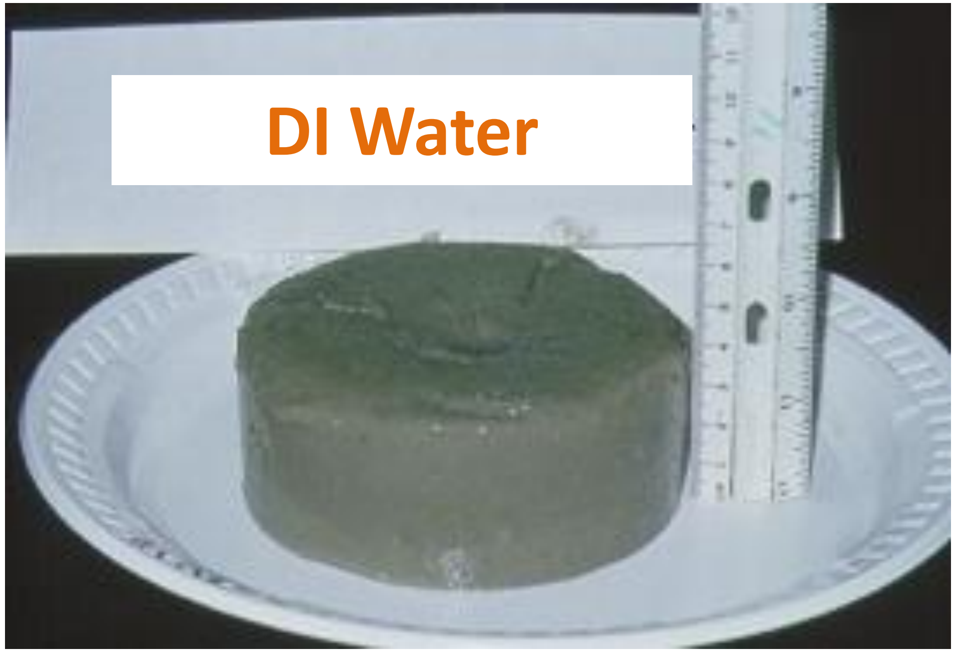
Bentonite Swelling – Geochemistry Matters!

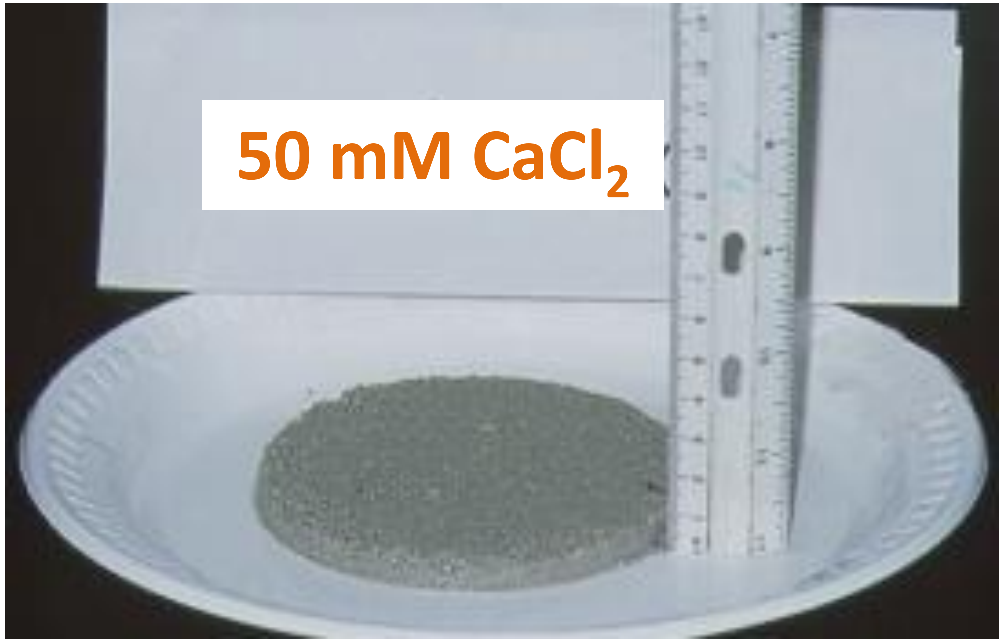


- When interlayer contains **monovalent cations** (e.g., Na+), significant swelling ("**osmotic swelling**") can occur, resulting in small inter-particle pores & low hydraulic conductivity.
- When the interlayer contains **divalent cations** (e.g., Ca^{2+}, Mg^{2+}), interlayer swell limited to 1 nm ("**crystalline swelling**"), resulting in larger inter-particle pores and **high hydraulic conductivity**.
- GCLs are **manufactured with Na-bentonite**, but can be transformed by geochemical environment.

Bentonite Swelling, Solution Chemistry, and Hydraulic Conductivity

GRI GCL-1 Swell Test



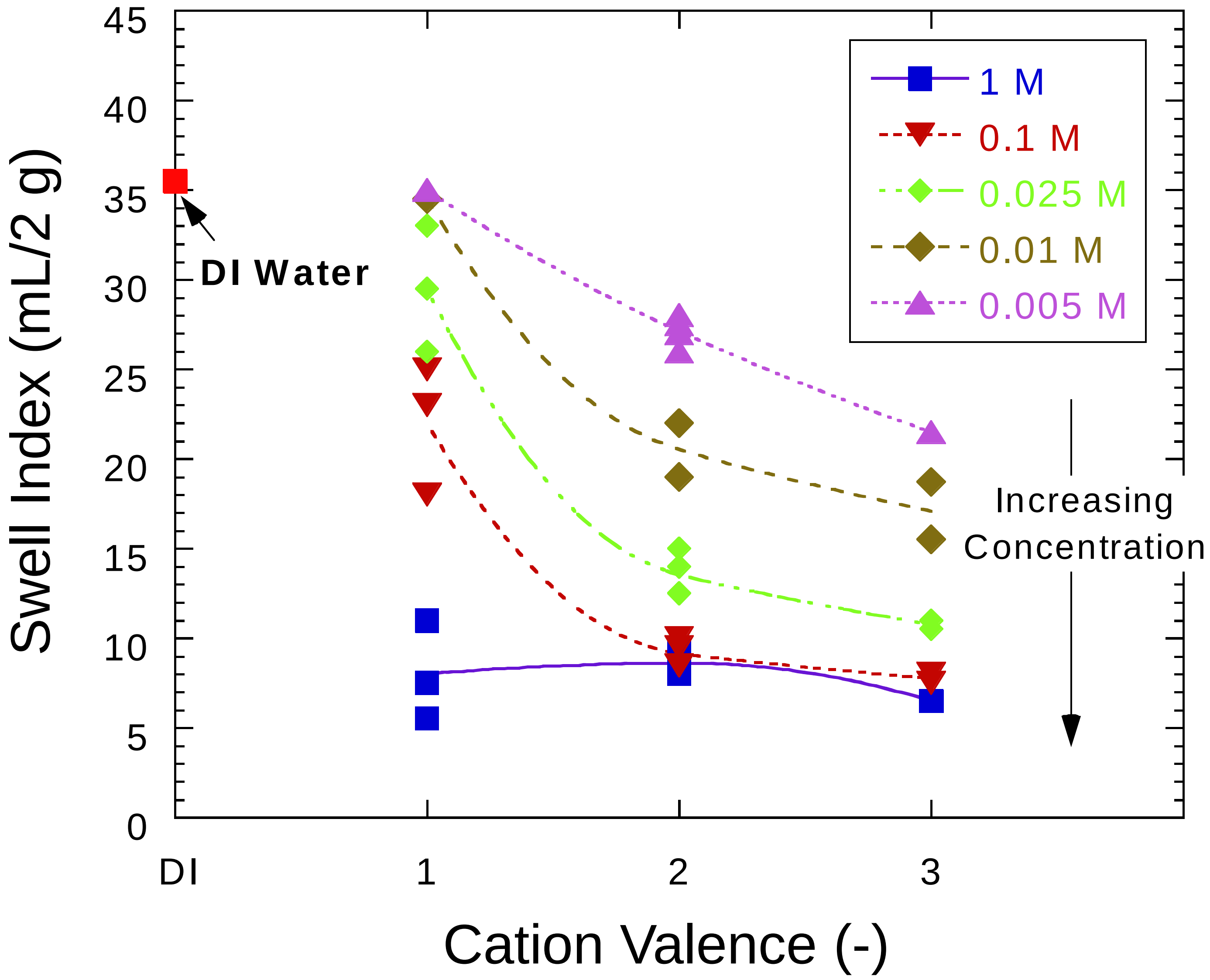


- Na-Bentonite in DI water (monovalent, Na^+) – crystalline & osmotic swell.
- Nanoscale pores and low hydraulic conductivity.

Na-Bentonite in calcium (Ca^{2+}) rich water (divalent) – crystalline swelling only.

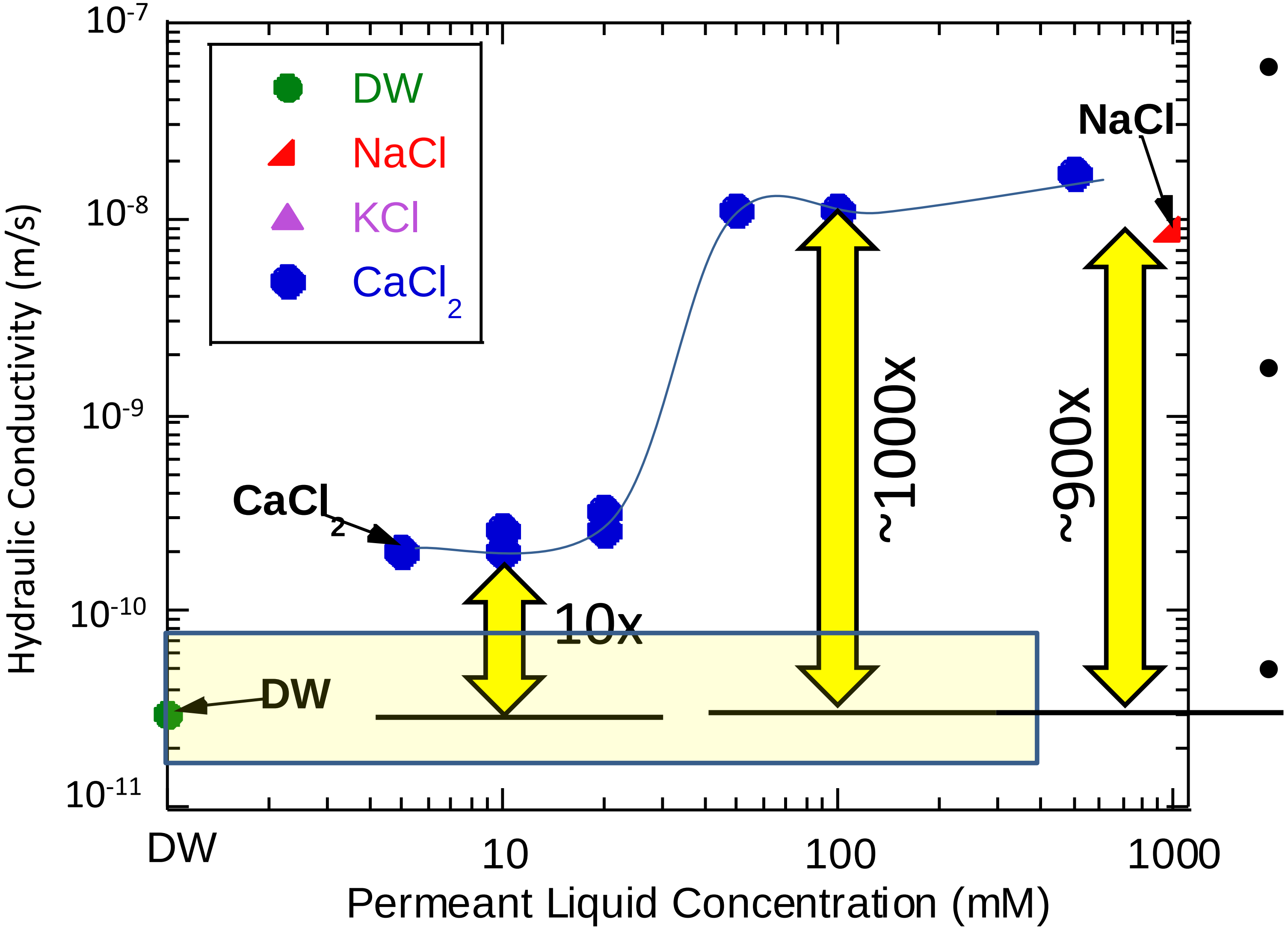
Visible pores and high hydraulic conductivity

