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Meter-scale MICP improvement of medium-graded very gravelly sands

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Why soil improvement?

Surface erosion
(Gomez, et al. 2015)

soil liquefaction during 1964
Niigata earthquake (Wikipedia)

coastal erosion at Happisburgh, UK
-- photo taken by Sandy Prior

Fundão Mine Tailings Dam failure
Image courtesy of Ibama

Microbially Induced Carbonate Precipitation

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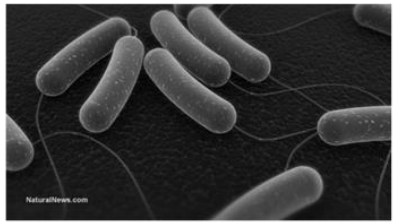
$$CO(NH_2)_2 + 2H_2O \dashrightarrow 2NH_4^+ + CO_3^{2-} + Ca^{2+} \Rightarrow CaCO_3\downarrow$$

Bacteria produce **urease enzyme** to promote urea hydrolysis

Urea fertilser $CO(NH_2)_2$

Bacteria *(S. pasteurii)*



Calcium source (CaCl2)

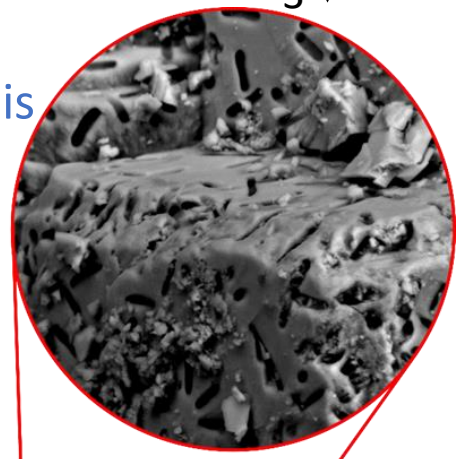
Ca^{2+}

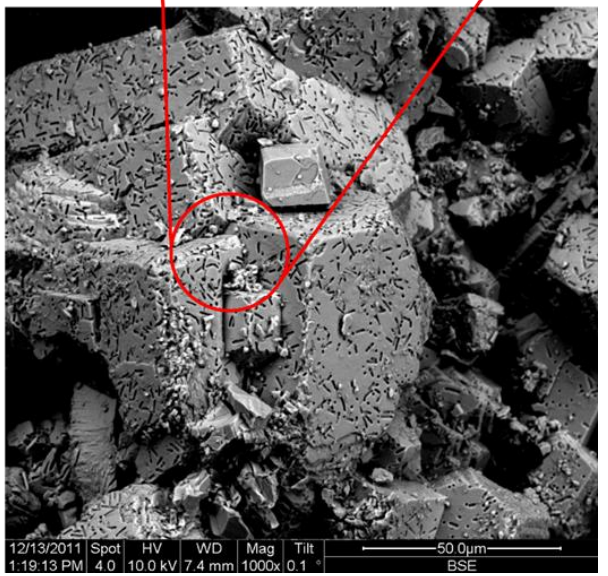
Urea hydrolysis

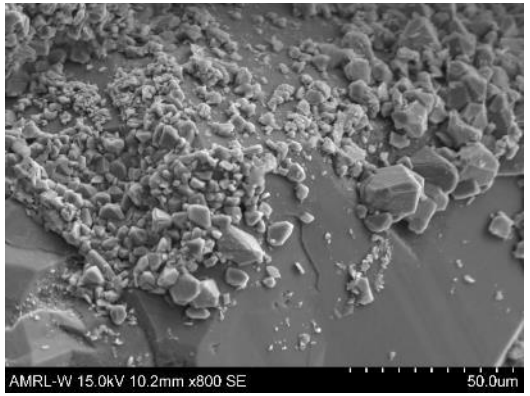
Ammonium & pH increase NH_4^+ & OH^-

Carbonate CO_3^{2-}

Calcium carbonate biogrout $CaCO_3$







Previous large-scale MICP trials

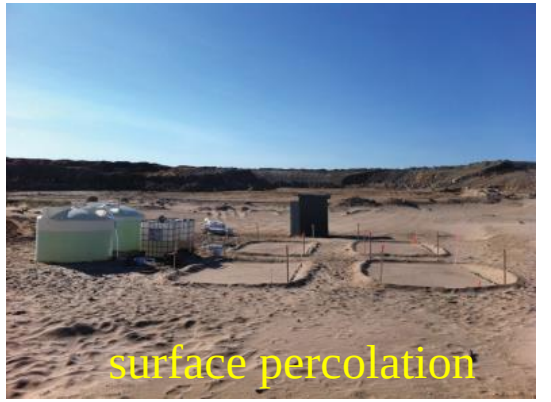
van Paassen et al. (2010)

100 m^3 (8 m × 5.6 m × 2.5 m)

van Paassen et al. (2011)

strengthening gravel for borehole stability

Gomez et al. (2015)

