A Review of Microbially Induced Carbonate Precipitation in the Remediation of Diverse Mine Tailings

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Goals and Agenda

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- Goal: Discuss MICP as a remedial strategy for mine sites
- Agenda
  - What is MICP?
  - Microbial Processes
  - Applications of MICP in Mining
  - Challenges Associated with MICP
  - Case Studies
  - Summary and Conclusions

What is MICP?

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MICP – What is it?

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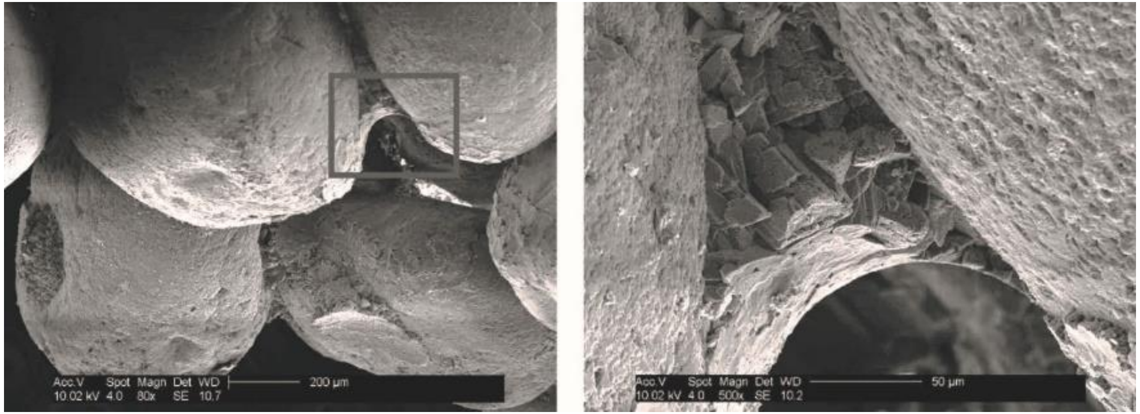
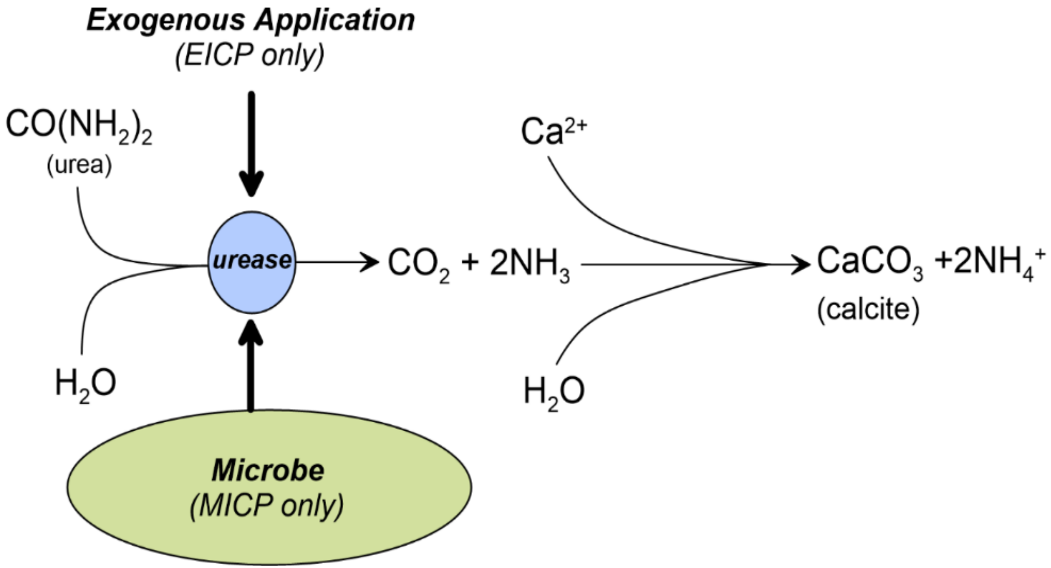
- MICP is a bio-based process that induces precipitation of carbonate minerals by increasing pH and alkalinity
- Common microbial processes that induce MICP include
  - Ureolysis
  - Denitrification
  - Sulfate Reduction
  - Methanogenesis
  - Photosynthesis



Ureolysis

- Ureolysis is catalyzed by the urease enzyme
- Urease is produced by several microbes and plants



Ureolysis (MICP)