Swell Index: Cation Valence & Ionic Strength



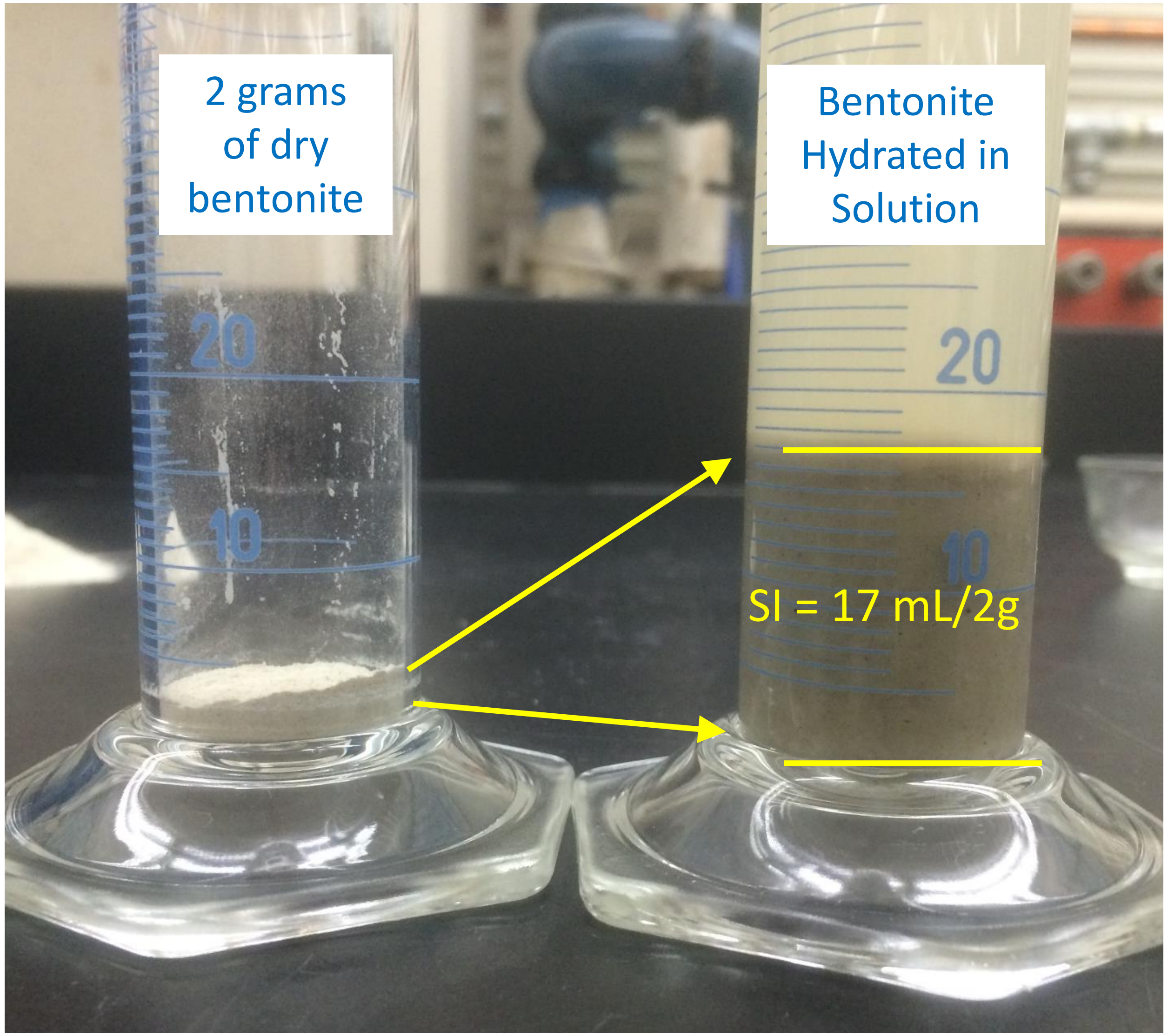
- Swell diminishes as valence increases
- Valence dominates at low ionic strengths
- Concentration dominates at high ionic strengths.

Hydraulic Conductivity, Cation Valence, & Concentration



- Dilute solutions with divalent cations – 10x higher.
- Modest concentrations – depends on valence – 1x, 10x, 1000x.
- Concentrated solutions, monovalent or divalent cations – 1000x.

ASTM D5890 Swell Index (SI) – Free Swell

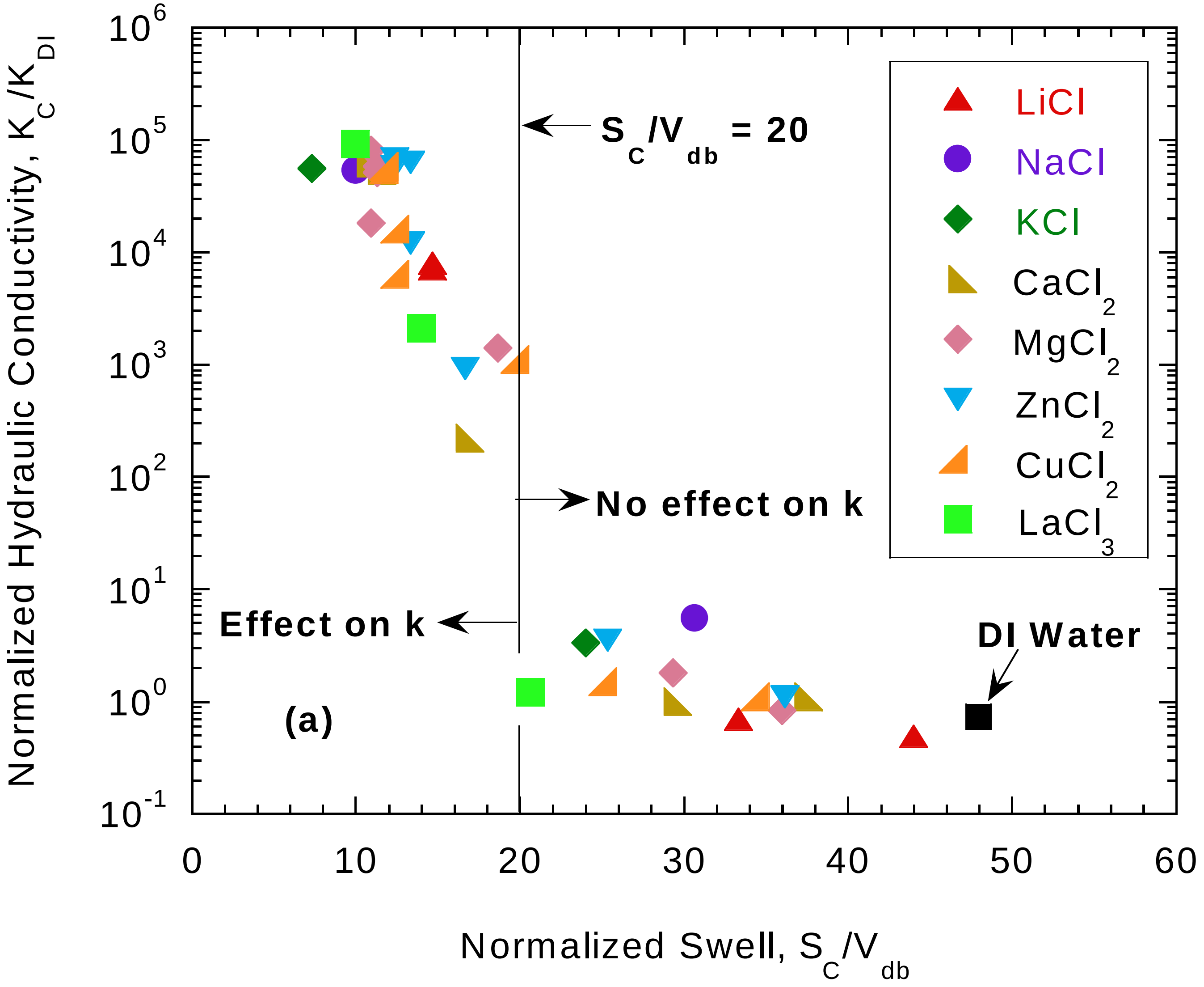


ASTM D5890 Swell Index Test

Miles bentonite, Queensland

Wyoming bentonite, USA

Hydraulic Conductivity and Swell Index (SI)



- Normalized hydraulic conductivity to chemical solution (K_c) by DI water (K_{DI}).
- Normalized SI by volume of dry bentonite (2 g ≈ 0.7 mL).
- Unique to each bentonite – granule size, distribution, mineralogy, and surface chemistry.
- For this bentonite, **SI must be > 15 mL/2g for K_c<10^{-11} m/s**

Jo, H., Katsumi, T., Benson, C., and Edil, T. (2001), Hydraulic Conductivity and Swelling of Non-Prehydrated GCLs Permeated with Single Species Salt Solutions, *J. of Geotech. and Geoenvironmental Eng.*, 127(7), 557-567.

Master Soution Variables for GCL Hydraulic Conductivity: Ionic Strength, RMD, and pH

$$I = \frac{1}{2}\sum_{i=1}^{n} c_i z_i^2$$

= ionic strength, c_i = concentration of i^{th} ion in solution and z_i = valence of i^{th} ion in solution.

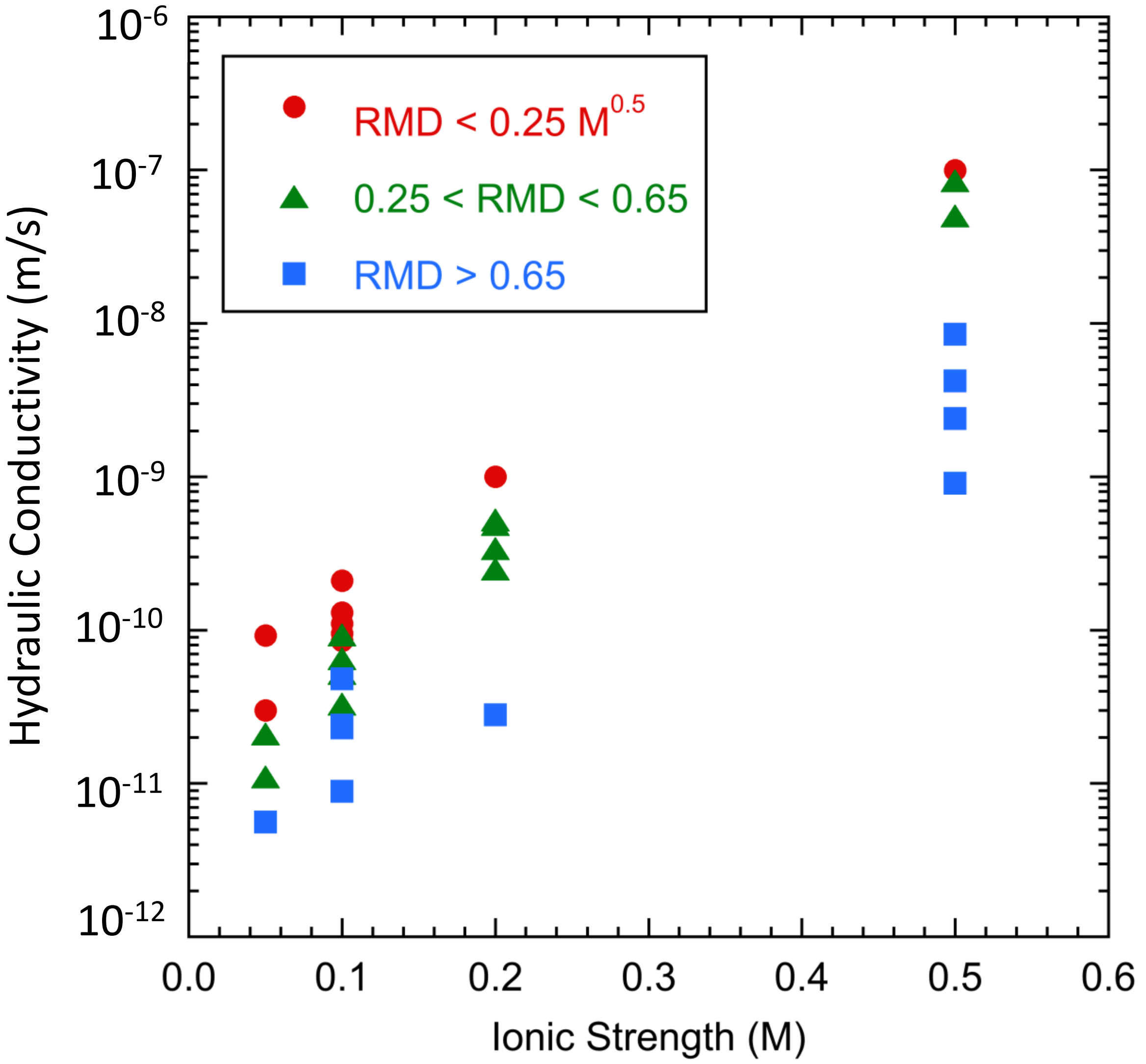
$$RMD = \frac{M_M}{\sqrt{M_D}} = \frac{\text{total molarity monovalent cations}}{\sqrt{\text{total molarity polyvalent cations}}}$$

RMD = **0** = all **polyvalent**

RMD = **infinite** = all **monovalent**

Kolstad, D., Benson, C., and Edil, T. (2004), Hydraulic Conductivity and Swell of Nonprehydrated GCLs Permeated with Multispecies Inorganic Solutions, *J. Geotech. and Geoenvironmental Eng.*, 130(12), 1236-1249.