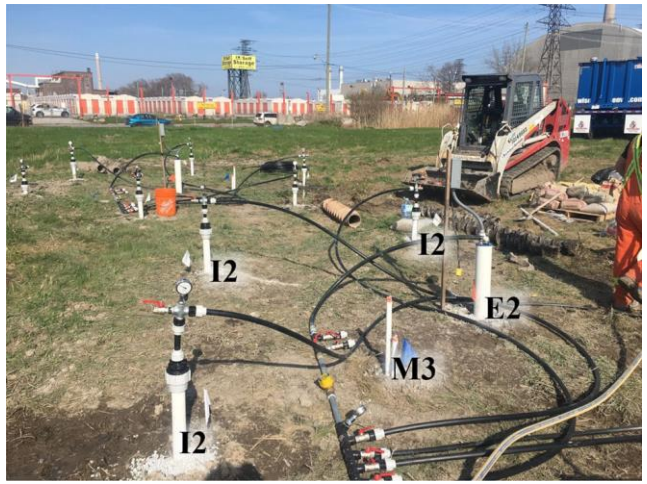


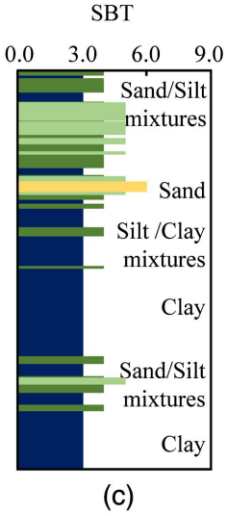
2.4 m × 4.9 m × 0.3 m

Dia. 1.7 m × 0.3 m thick

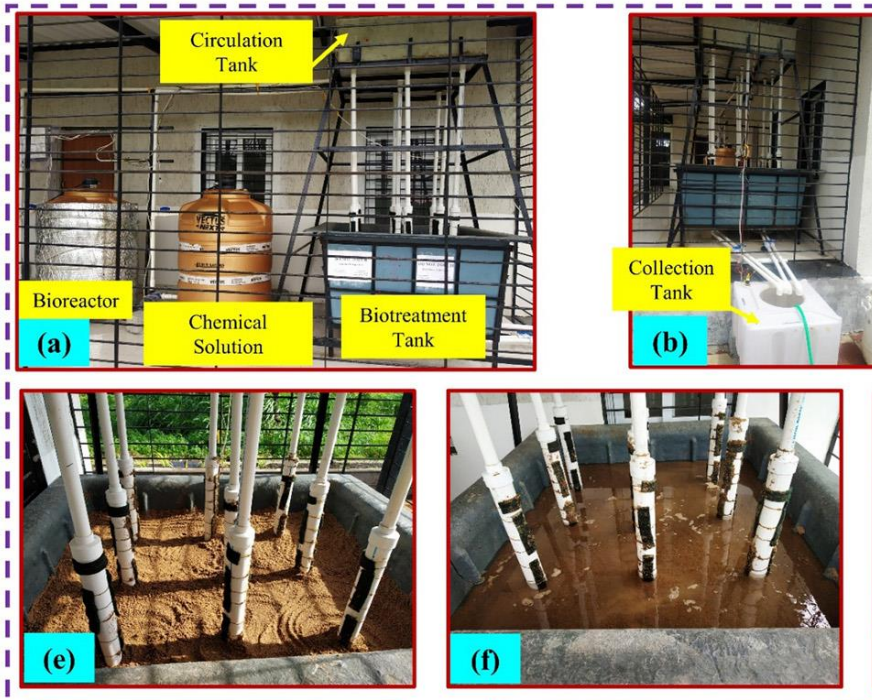
Gomez et al. (2017)

Wu et al. (2020) 1×1×1 m^3





Zeng et al. (2021, 2022) 5 × 5 × 5 m^3

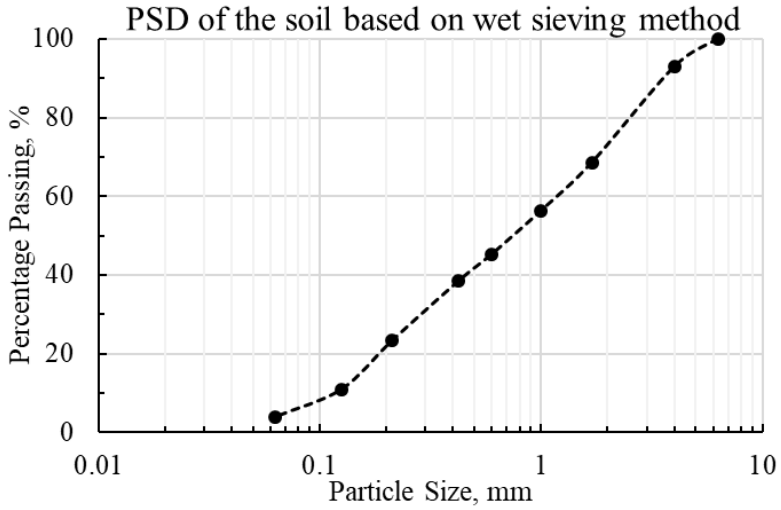


Sharma et al. (2022) 1.35m × 1.35m × 0.65m

Laboratory MICP test in a radial flow cell

medium-graded very gravelly sands - BSI

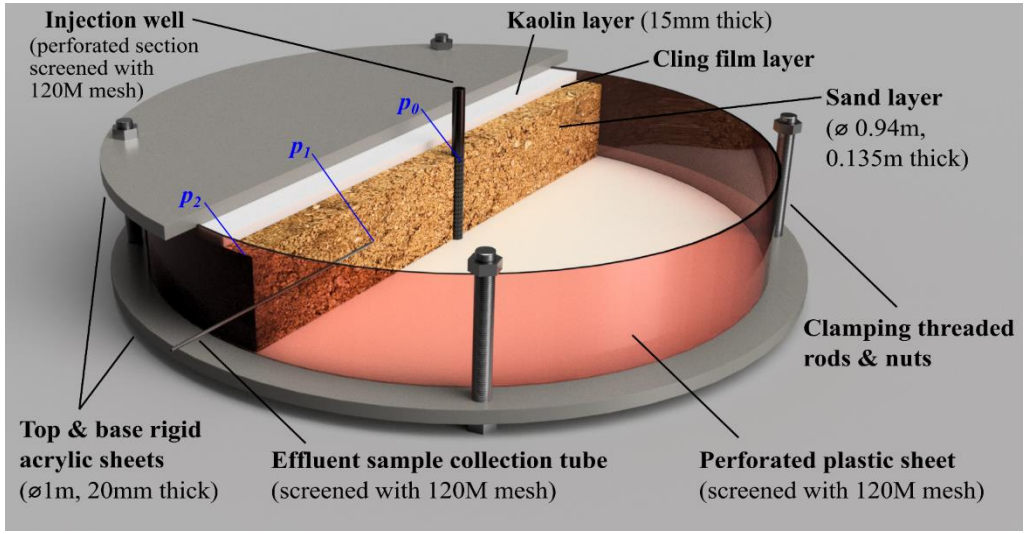
- d_{50} = 0.75 mm
- d_{60}/d_{10} = 10.0
- $d_{30}^2/(d_{60}*d_{10})$ = 0.63