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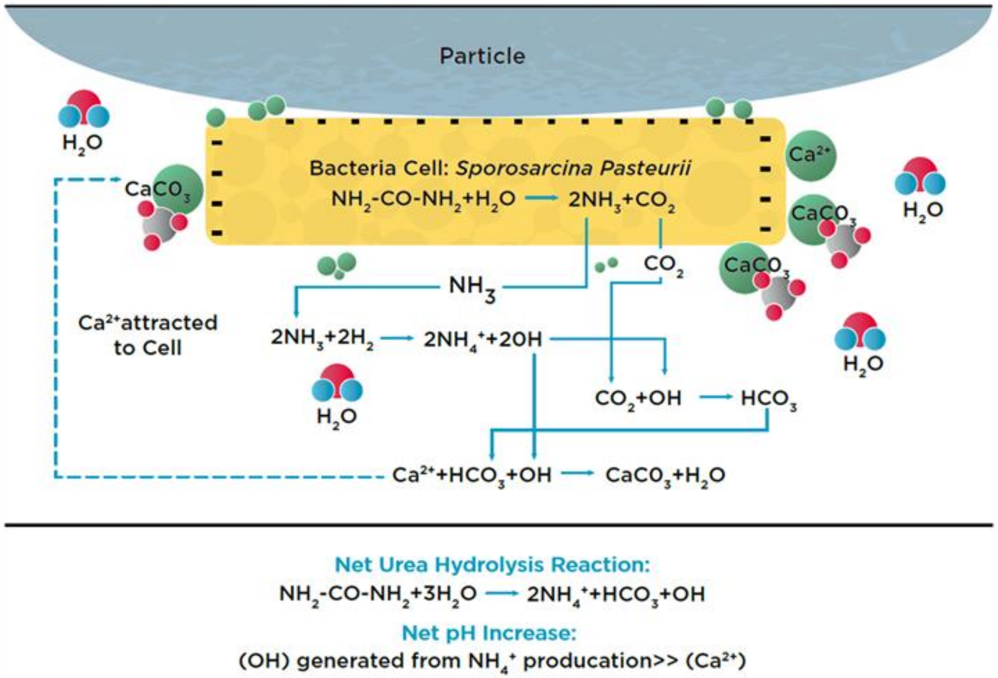
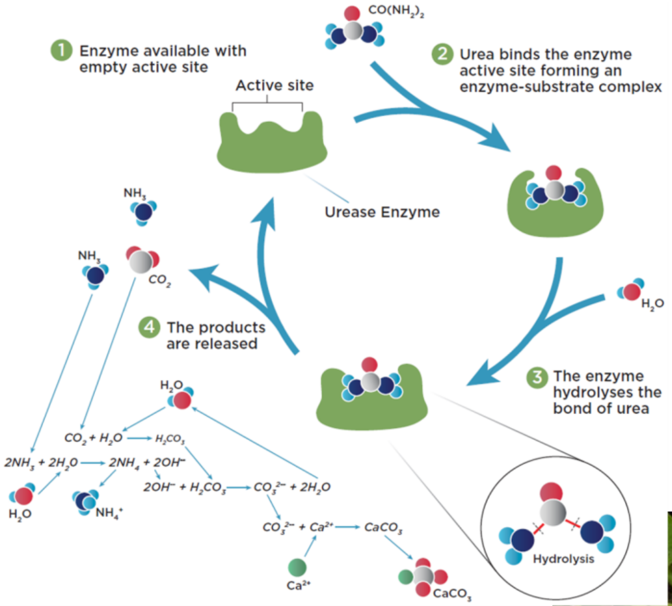
- MICP is catalyzed by ureolytic microbes (e.g., *Sporosarcina pasteurii*, *Lysinibacillus, Pararhodobacter)*
- These microbes produce urease and perform ureolysis
  - Scavenge nitrogen for incorporation into amino acids and proteins
  - Generate energy (ATP)
- Application requires stimulation of native microbes or augmentation with exogenous microbes
  - Stimulation may be more cost effective and easier to implement under existing regulations
  - Augmentation may be necessary if tailings are fairly sterile (i.e. limited native microbial ecology)



Ureolysis (EICP)

- Application requires an exogenous source of urease
- Urease is produced by plants in addition to microbes
  - Sword jack bean, watermelon seeds, soybeans
- Extraction of urease from plants is simple
  - Current research by CBBG (at ASU)
  - As much as 40x cheaper than purchasing laboratory-grade urease
  - Effective for carbonate precipitation and soil improvement