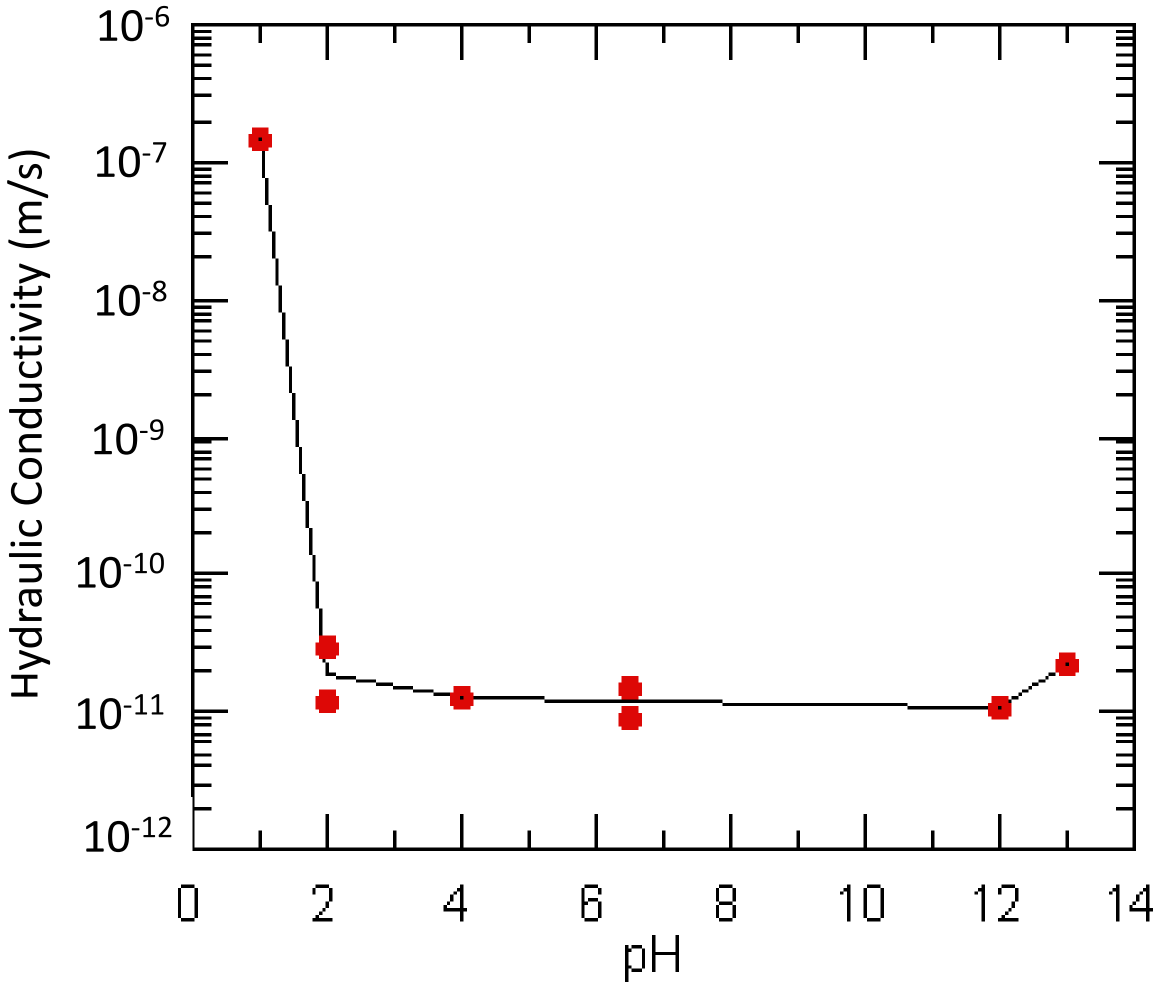
Effect of Ionic Strength & RMD on GCL Hydraulic Conductivity



- Hydraulic conductivity increases as:
  - ionic strength increases
  - RMD decreases
- Swelling suppressed as:
  - ionic strength increases
  - RMD decreases
- Estimate effects with "Kolstad" equation using I (M) and RMD ($M^{0.5}$)

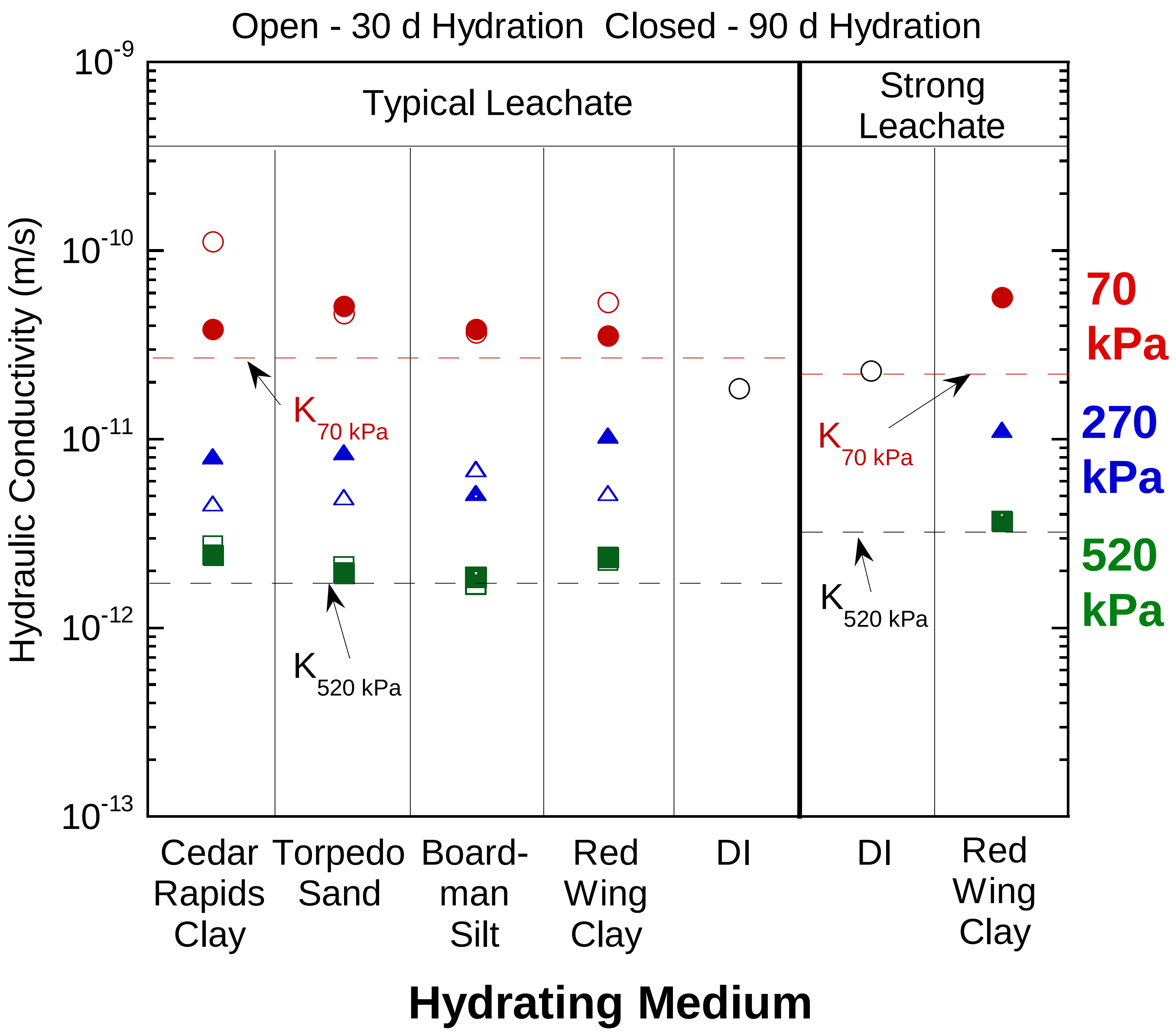
$$\frac{\log K_c}{\log K_{DI}} = 0.965 - 0.976\ I + 0.0797\ RMD + 0.251\ I^2\ RMD$$

pH Effect – Another Master Variable (?)



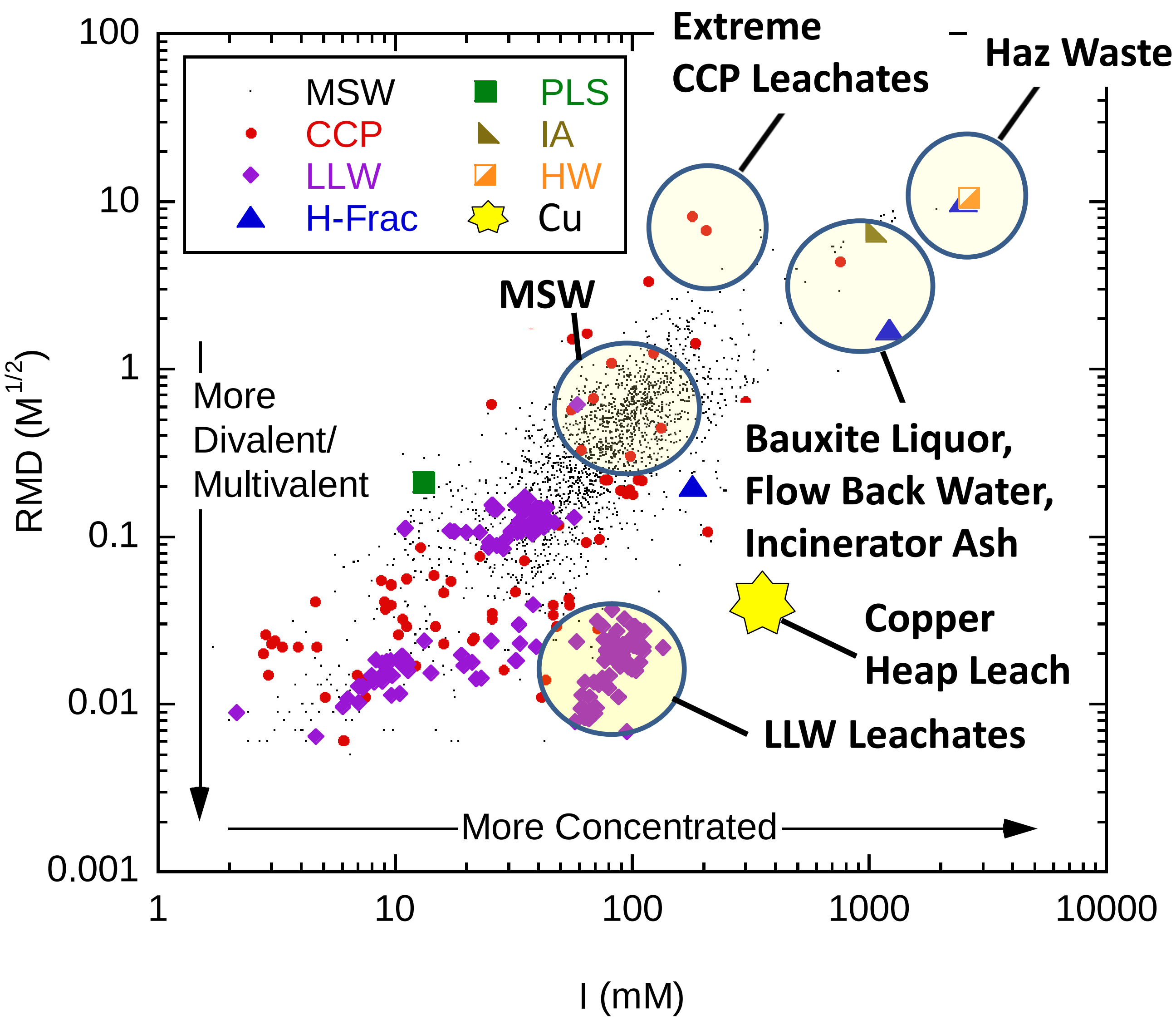
- pH important in extreme cases, **pH < 2 and pH > 13**
- Highly acidic or alkaline conditions lead to dissolution of mineral, **loss of solid**.
- Predominant effect is ionic strength: elevated H^+ concentration at very low pH; elevated cation concentration at very high pH (e.g., NaOH)

Impact of MSW Leachates on GCLs



- MSW landfill leachates have low to modest impact on hydraulic conductivity (6x)
- Preponderance of Na^{+}, NH_4^{+}
- Modest concentration