Pumping Strategy for each cycle

In total 9 cycles

Fluid type	volume	Flow rate
Bacteria solution (1 OD_{600})	52L (2PV)	2.9 L/min
Tap water	0.26L	
1-hour static period		
1st cementing solution	26L (2PV)	1.4 L/min
4-hour reaction		
2nd cementing solution	26L (2PV)	1.4 L/min
Reaction until next day/cycle		



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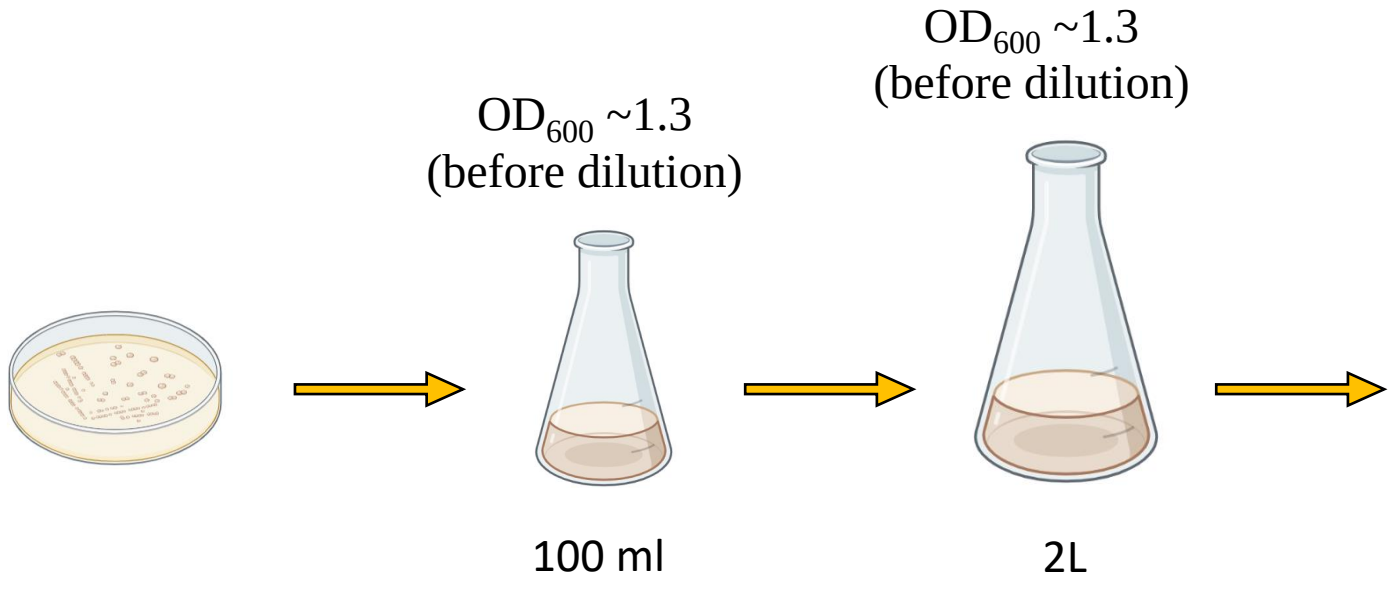
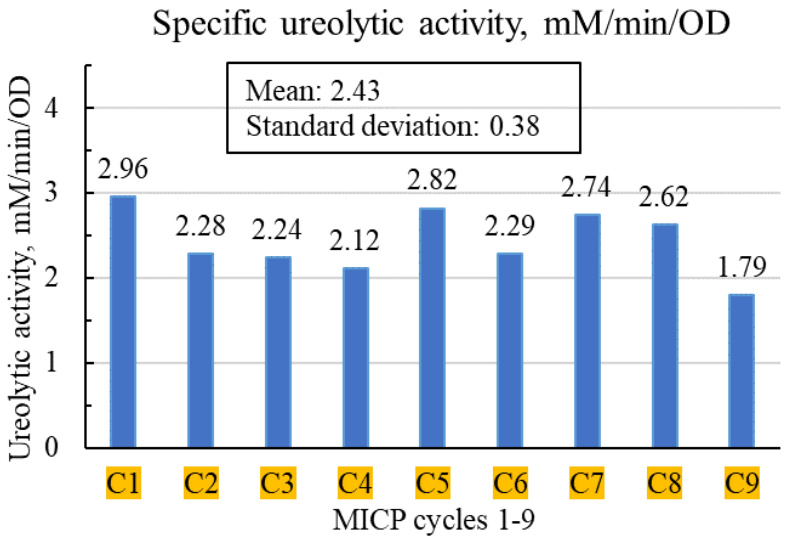
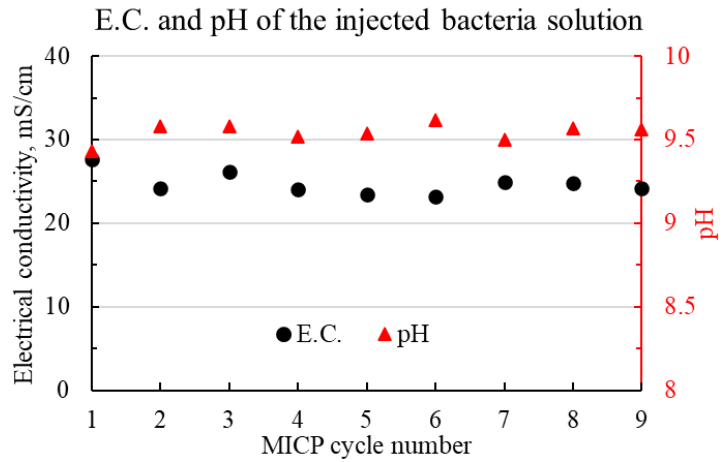
Bacteria culture and urease activity