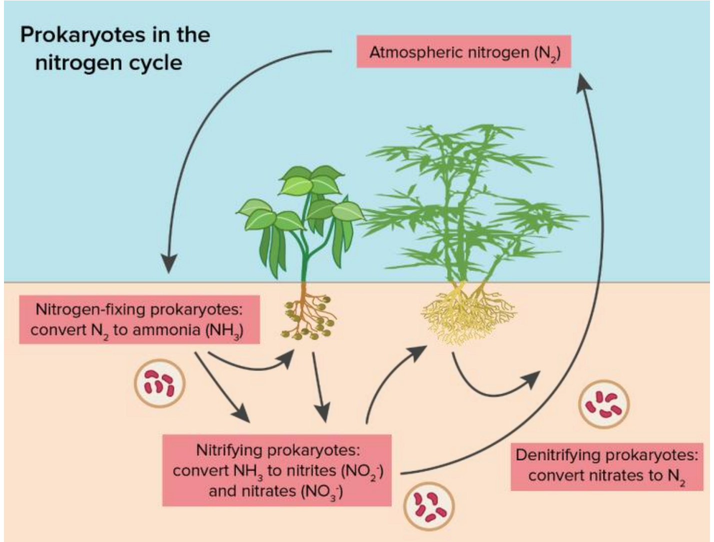


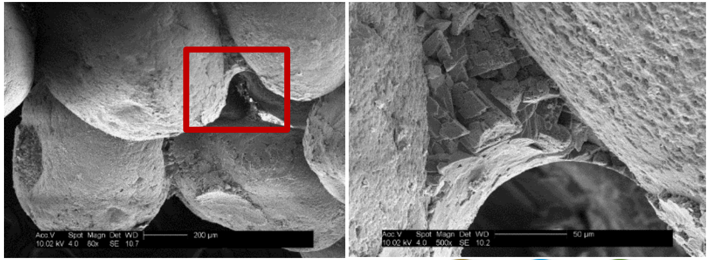
Center for Bio-mediated & Bio-inspired Geotechnics (CBBG)

Denitrification (MIDP)

- MIDP is induced by microbial denitrification
- Denitrification is an anaerobic microbial metabolism in which nitrate is reduced to nitrogen gas
- Depending on geochemistry, denitrification can also increase pH and alkalinity
- MIDP improves soil properties in two ways:
  - Biogas generation = desaturation = permeability reduction and liquefaction mitigation.
  - pH and alkalinity increase = carbonate precipitation = interparticle cementation, improved strength, stiffness, dilatancy; reduced permeability

$$16NO^{-}_{3(aq)} + 10CH_3COO^{-}_{(aq)} + 13Ca^{2+}_{(aq)} \longrightarrow 8N_{2(g)} + 7CO_{2(aq)} + 15H_2O_{(l)} + 13CaCO_{3(s)}$$





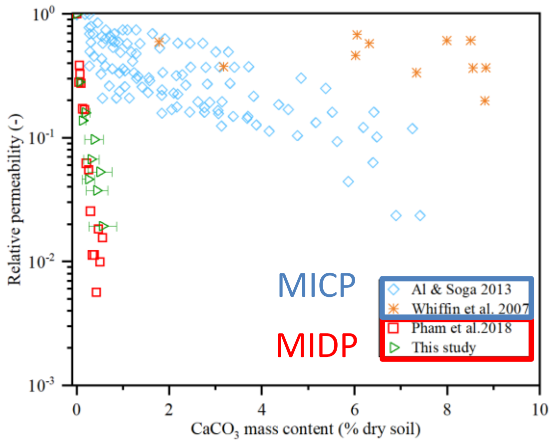
Advantages and Disadvantages

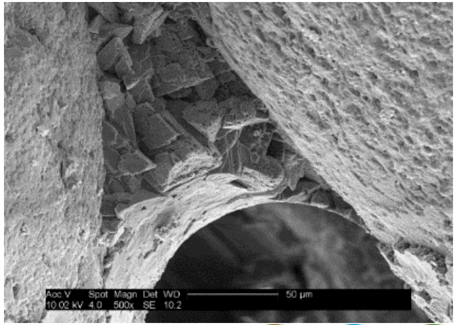
- MICP
  - Advantages: fast, aerobic microbes
  - Disadvantages: byproduct generation (ammonium), harder to stimulate
- EICP
  - Advantages: fast, no microbes
  - Disadvantages: expensive (enzyme extraction), byproduct generation (ammonium)
- MIDP
  - Advantages: desaturation and carbonate precipitation, microbes ubiquitous in subsurface, no major byproducts (nitrogen gas)
  - Disadvantages: slow, anaerobic microbes

Applications of MICP in Mining

Permeability Reduction

- Application: prevent migration of contaminants
- Mechanisms for permeability reduction:
  - Void filling from carbonate precipitation and biomass growth (MICP, EICP, MIDP)
  - Desaturation from gas generation (MIDP only)
- Applicable technologies: MICP, EICP, MIDP
  - More efficient permeability reduction from MIDP compared with MICP or EICP
    - Combined effects of desaturation and void filling
    - Gas bubbles force carbonate precipitation at pore throats
- Implementation: subsurface injection of nutrients through injection wells