Master Variables: Ionic Strength & RMD



$$I = \frac{1}{2}\sum_{i=1}^{n} c_i z_i^2$$

I = **ionic strength**

c_i = conc. ith ion

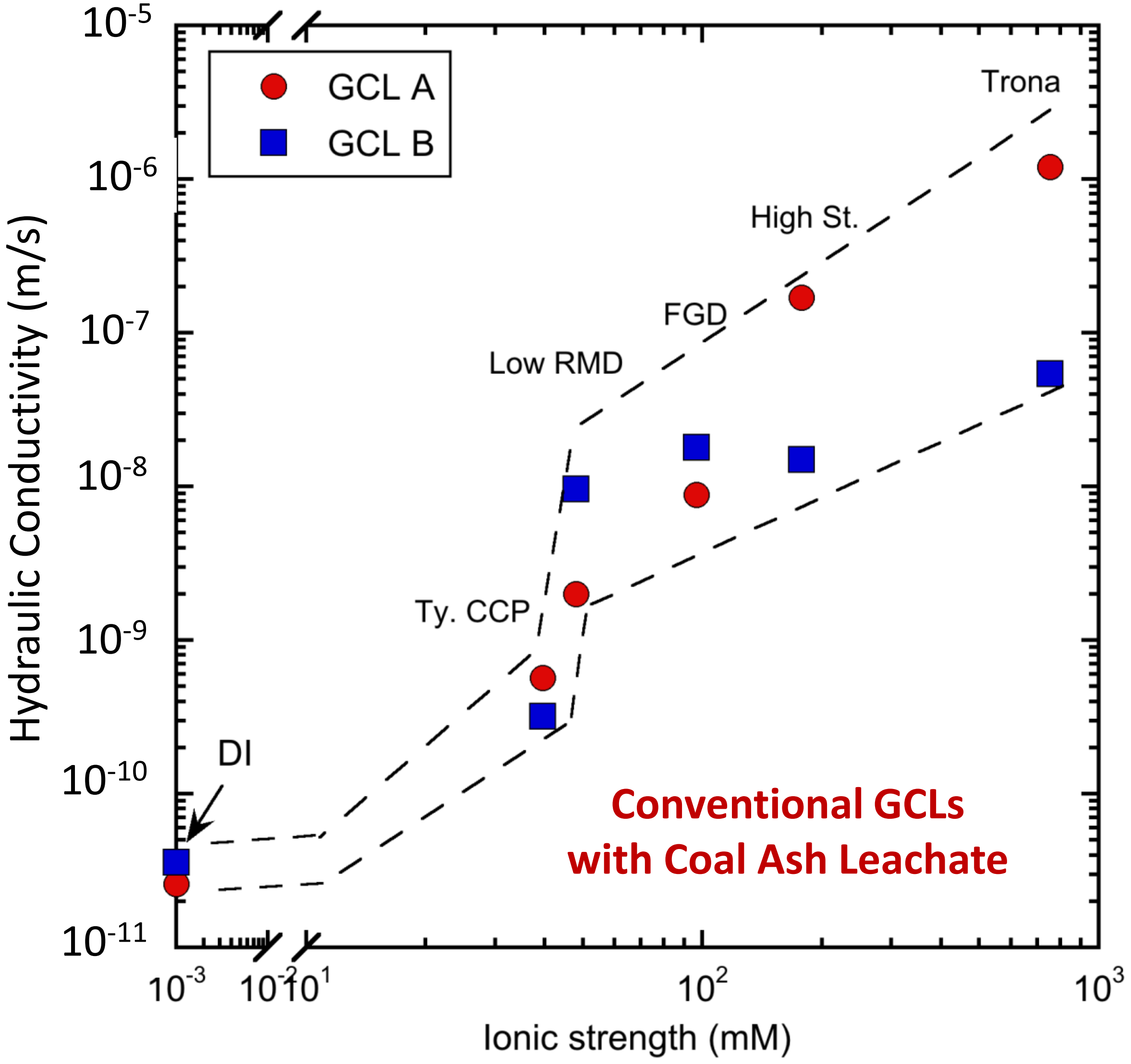
z_i = valence ith ion

$$RMD = \frac{M_M}{\sqrt{M_D}}$$

M_m = total molarity **monovalent** cations

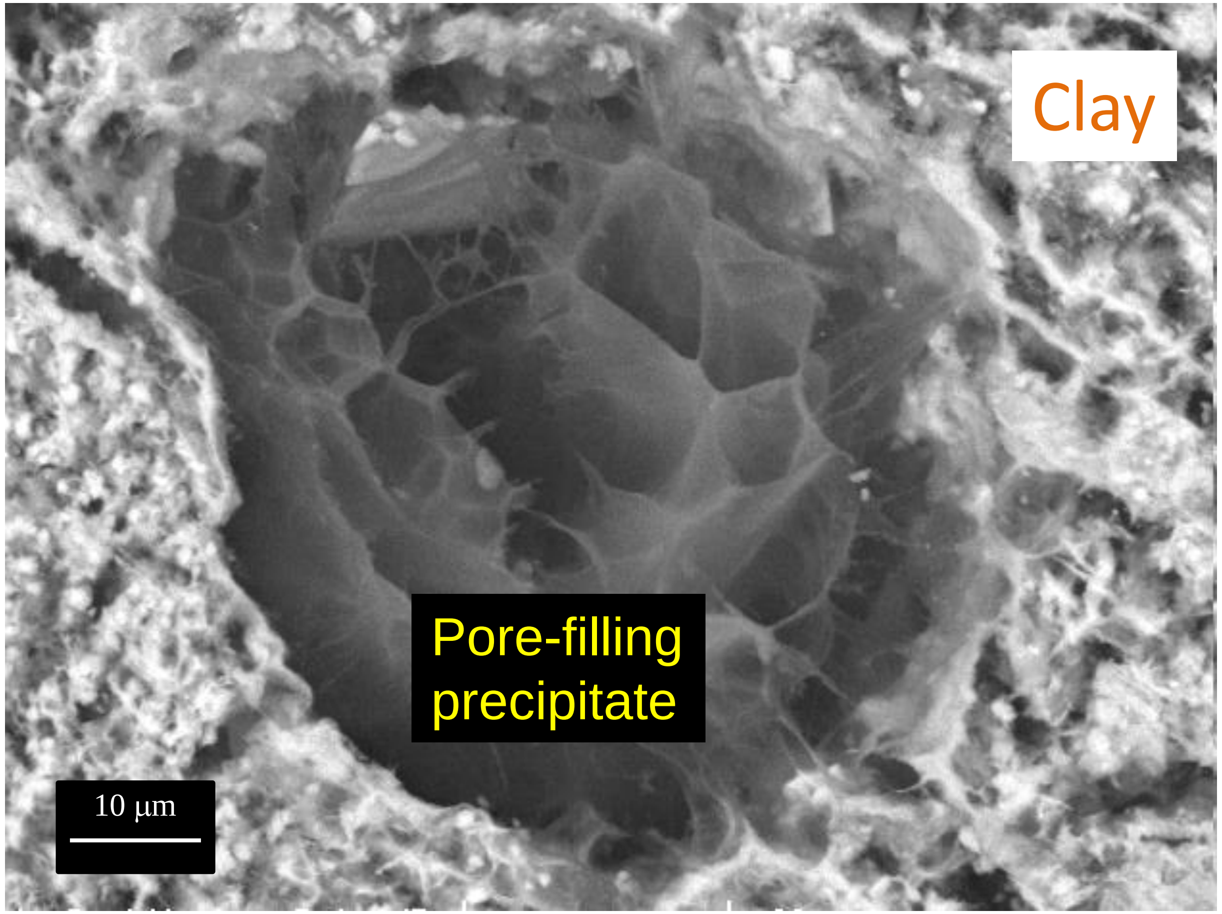
M_D = total molarity **polyvalent** cations

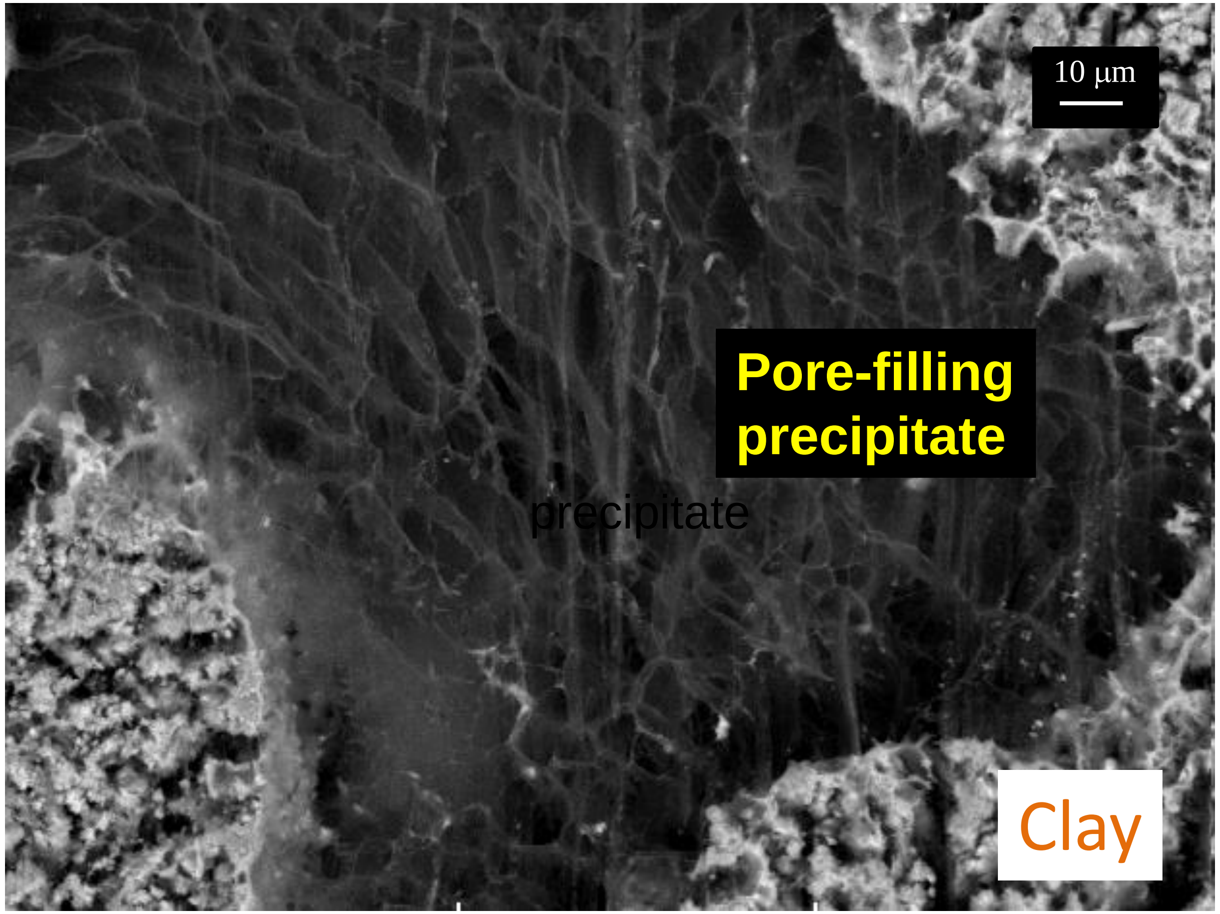
Ionic Strength is Dominant Variable for Most Industrial Liquids



- Hydraulic conductivity strongly & directly related to ionic strength of leachate.
- Modest sensitivity to RMD of leachate.
- Two different GCLs – two different hydraulic conductivities.

Siliceous Precipitates In Highly Alkaline Solutions





In some cases, geochemical reactions with mineral creates precipitates that fill pore and block flow – powdered bentonites with highly alkaline bauxite liquors.

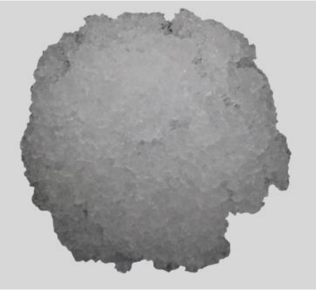
Photographs courtesy of Will Gates, Monash University.

What if my Conventional NaB GCL is Too Permeable?

Bentonite-Polymer Composite GCLs

(aka PMGs or polymer-modified GCLs)

Bentonite



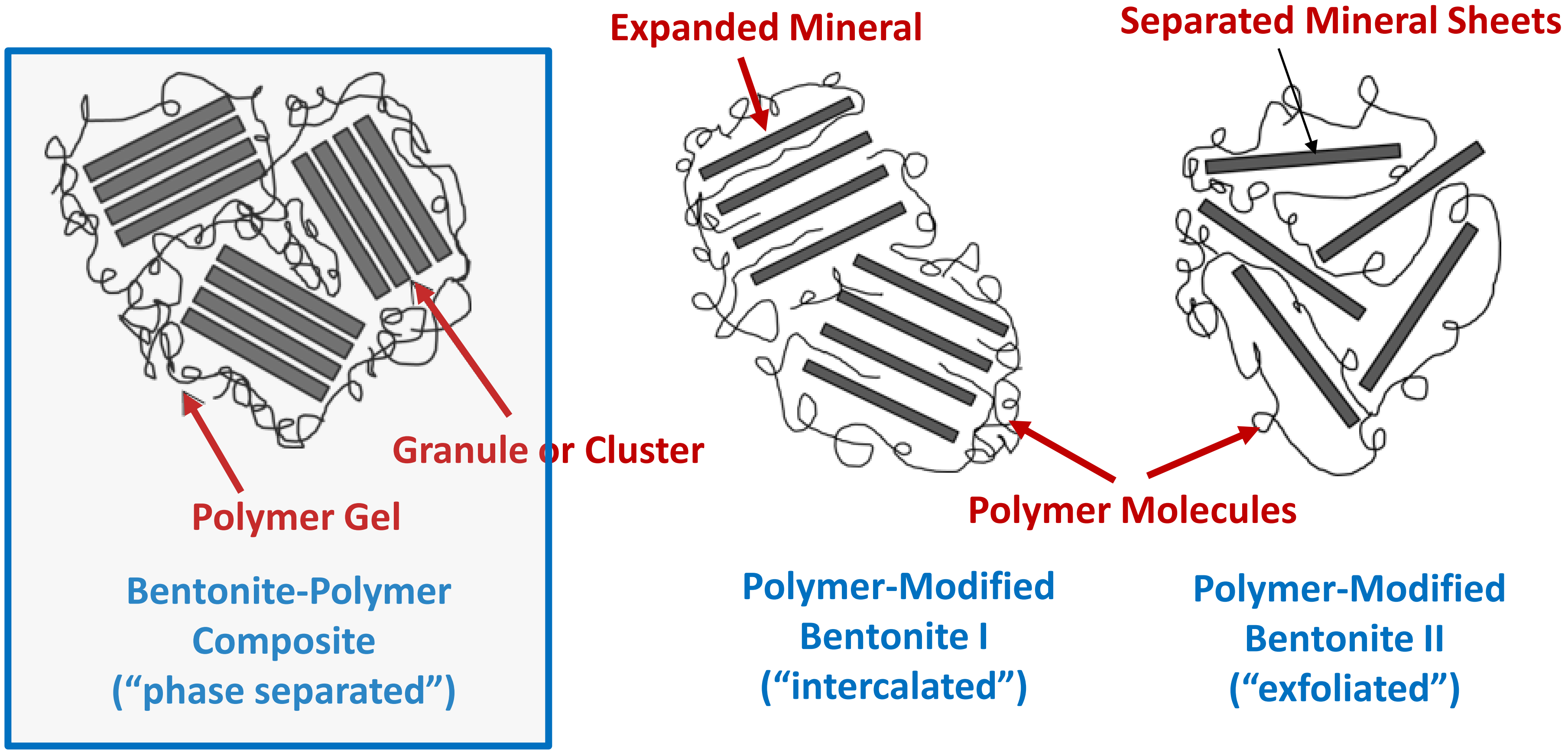
Polymer

Bentonite-Polymer Composite

- Bentonite functions in less concentrated leachates, swelling and blocking flow channels.
- Polymer functions in more concentrated leachates, filling channels between bentonite granules for which swelling is modest.