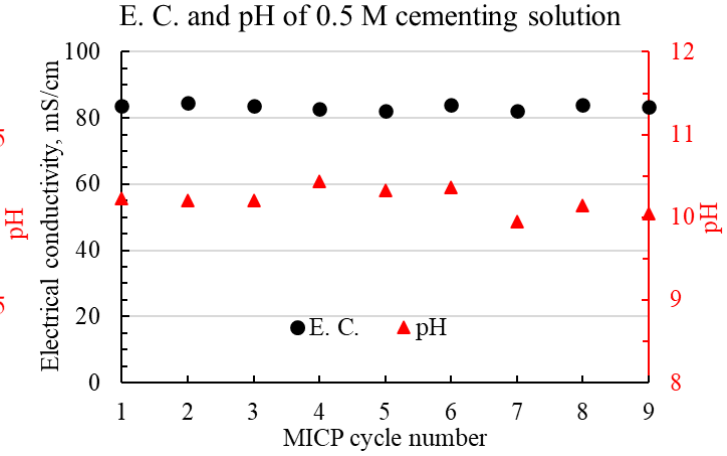


OD_{600} ~1.6
(before dilution)

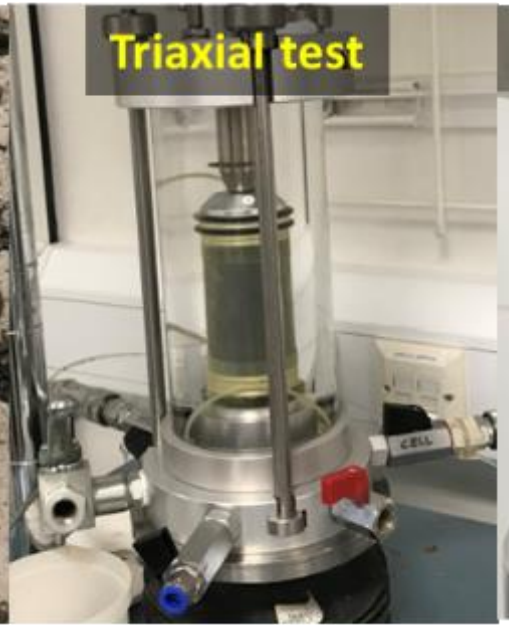
Fermentation tank: 40 L

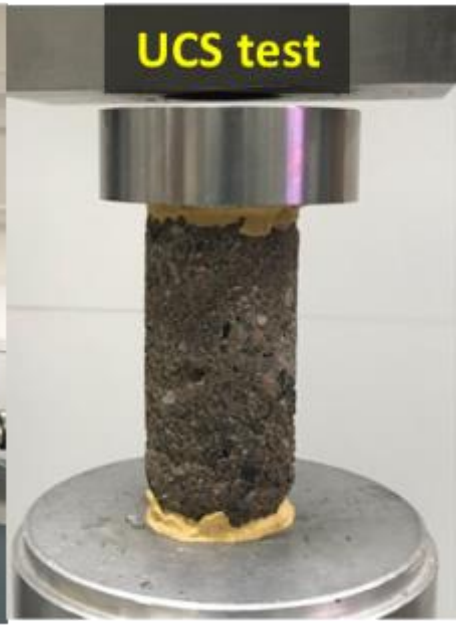






Coring and hydro-mechanical tests





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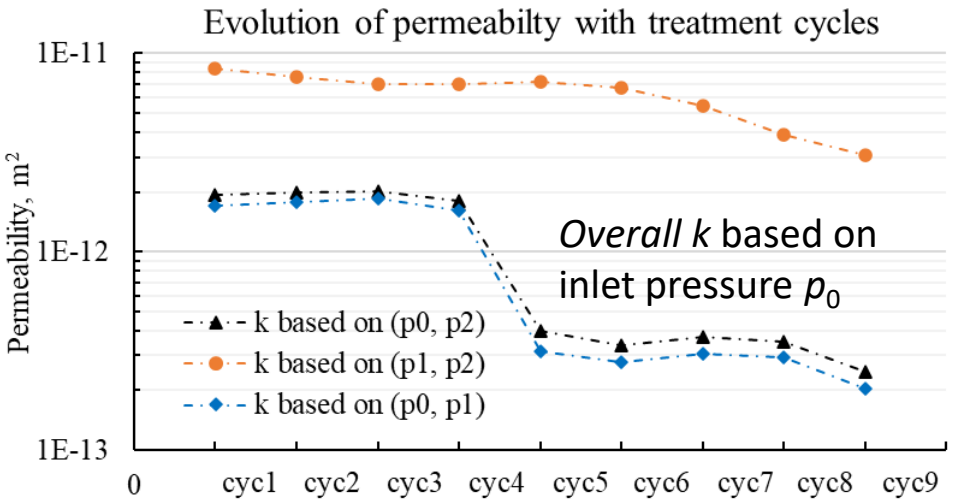
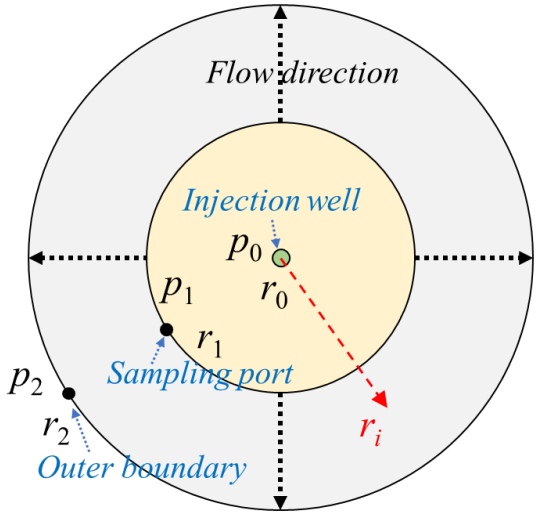
Permeability