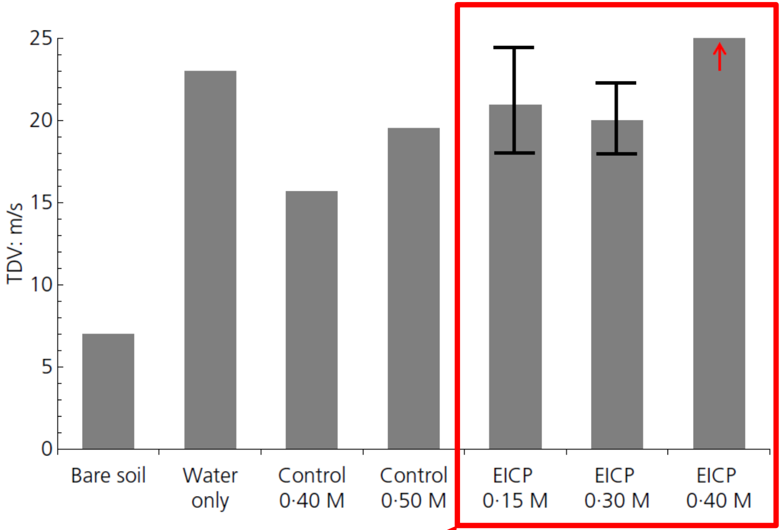


Contaminant Binding

- Application: prevent migration of contaminants
- Mechanisms for contaminant binding:
  - Contaminants of concern are contained within crystal structure of precipitated carbonates
- Applicable technologies: MICP, EICP, MIDP
  - MICP and EICP may be more efficient b/c carbonate precipitation occurs faster
- Implementation: subsurface injection of nutrients through injection wells

Dust Control

- Application: prevent offsite migration of fugitive dust from TSFs
- Mechanism for dust control
  - Cementation of particles at the tailings surface
- Applicable technologies: MICP, EICP
  - MIDP generally not preferred (slower, anaerobic microbes)
- Implementation: surface application of nutrients/microbes



EICP treatment results in higher detachment velocity than water or salt treatments

Strength/Stability Improvement

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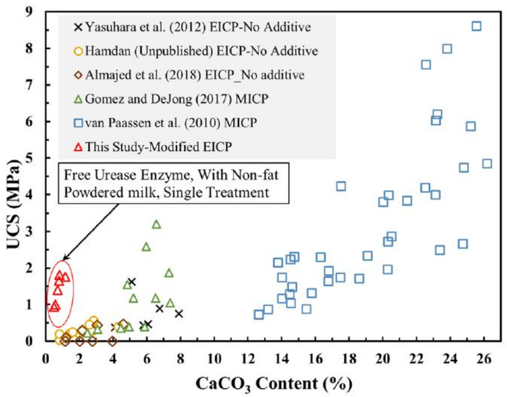
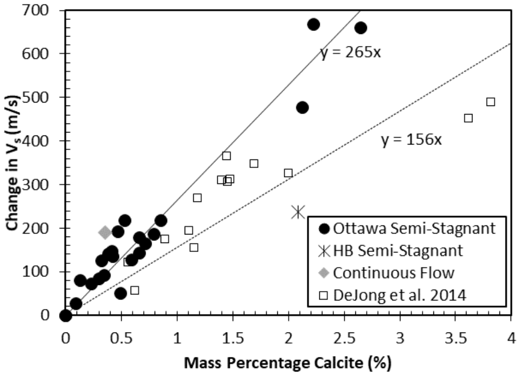
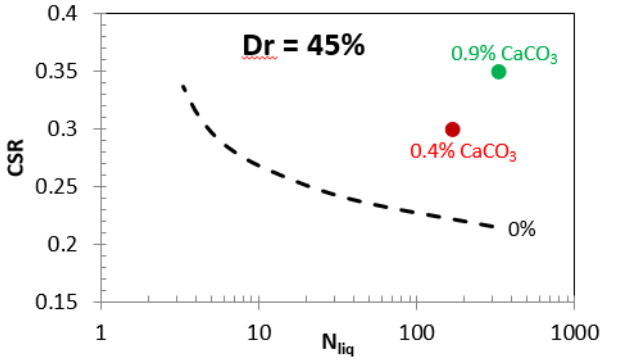
- Application: prevent geotechnical failure of TSFs
- Mechanism for strength/stability improvement
  - Mass cementation/solidification of tailings particles (carbonate precipitation)
  - Particle roughening (carbonate precipitation)
- Applicable technologies: MICP, EICP, MIDP
  - MICP and EICP are generally much faster
  - MIDP is slower
- Implementation:
  - Subsurface injection of nutrients/microbes for in-place tailings
  - Injection of nutrients/microbes during placement of tailings

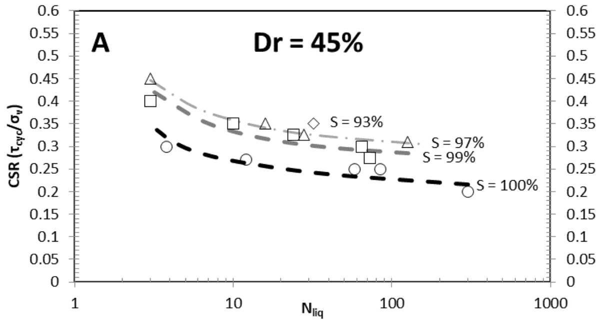




Liquefaction Mitigation

- Application: Mitigate liquefaction risk for tailings
- Mechanisms for liquefaction mitigation:
  - Densification/cementation from carbonate precipitation (MICP, EICP, MIDP)
  - Desaturation from gas generation (MIDP only)
- Applicable technologies: MICP, EICP, MIDP
- Implementation: subsurface injection of nutrients through injection wells