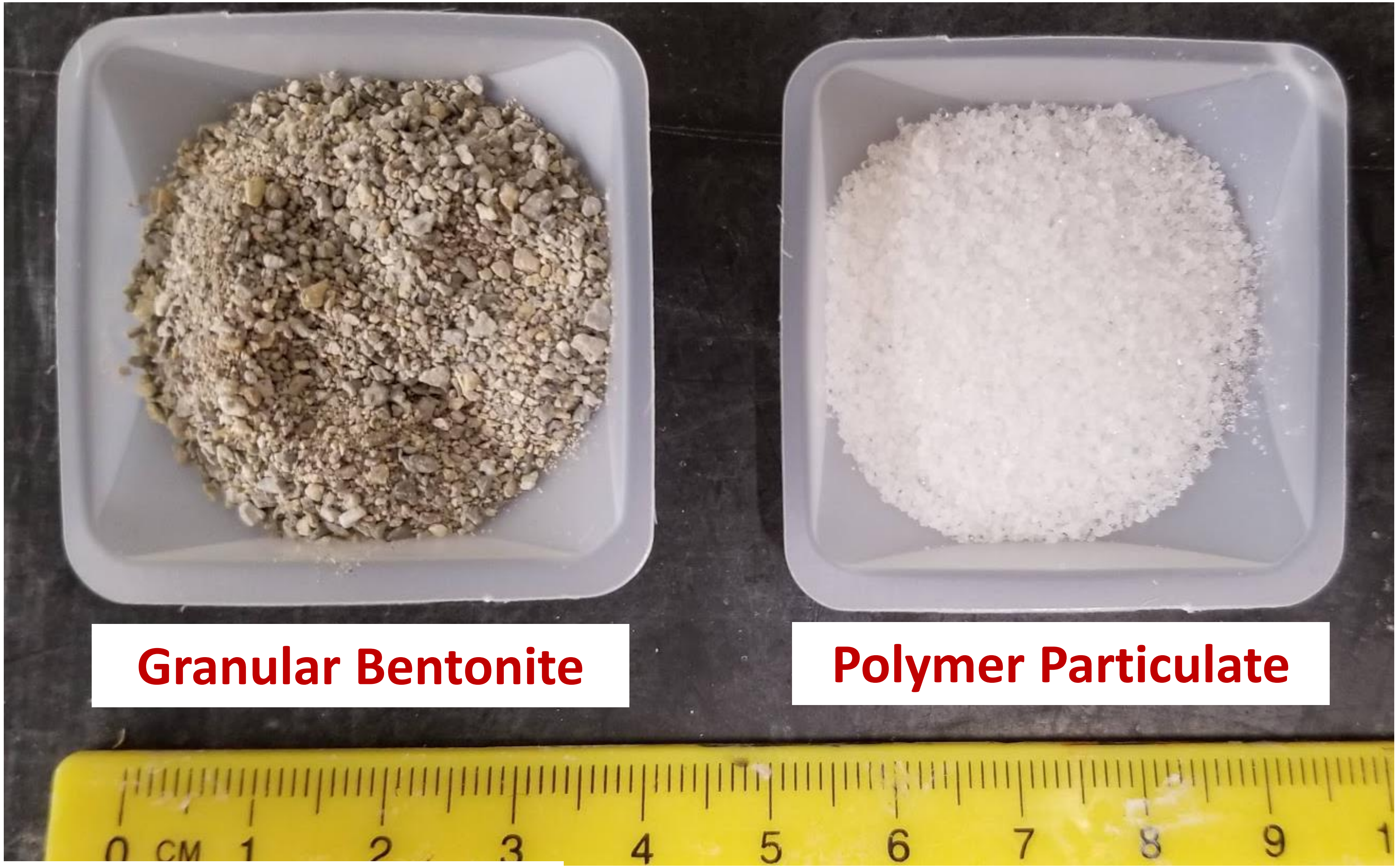
Scalia, J. and Benson, C. (2016), Polymer Fouling and Hydraulic Conductivity of Mixtures of Sodium Bentonite and a Bentonite-Polymer Composite, *J. Geotech. Geoenvironmental Eng.*, 04016112.

Types of Bentonite-Polymer Mixtures



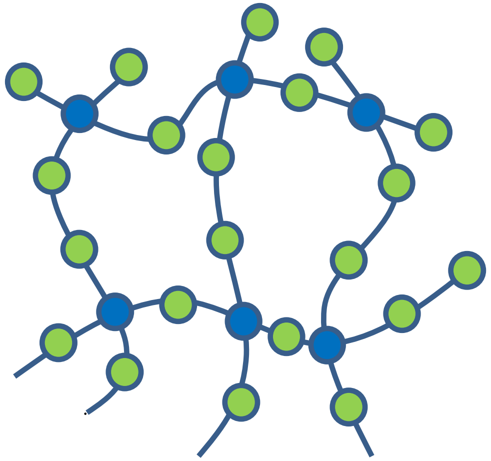
adapted from: Kim S. and Palomino, A. (2011), Factors influencing the synthesis of tunable clay–polymer nanocomposites using bentonite and polyacrylamide, *Applied Clay Science*, 51 (2011) 491–498

Dry Mixture: Granular Bentonite and Polymer Particulate

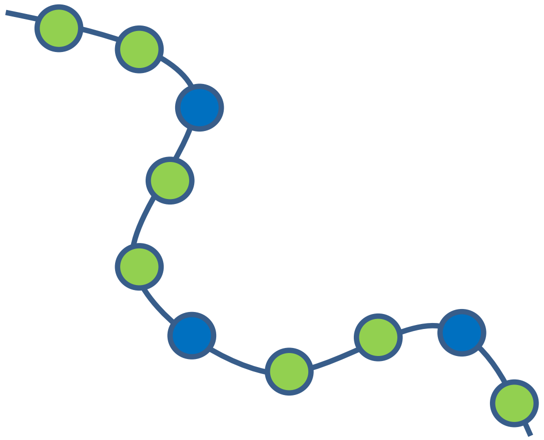


Types of Polymers in BPC GCLs

Cross-Linked Polymer

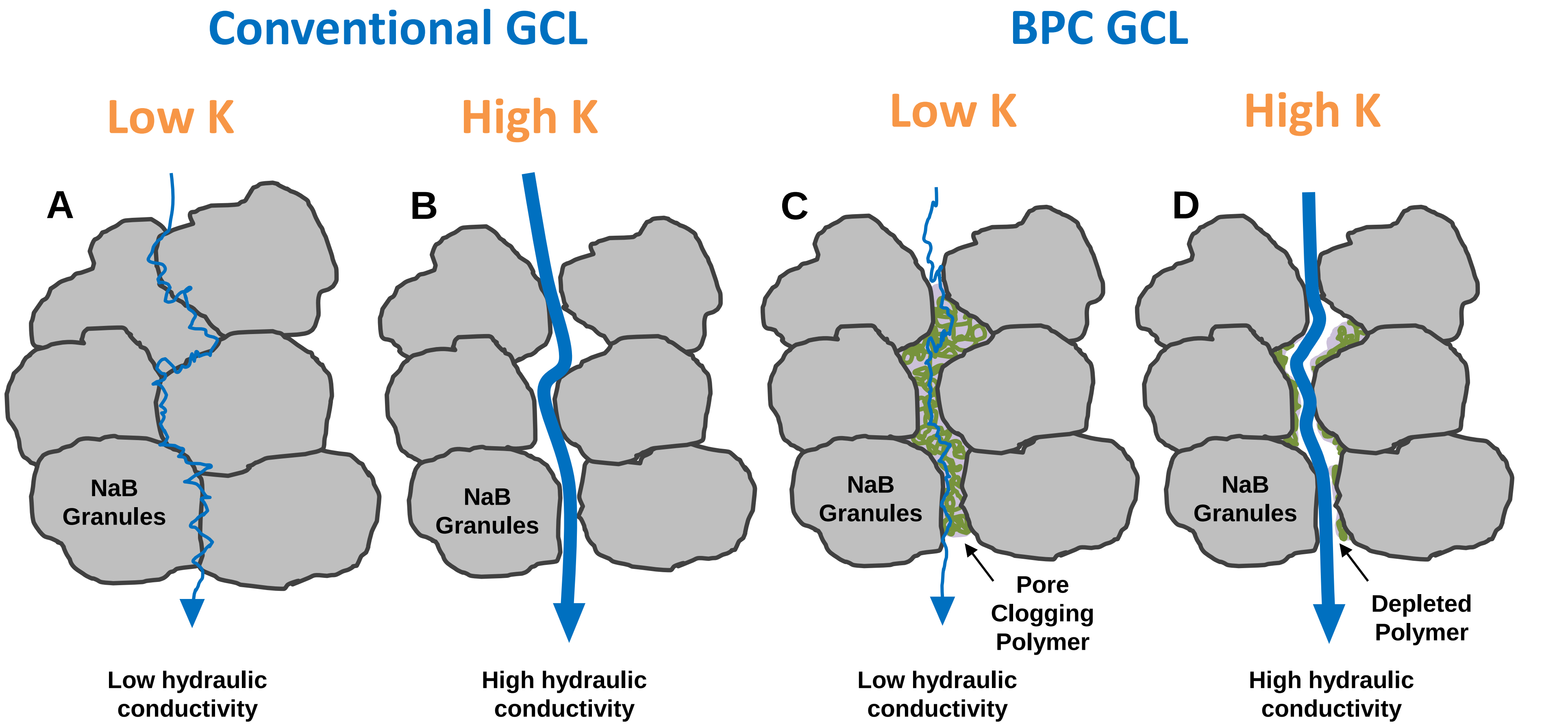


Linear Polymer



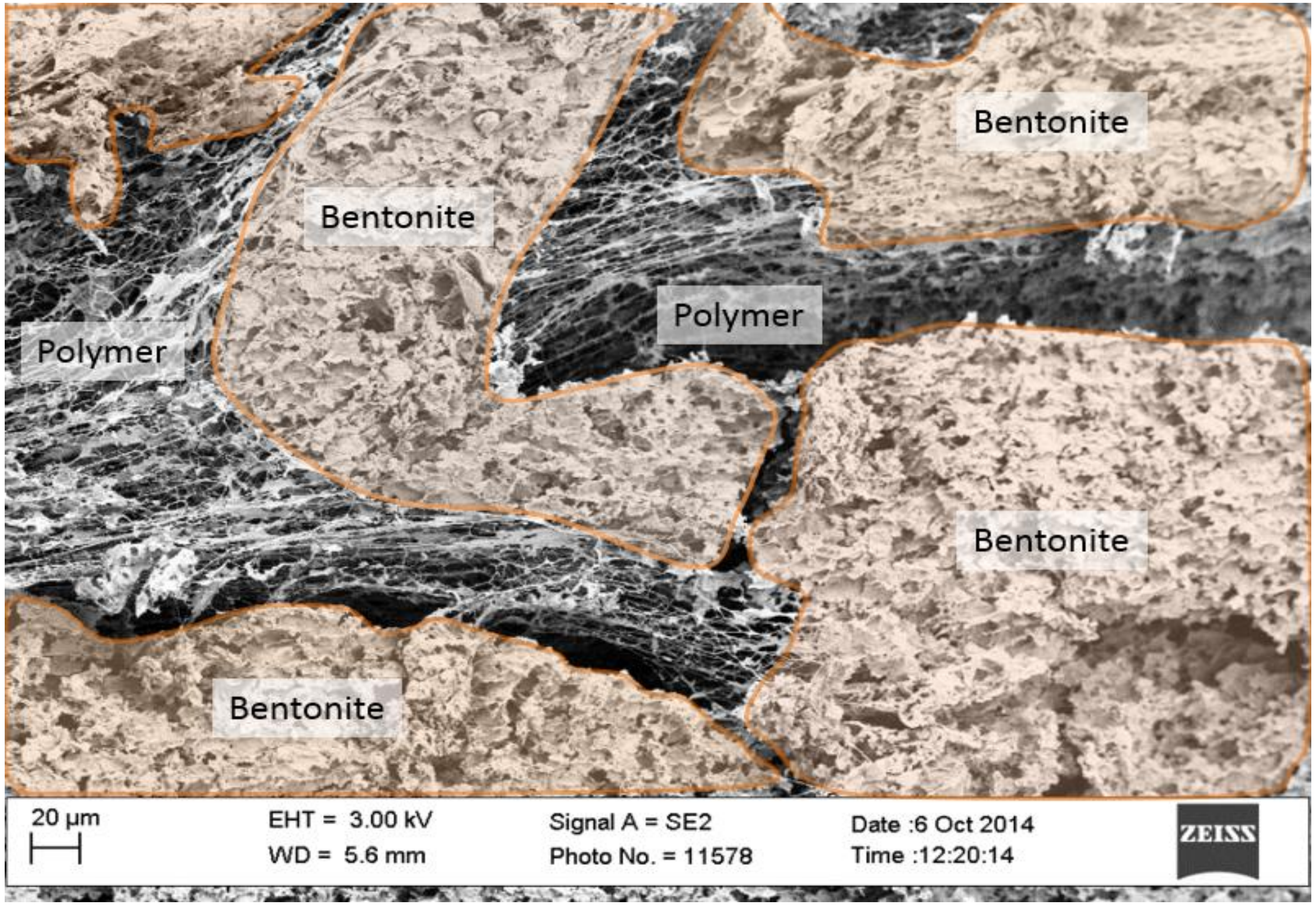
Superabsorbent polymers also used (baby diapers).