Permeability of RFC during treatment





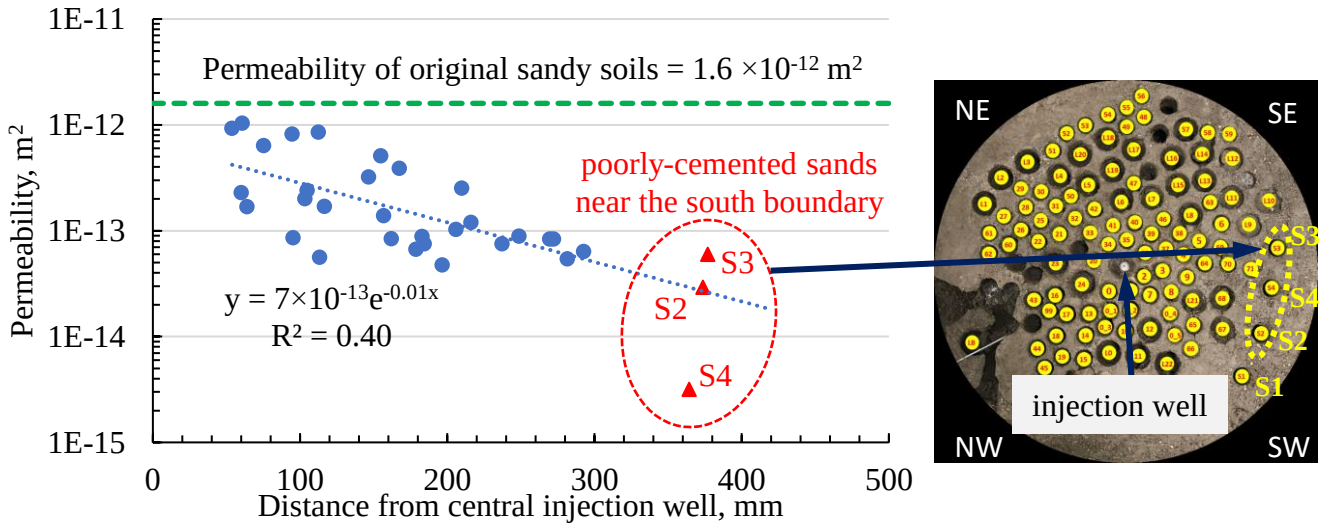
$$k = \frac{q\mu}{2\pi h} \cdot \frac{\ln(r_i/r_j)}{p_i - p_j}$$

q: injection rate, m³/s
h: thickness, m
μ: dynamic viscosity, Pa·s

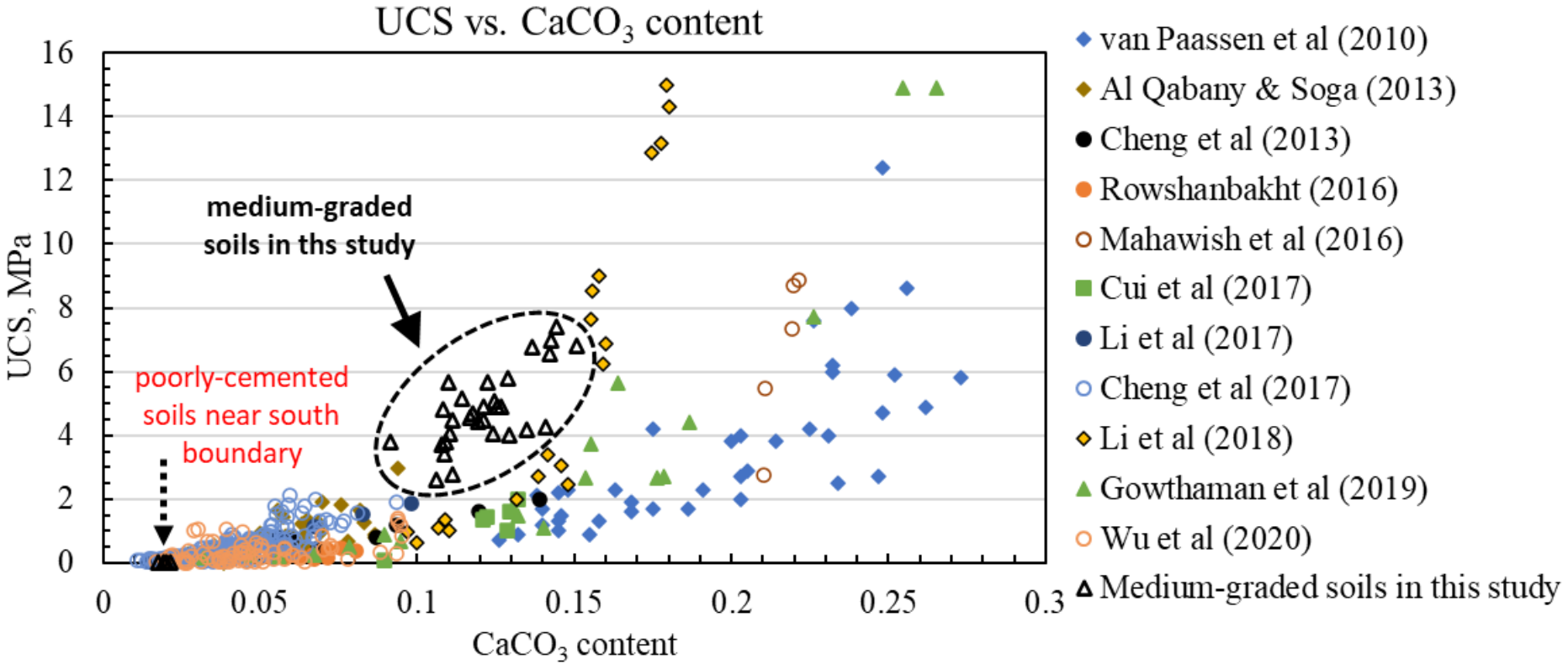
p_i and p_j (i, j=0, 1, 2; $i \neq j$) are the pressures at the radius of r_i and r_j respectively.