Challenges Associated with MICP

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- Nutrient delivery – how do we get the nutrients where we need them to go?
- Byproducts (ammonium)
- Reaction rate (MIDP can be slow)
- Microbial inhibition (nitrite)
- Inhibition of calcite precipitation (metals, organic acids)
- Immature technology (cost)

Case Study 1: Dust Control

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Experimental Program

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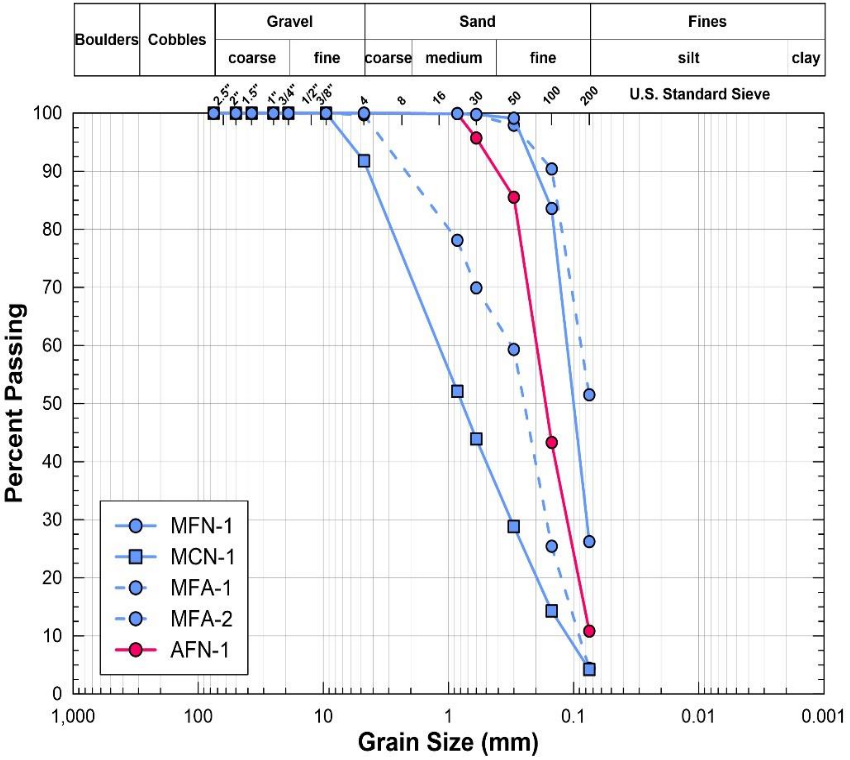
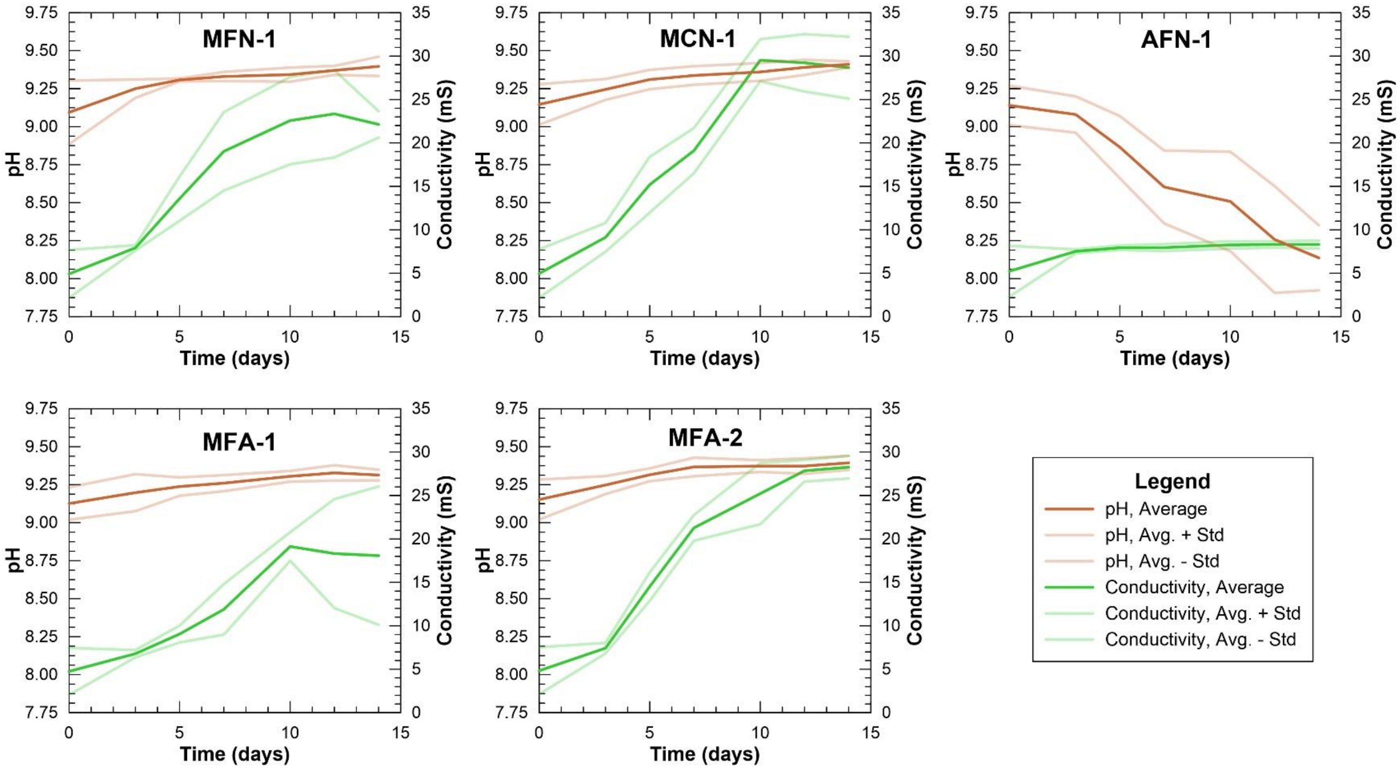
- Five samples of tailings obtained for the research program
  - Four are from taconite tailings facilities in Minnesota
  - One is from a copper-molybdenum ore site in Arizona
- Stimulation experiments (5) performed on each tailings sample
  - Test the feasibility of MICP at TSFs
- Wind tunnel testing of EICP-treated tailings
  - Compare with control tests
  - Test the feasibility of bio-based carbonate precipitation for dust control
- Freeze-Thaw Resistance of EICP-treated tailings
  - Determine the service life of EICP