Mechanisms Controlling Hydraulic Conductivity of BPC GCLs

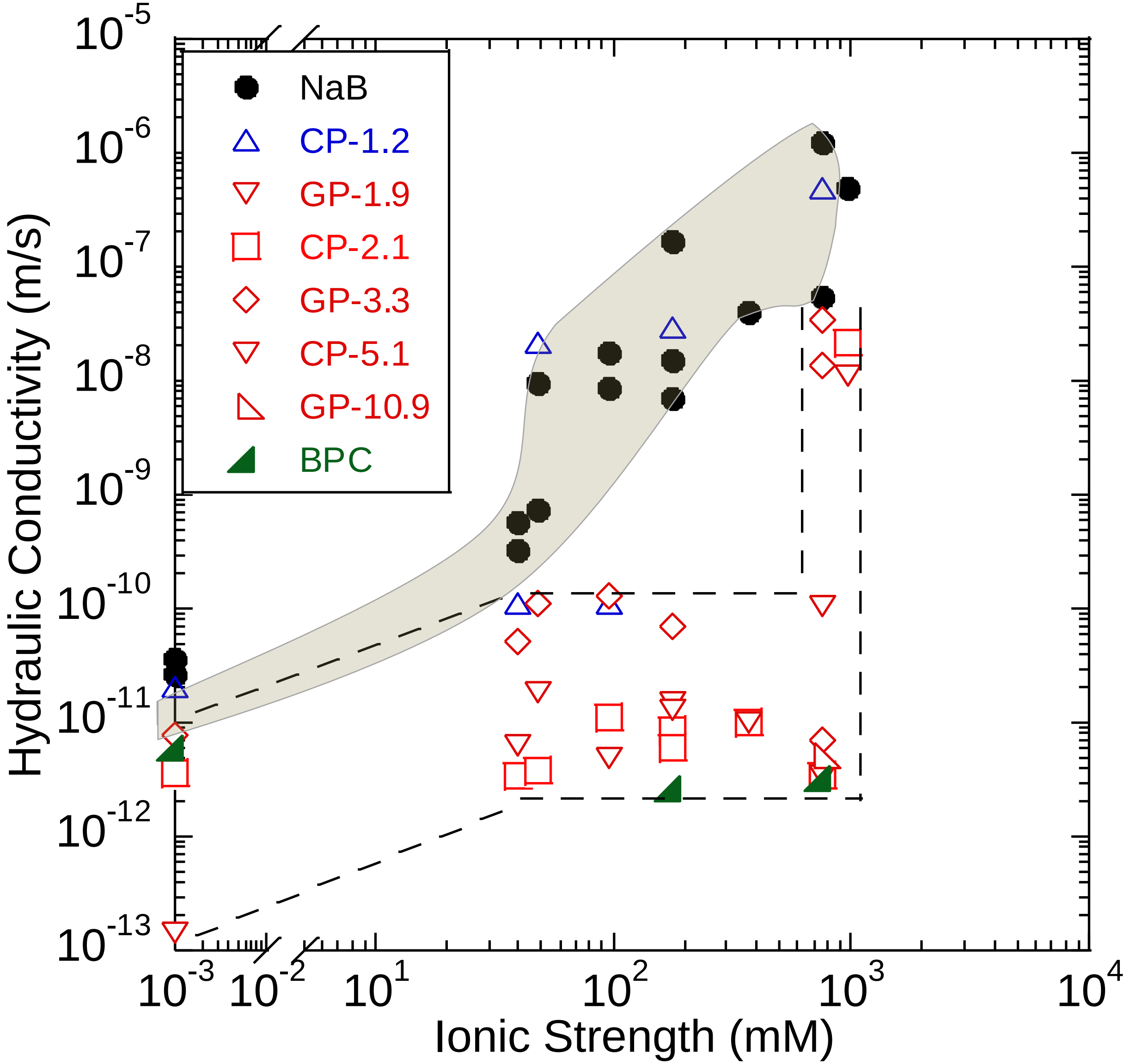


BPCs are Composite Materials – BPCs Not Surface-Modified Clays

Polymer Hydrogel Clogging Mechanism



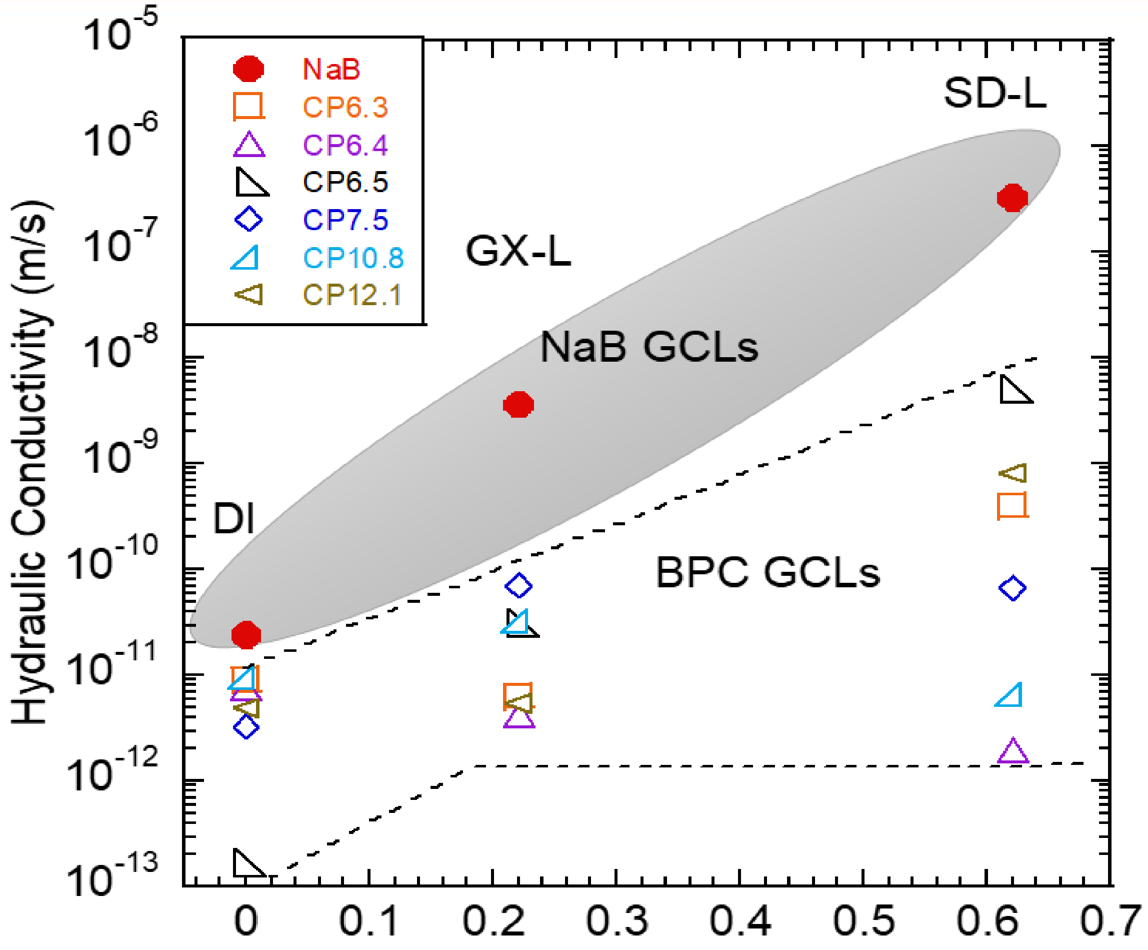
Bentonite-Polymer Composites with Coal Combustion Product Leachates



- BPCs with low polymer loading behave like bentonite, with strong sensitivity to ionic strength.
- Insensitive to ionic strength when polymer loading is sufficient.
- Behavior of BPC is more abrupt, reaching a threshold (about 750 mm here) at which K changes dramatically.

Chen, J., Salihoglu, S., Benson, C., Likos, W., and Edil, T. (2019), Hydraulic Conductivity of Bentonite-Polymer Composite Geosynthetic Clay Liners Permeated with Coal Combustion Product Leachates, *J. Geotech. Geoenvironmental Eng.*, 145(9), 04019038.

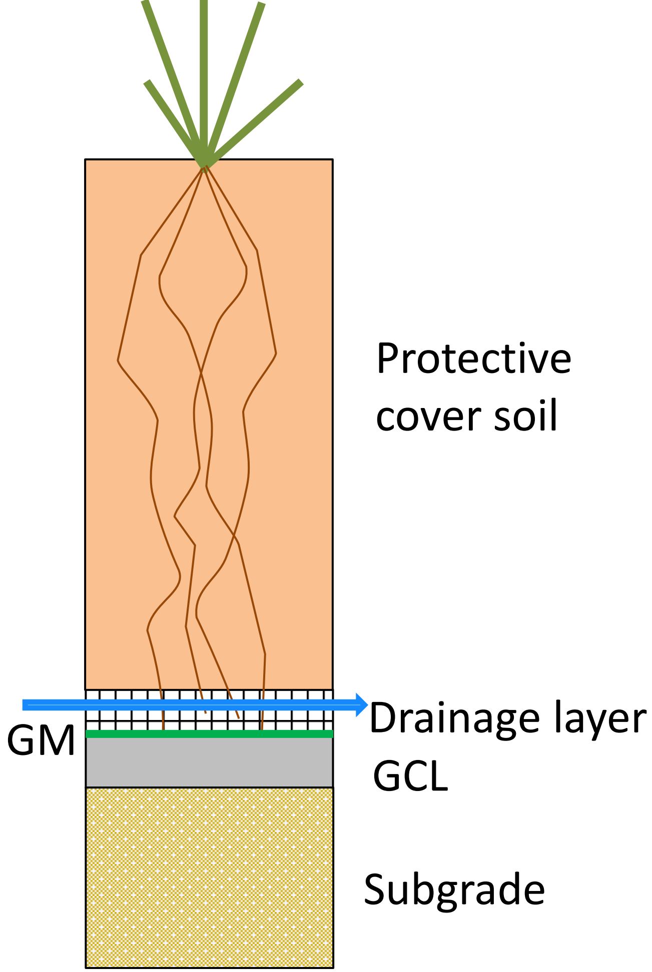
Bentonite-Polymer GCLs & Bauxite Liquors



- Solid Symbols: NaB GCLs, Open Symbols: BPC GCLs, Numbers: polymer loading.
- BPC GCLs have lower hydraulic conductivity than NaB GCLs at all ionic strengths.
- BPC hydraulic conductivity varies with product and polymer loading.

Li, Q., Chen, J., Benson, C., and Chen, D. (2020), Hydraulic Conductivity of Bentonite-Polymer Composite Geosynthetic Clay Liners Permeated with Bauxite Liquor, *J. Geotextiles and Geomembranes*, 49, 420-429.

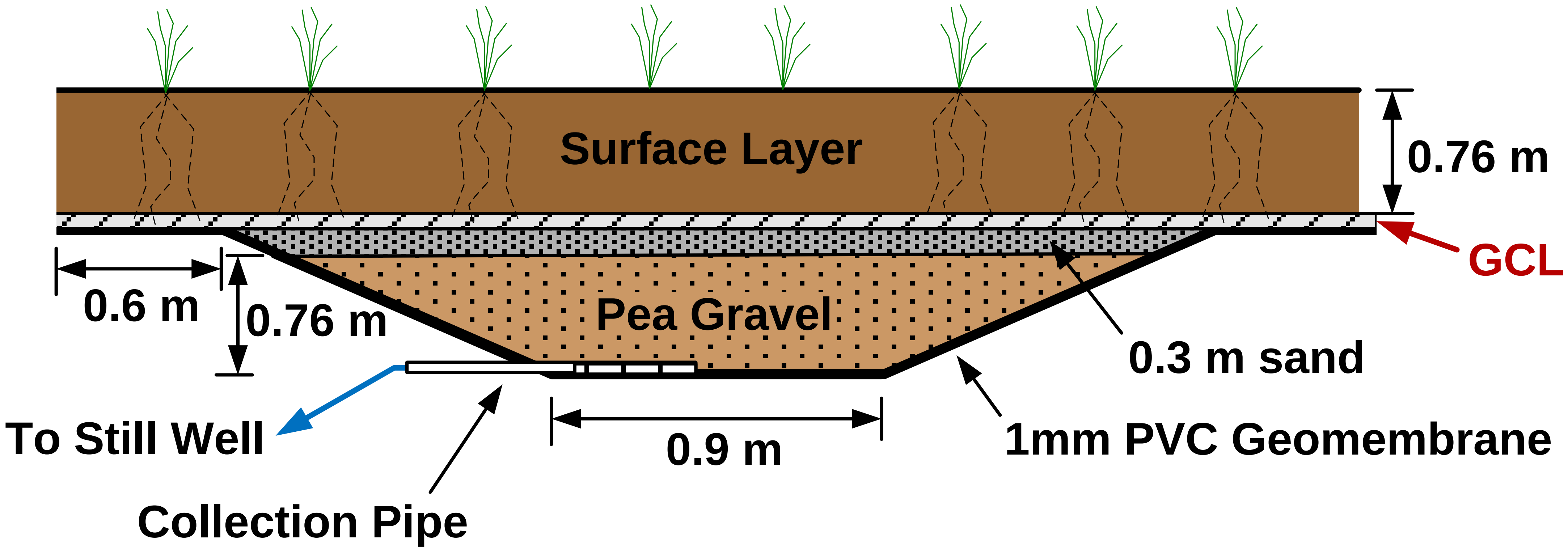
Using GCLs in Covers



- Do we see similar geochemical issues in covers?
- For the same reasons?

Wisconsin GCL Case History

Leakage monitored with lysimeter (collection pan) directly beneath GCL



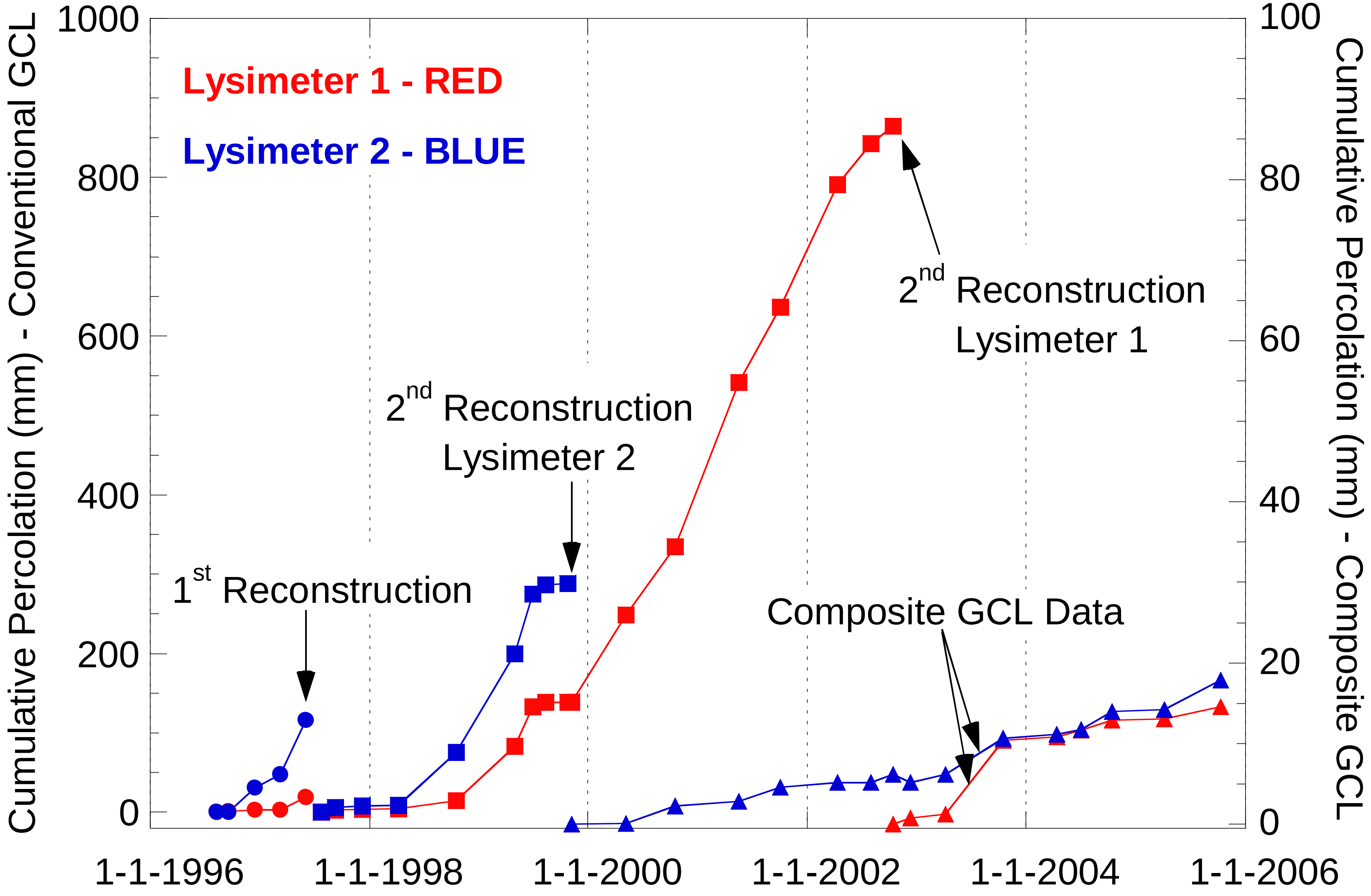
- Not to Scale -

Percolation Data from Lysimeters: Expecting Few mm/yr

1997 - Lysimeters reconstructed. Thinning of GCL by underlying gravel purported failure mechanism. Rebuilt with geotextile and sand on top of gravel.