- Overall permeability dropped by 1 order of magnitude;
- Flow (permeability) heterogeneity;
- Fine migration.

Permeability of cores drilled after MICP



Unconfined compressive strength



The gravelly sands vs. Uniform sands

UCS deviates upwards from the UCS – $CaCO_3$ relation

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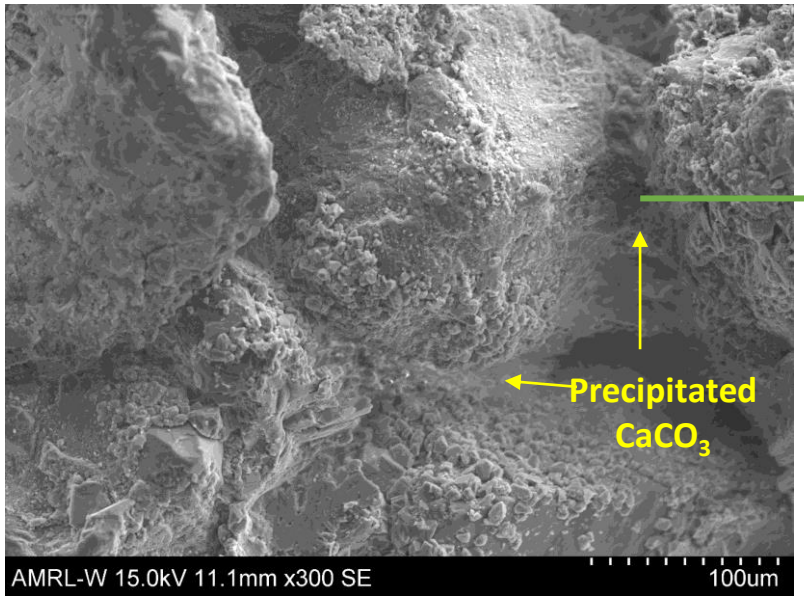
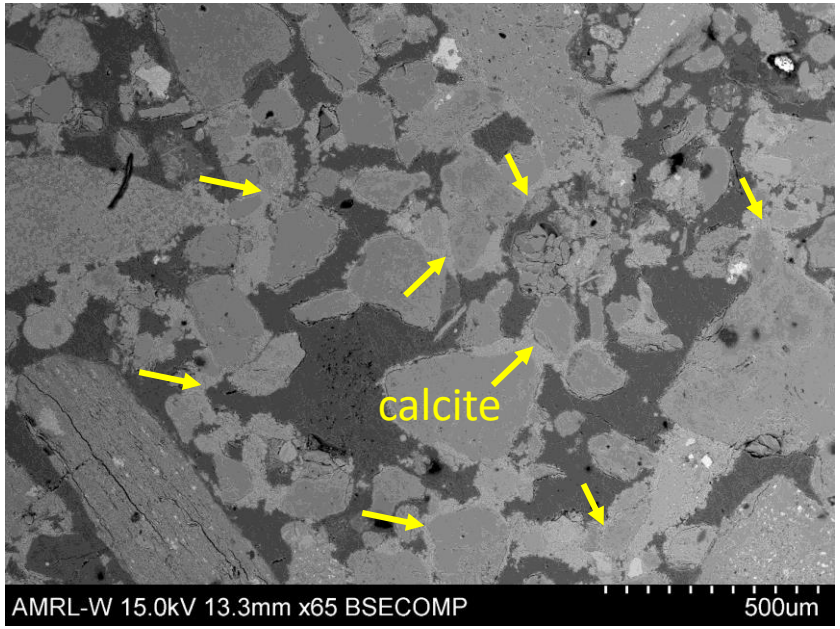
Microstructural analysis