Description of Tailings

- Five samples
  - MFN-1: fine, freshly deposited MN taconite tailings
  - MCN-1: coarse, freshly deposited MN taconite tailings
  - MFA-1: fine, aged MN taconite tailings (1-year old)
  - MFA-2: fine, aged MN taconite tailings (9-years old)
  - AFN-1: fine, fresh Arizona copper-molybdenum tailings

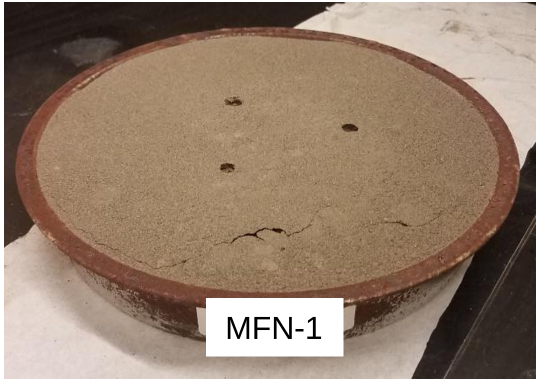


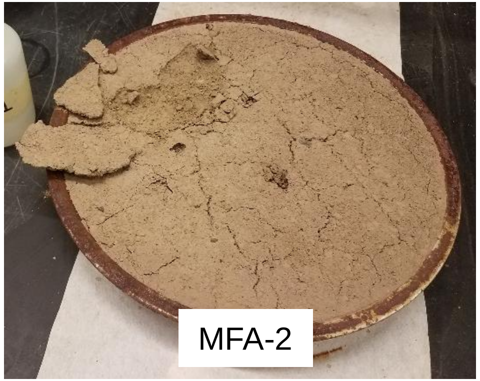
Stimulation Experiments



Wind Tunnel Testing

- EICP-treated tailings cured and dried prior to testing in wind tunnel
  - 5-minute exposure in wind tunnel (same as controls)
- Pocket penetrometer used to measure crust strength
- Crust thickness measured with calipers
- Carbonate content of crust measured using acid digestion





Results (EICP for Dust Control)

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- Thin, but measurable crust formation on all tailings
- Small, but measurable crust strength on all tailings
- Between 1-12% carbonate in samples of cemented crust
- Reduction in mass loss by 3 orders of magnitude compared with untreated controls
- Significant freeze-thaw resistance
  - Negligible reduction in mass loss or crust strength after three freeze-thaw cycles

Next Steps

- Field trials
  - Five ¼ acre test plots at Minnesota TSF
    - Two control plots (untreated and treated with tack and straw)
    - Three test plots (EICP)
  - Treatment by truck (water trucks with spreader bars)
  - Mechanical dust generation and monitoring
    - Video monitoring
    - PI-SWERL