1999 - Lysimeter 2 reconstructed again. Dry and cracked GCL exhumed. Replaced with laminated GCL in November 1999. Low leakage rate since.

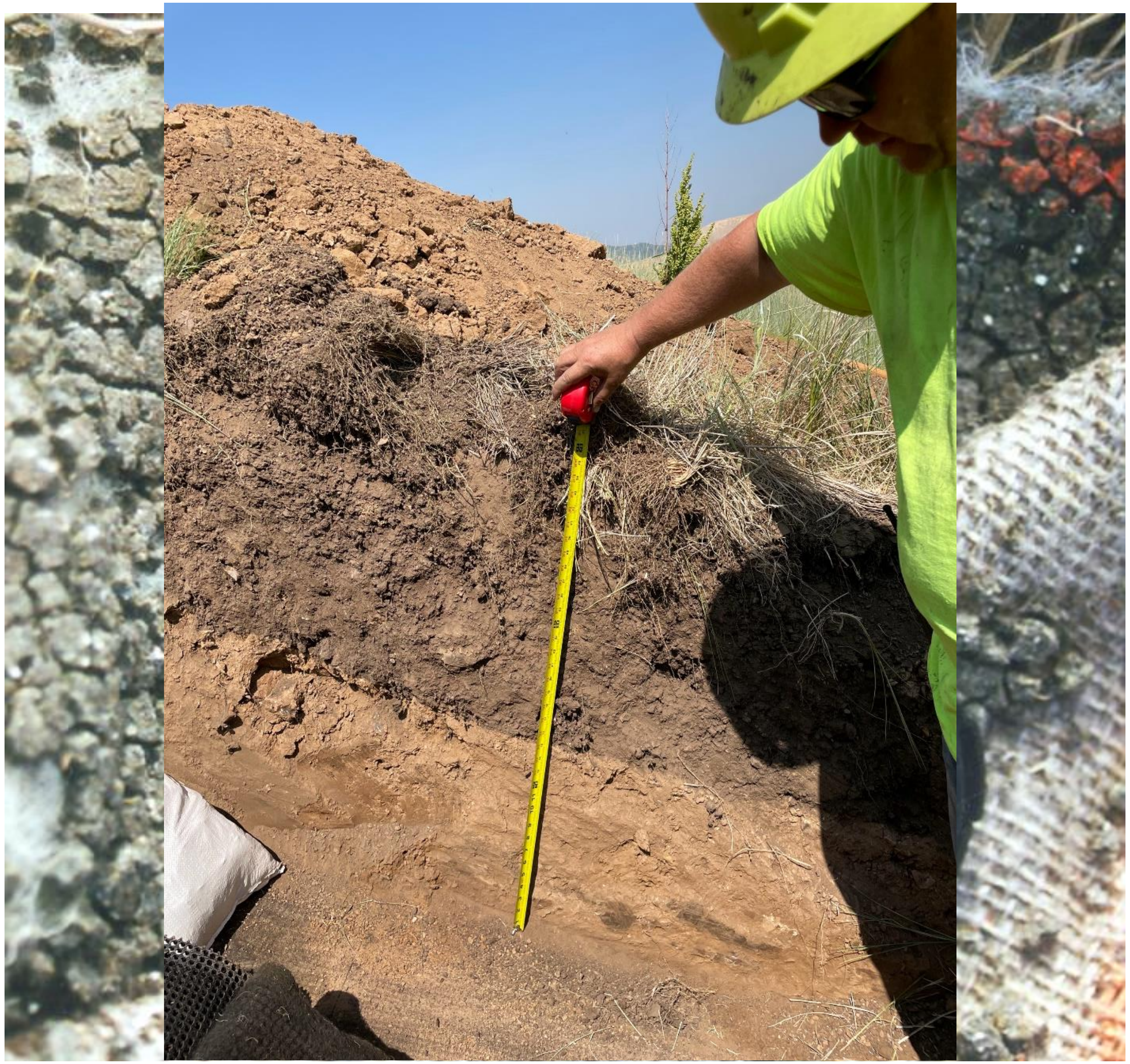
2002 - Lysimeter 1 reconstructed again with laminated GCL.



Conventional GCL: 203-262 mm/yr

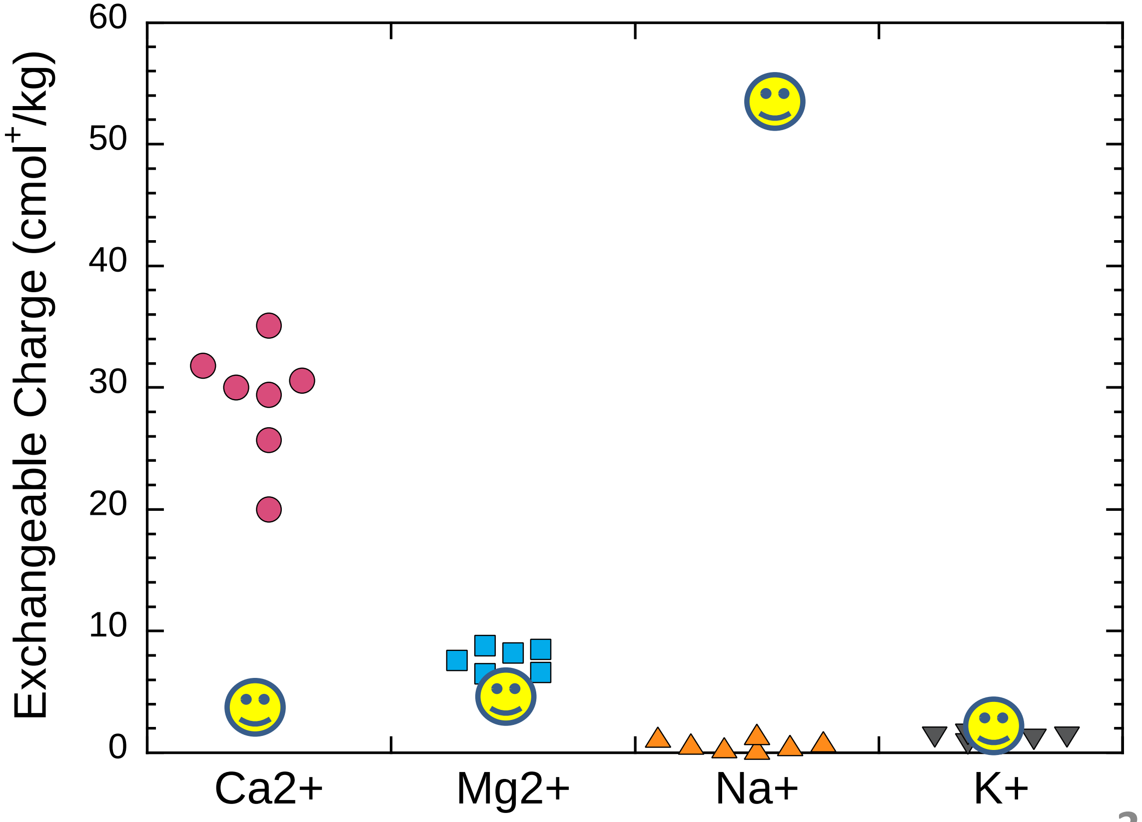
Laminated GCL: 2.6-4.1 mm/yr

Severe Desiccation Cracking, Lost Swelling Capacity

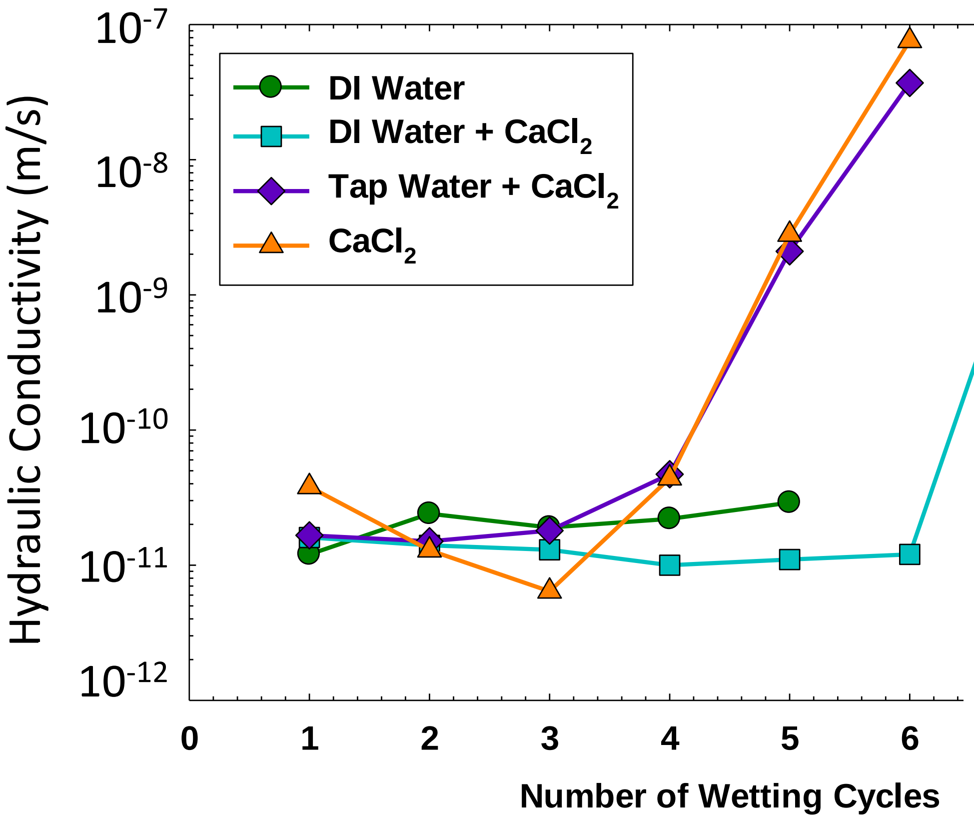


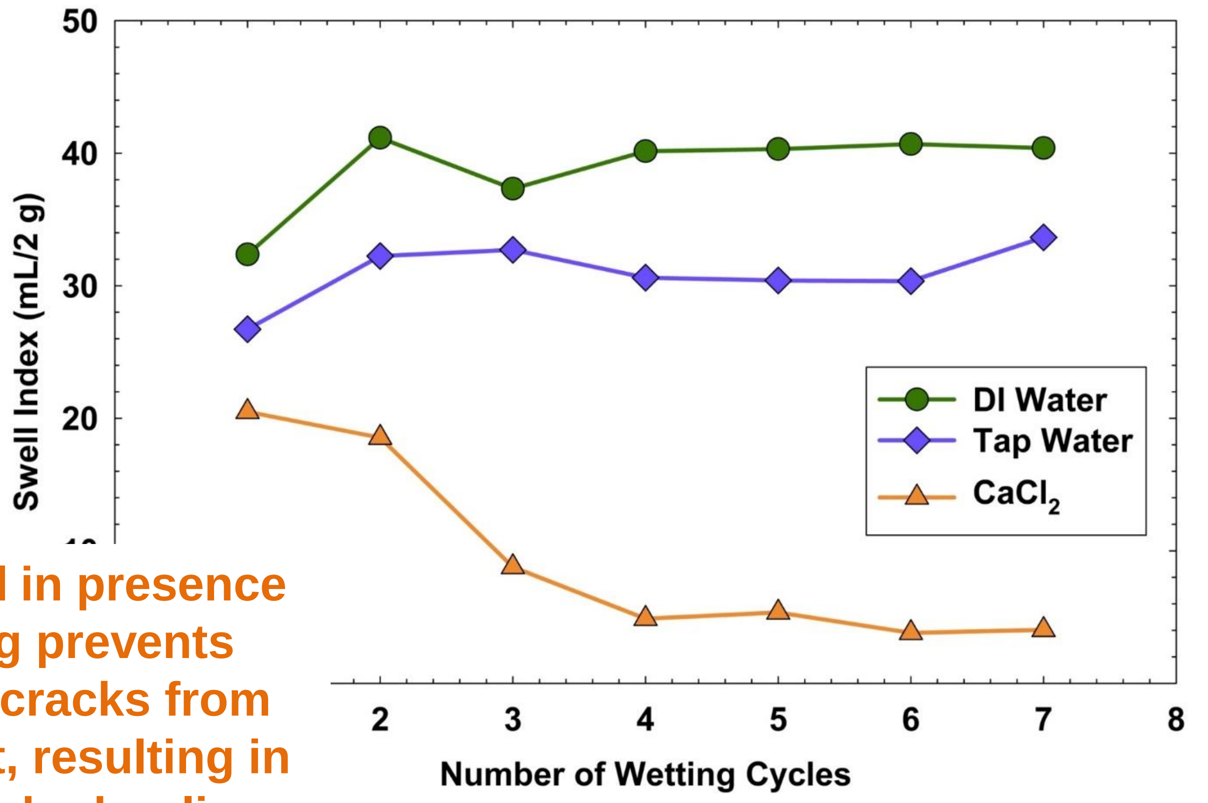
Hydraulic conductivity:
1×10^{-5} to 1×10^{-4} cm/s