Higher UCS at a given $CaCO_3$ content: meaning more effective cementation



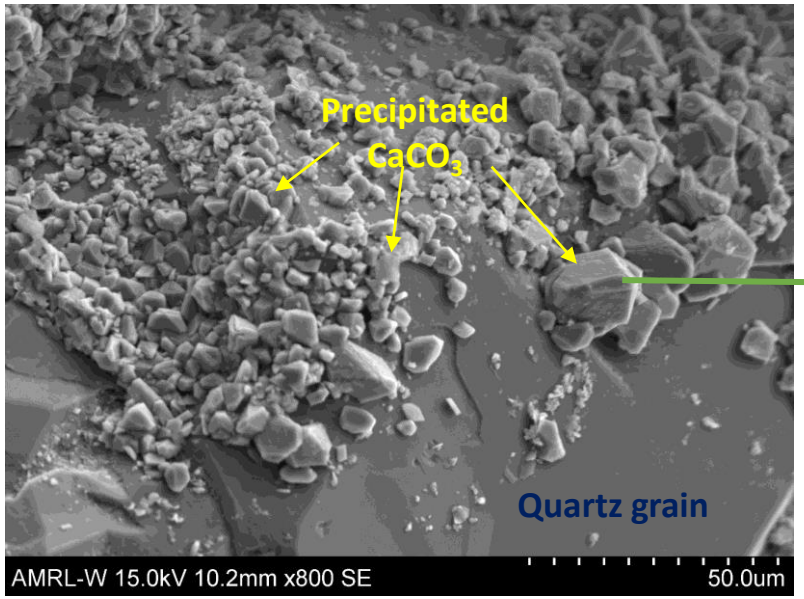
Effective cementation



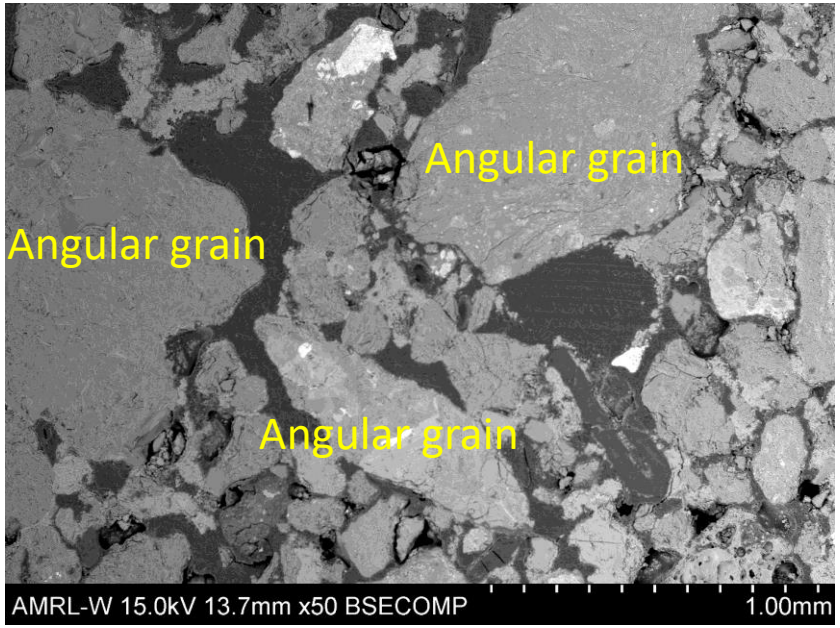
- Better gradation
- More contact points

↓

More effective cementation



Ineffective cementation



- Higher angularity

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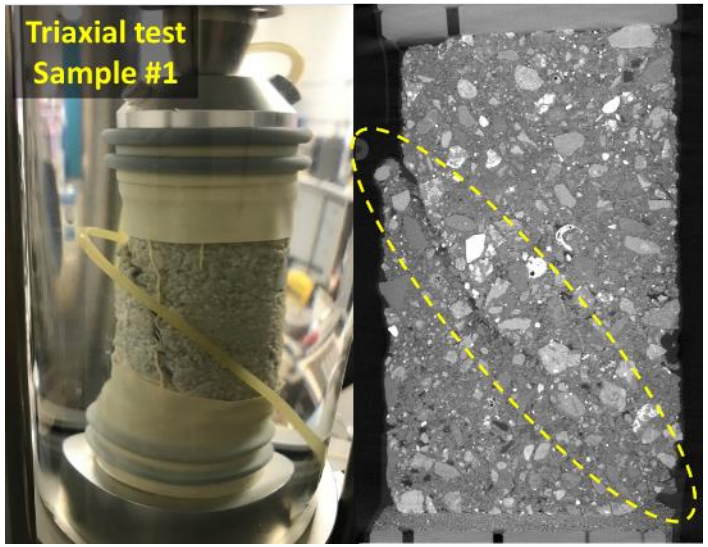
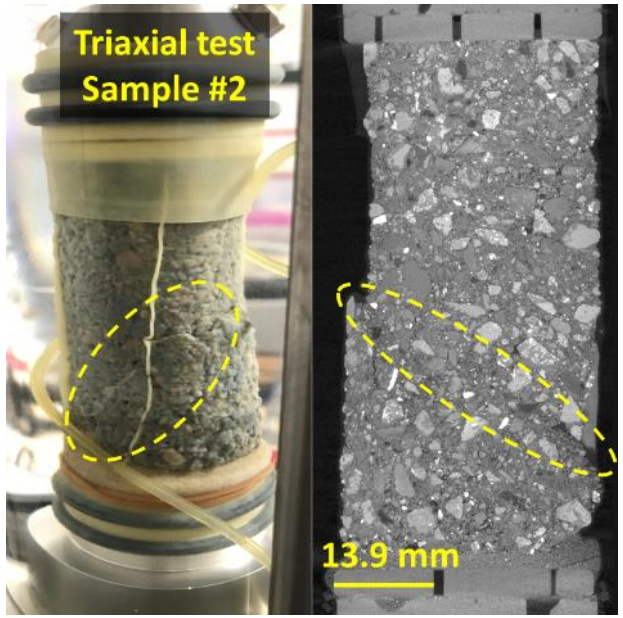
Interlocking effect