Case Study 2: Containment Barrier

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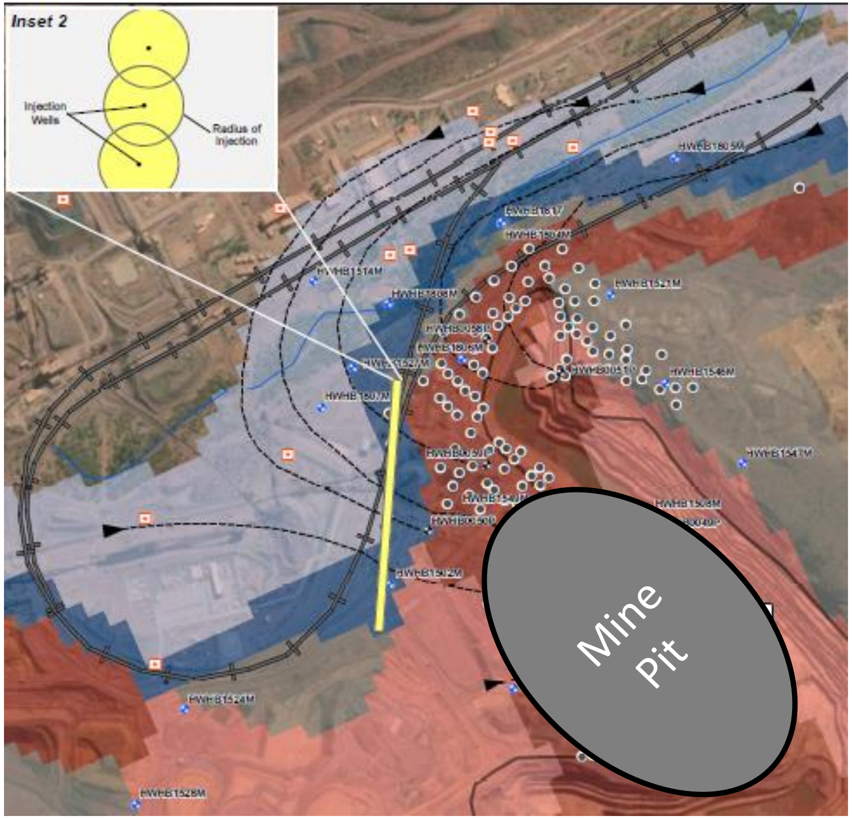
Project Overview

- Goal: reduce PFAS mass flux into mine pit to aid dewatering
- Solution: construct MIDP cutoff wall to restrict flow through high permeability pathways (fractured rock)



Selected Remedy (MIDP)

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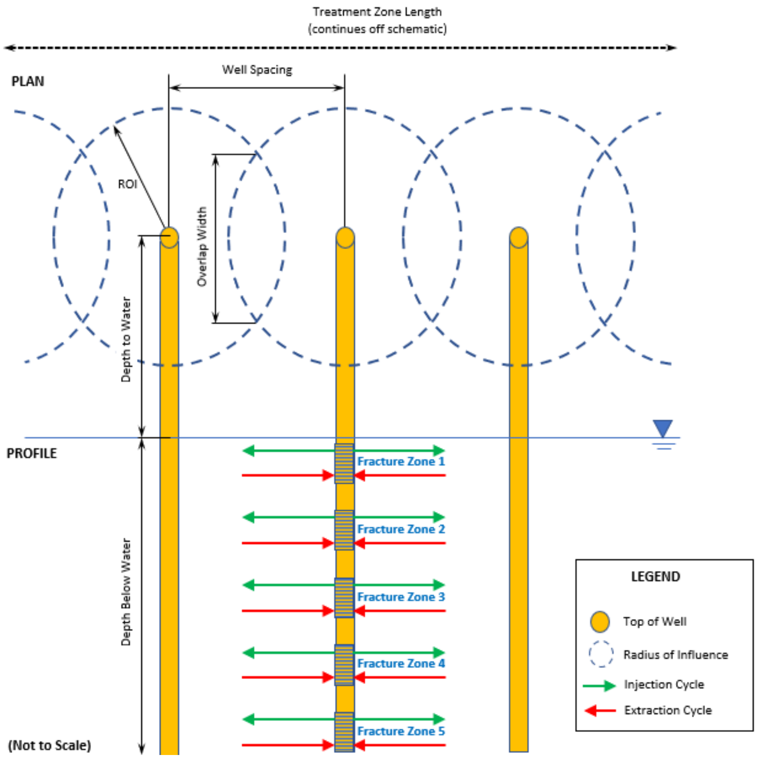
- Implementation
  - Assume stimulation of denitrifiers (to be assessed via treatability studies)
  - Void filling and stimulation occur simultaneously
- Advantages
  - Efficient void clogging (interplay between gas, carbonate, and biomass)
  - No by-products
- Disadvantages
  - Long reaction times (potential to shorten)
  - Potential for gas migration
  - Fracture size and shape may affect performance