Swell index: 8-10 mL/2g



GCL Damaged by Desiccation Coupled with Cation Exchange

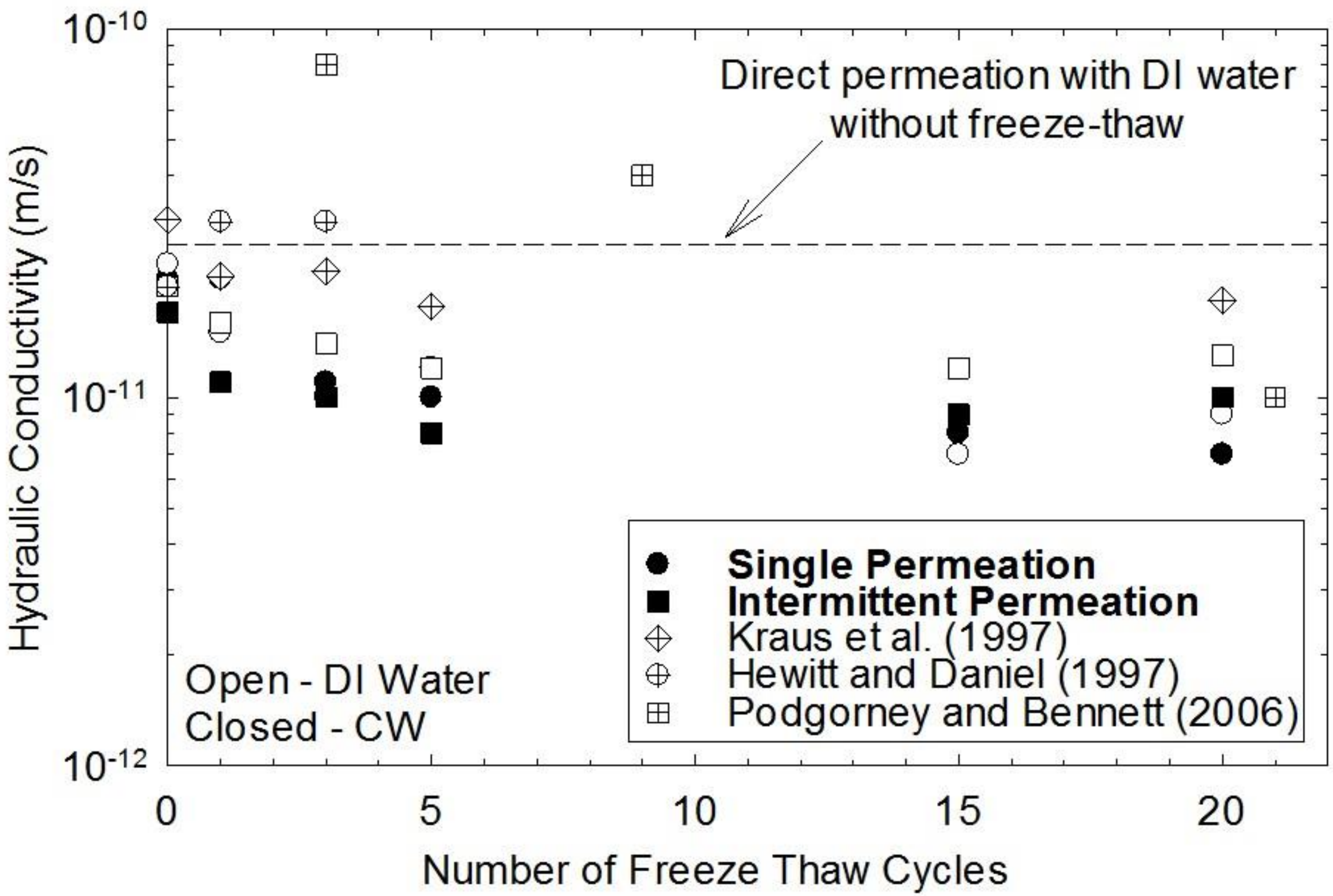




Loss of swell in presence of Ca or Mg prevents desiccation cracks from swelling shut, resulting in increase in hydraulic conductivity.

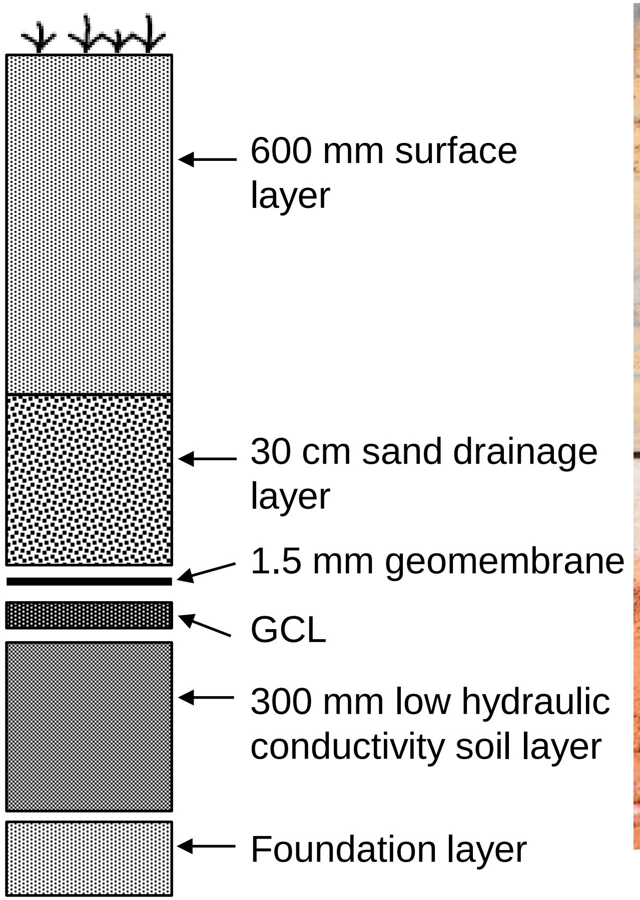
Lin, L. and Benson, C. (2000), Effect of Wet-Dry Cycling on Swelling and Hydraulic Conductivity of Geosynthetic Clay Liners, *J. of Geotech. and Geoenvironmental Eng.*, 126(1), 40-49.

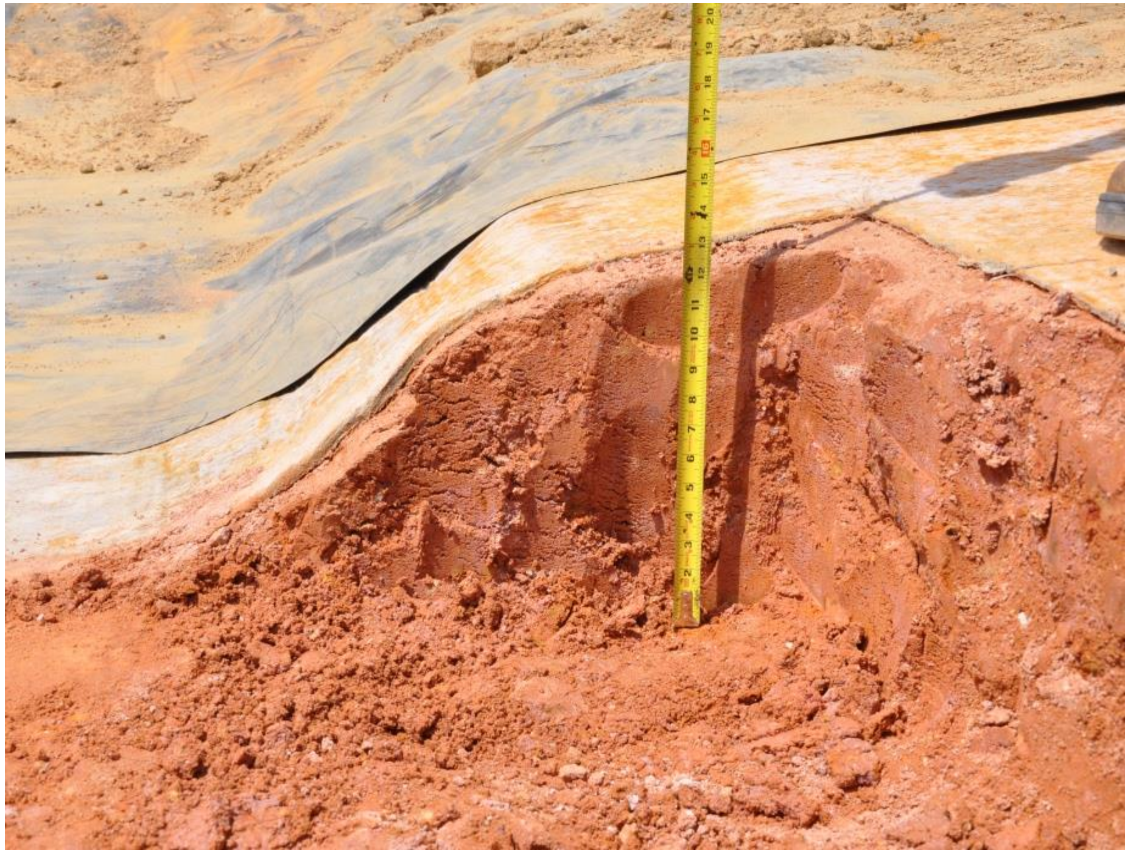
Does Freeze-Thaw Cycling Cause Similar Damage?



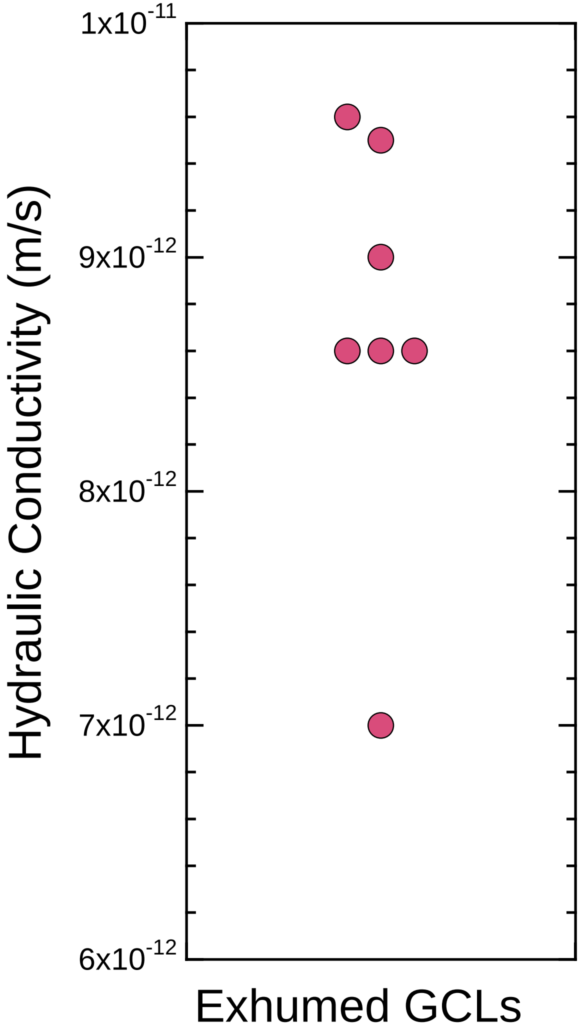
- Freezing similar thermodynamically to desiccation (reduce in liquid water content).
- **Bentonite subjected to freezing does NOT dehydrate, making freeze-thaw impact different from desiccation**.
- Hydraulic conductivity diminishes modestly due to freeze-thaw cycling.

GCL Exhumation at LLW Disposal Site in Southeastern USA





In service for 14 yr



Key Take Away Messages

- GCLs can be **exceptional barriers** that are deployed expediently, function well, and are resilient – **when engineered and installed carefully**.
- Hydraulic conductivity of **conventional NaB GCLs controlled by swelling of bentonite** granules – **intergranular pores and needlepunching fibers must swell shut** to achieve low hydraulic conductivity. **Strongly influenced by geochemistry**. True for both granular and powdered bentonites.
- Proper design requires that we **understand the geochemistry** and **impact on engineering behavior** – true for GCLs deployed in liners and covers.
- More extreme cases may require bentonite-polymer composite GCLs (**BPC GCLs**) or other modified GCLs may be required. For these GCLs, must **understand geochemistry** and **impact on engineering behavior** .

When the door of opportunity opens, walk ***through***.

Lake Wallenpaupack, Pennsylvania, USA, ca. 1968

Learn More About GCLs from these Webinars
(all free to download)

GCL 101 - GCL Fundamentals

https://drive.google.com/file/d/1y4mqkaxgNwtE_3VTaWxYviKkkNWT6KpE/view?usp=sharing

GCL 201 – Bentonite-Polymer Composite GCLs for Aggressive Conditions

https://drive.google.com/file/d/15QKwbDzwpK6pfH1qCuSR0scn7e4xinuO/view?usp=sharing

GCL 301 - Evaluating GCL Chemical Compatibility

https://drive.google.com/file/d/1qW6PgRCe5L1pq_NgwPKdWsaSQ-S1wD37/view?usp=sharing

GCL 401 - Lessons Learned from GCL Case Histories

https://drive.google.com/file/d/1qft2DRZpAaKMz76hTRY36Jz-_FVXhG1z/view?usp=sharing

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