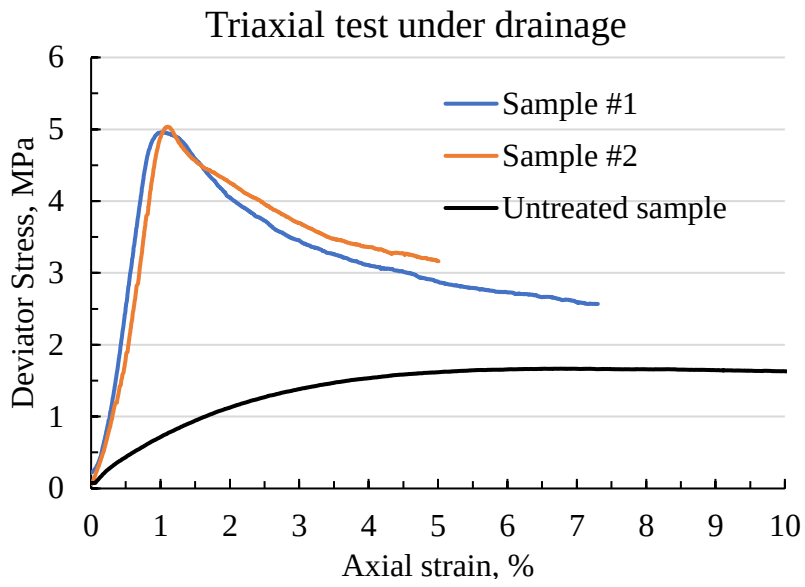
Triaxial test

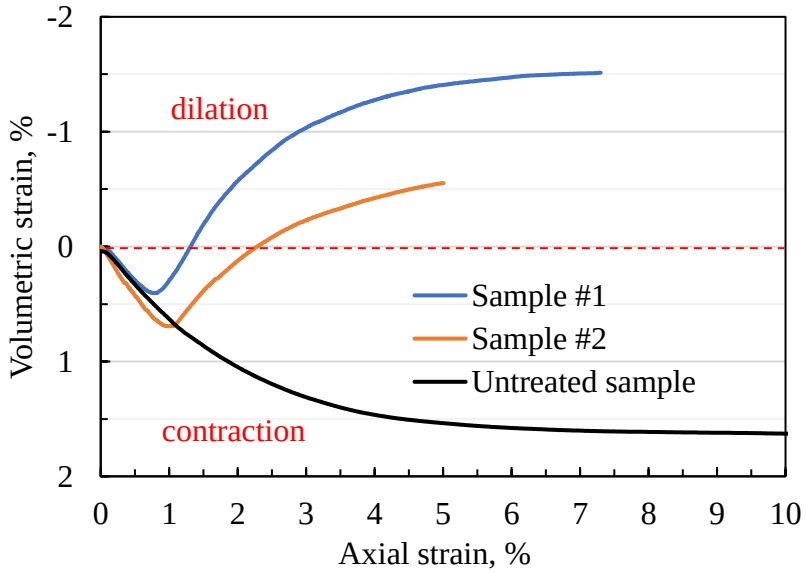
- Effective confining: 500 kPa
- Peak deviator stress: ~5 MPa

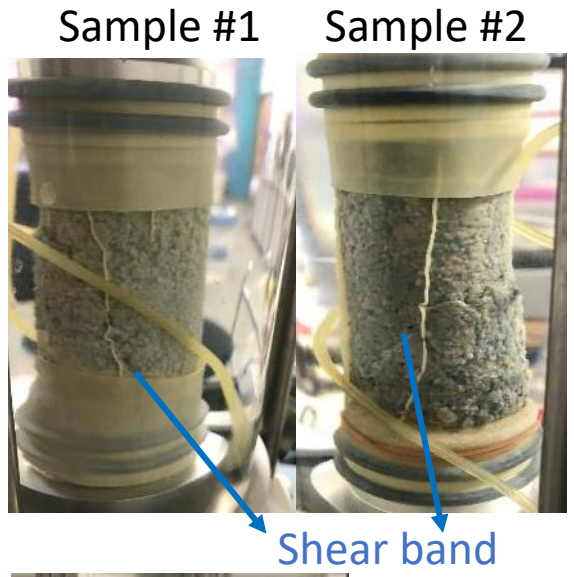


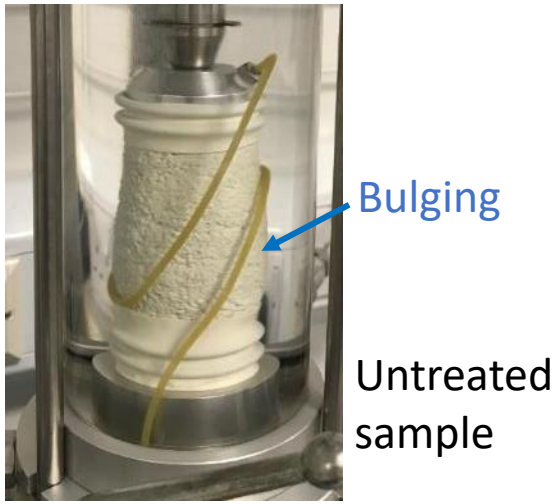
A Shear band was formed











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Conclusions

- MICP successfully turned the initially loose sands into “sandstones”;
- The UCS of 2.6-7.4 MPa with calcite content of 9.2%-15.1% was achieved;
- The higher UCS value at a given $CaCO_3$ content than that for the poorly-graded soils possibly results from more effective cementation due to higher grain angularity and better gradation.
- Flow heterogeneity existed for the tested medium-graded sands;
- The migration of fines and the formation of preferential flow paths may be challenges for producing uniform biocementation throughout the treated zone.

Acknowledgement

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