Remedy Design

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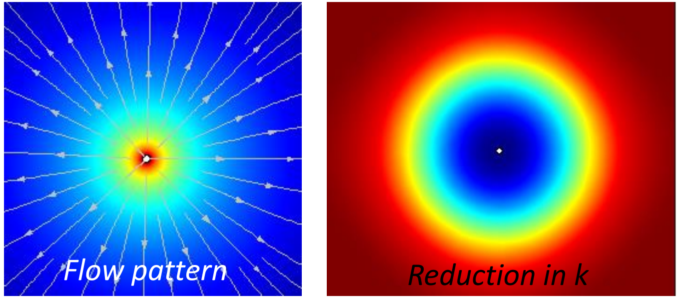
- Model implemented in COMSOL Multiphysics
  - Groundwater flow based on Darcy's Law
  - Reactive transport (advection and diffusion)
- Two geometries were considered
  - 2D plane strain (top view) – comparison of single injection versus injection-extraction system
  - 2D axisymmetric geometries – single well injection

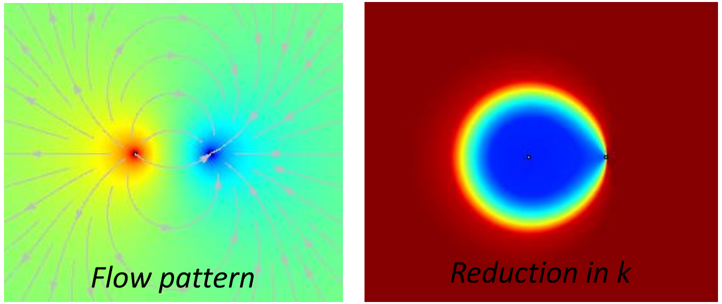
Remedy Design

- 2D Plane strain simulations
  - Single injection (left) and injection extraction (right) show no major differences in shape and extent of treatment zone or clogging efficiency
  - Treatment zone affected by porosity distribution, controlled by flow rate, flow strategy (continuous or pulsed), and substrate concentrations

SINGLE INJECTION



INJECTION-EXTRACTION



Remedy Design

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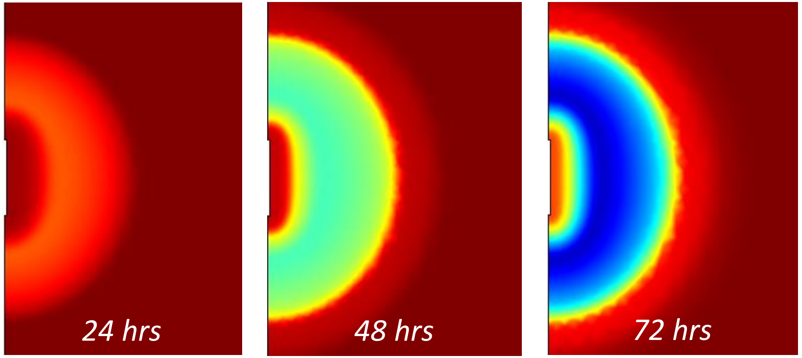
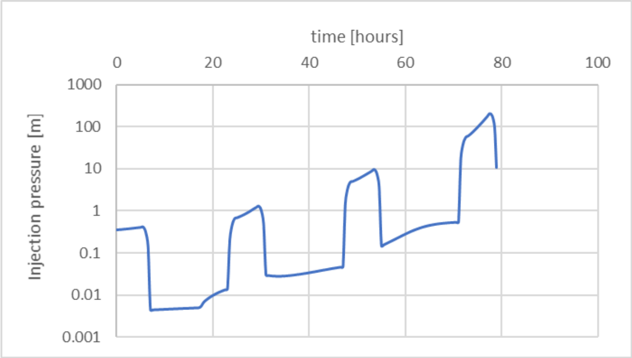
- 2D axisymmetric simulations:
  - Assumes homogeneous, isotropic initial porosity and permeability of fractured rock mass
  - Four MIDP treatment cycles: 6 hours injection (50 l/min) + 18 hours reaction (with water injected at 1/100 flow rate during reaction)
  - Results: spherical 14-m diameter treatment zone with reduction in hydraulic conductivity > two orders of magnitude.





Summary and Conclusions

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Summary and Conclusions

- MICP shows promise as a remedial strategy for mine sites
- Three major mechanisms for MICP were considered:
  - MICP (Ureolysis)
  - EICP (Ureolysis)
  - MIDP (Denitrification)
- Variety of applications
  - Contaminant binding
  - Permeability reduction
  - Dust control
  - Strength/stability
  - Liquefaction mitigation
- Case Studies

Questions?