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Bio-cementation for Soil Stabilization in Civil Infrastructure

Professor Mohamed Shahin
Curtin University, Australia

Sustainable Geotechnical Engineering Summit (DFI)
December 5, 2022

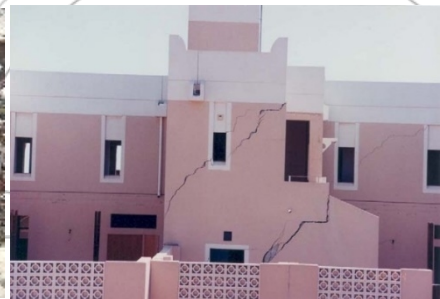
Outline

- Introduction to Unstable Soils and Existing Treatment Methods
- Bio-cementation for Treating Unstable soils:
  - Ground Improvement
  - Marine Environment
  - Construction Materials
  - Geothermal Energy
- Concluding Remarks

Unstable Soils

- Soils of low-density that heavily compact under loading (e.g. loose and calcareous sand) or collapse by the addition of water (e.g. sabkha).
- Soils of low-bearing capacity and high compressibility (e.g. soft clay).
- Soils of high-plasticity that swell/shrink upon wetting/drying (e.g. reactive).



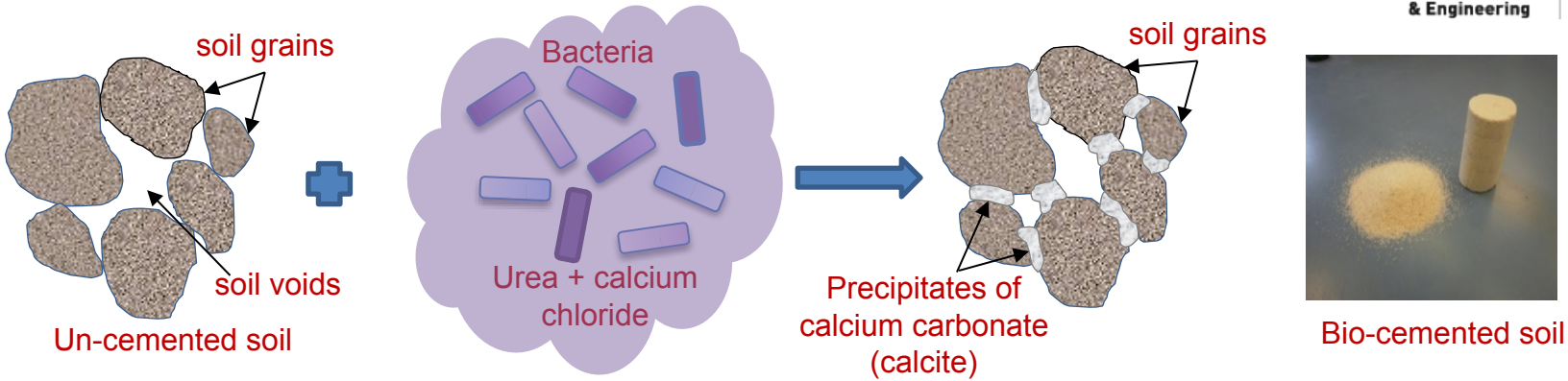
Solutions for Treating Unstable Soils

- ❑ Replacement of the entire unstable soil material.
- ❑ Use of pile foundations or stiffened rafts.
- ❑ Chemical stabilisation by additives (e.g., lime or cement).

- ✓ There are currently 40,000 projects per year performed worldwide employing chemically stabilised soils at a total cost of US$6 billion.
- ✓ Chemical treatment by Ordinary Portland Cement (OPC) is by far the most commonly used soil stabilisation method.
- ✓ Chemical treatment by OPC is not environmentally-friendly and is responsible for 10% of CO_2 emissions.

Manufacturing of OPC

Microbial Induced Calcite Precipitation (MICP)



- Urea is hydrolysed by the bacteria in the presence of water to form carbonate ions and ammonium.
- The produced carbonate ions react with the calcium ions of the calcium chloride and precipitate as calcium carbonate (calcite) crystals.

Bio-cementation in Civil Infrastructure

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- Ground Improvement:
  - Degree of saturation (fully saturated versus partially saturated treatment).
  - Degree of temperature (normal 25^{o}C versus hot 50^{o}C & cold 4^{o}C).
  - Permeability of bio-treated soil.
  - Soil healing and self-healing.
- Marine Environment (control of coastal erosion).
- Construction Materials (production of bio-bricks).
- Geothermal Energy (soil thermal conductivity).

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Ground Improvement

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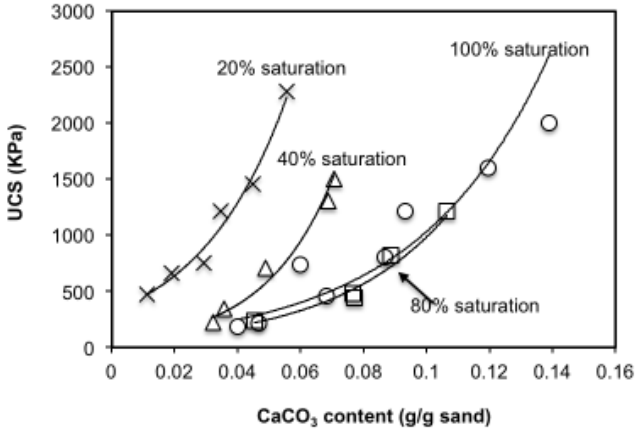
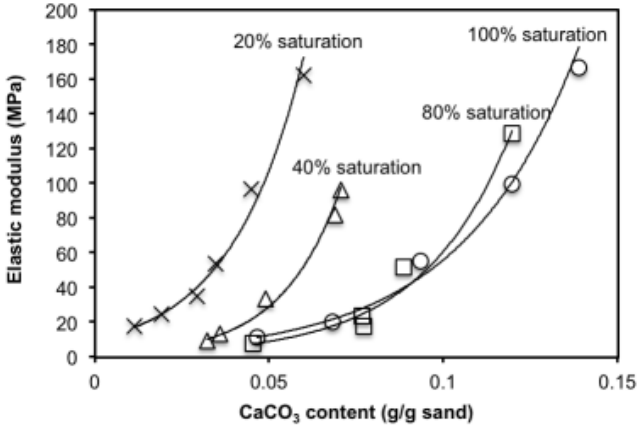
Degree of Saturation

- The increase in shear strength or elastic modulus is directly proportional to the increase in calcite content.
- At the same calcite content, soil treated at lower degree of saturation exhibits higher values of shear strength or elastic modulus.

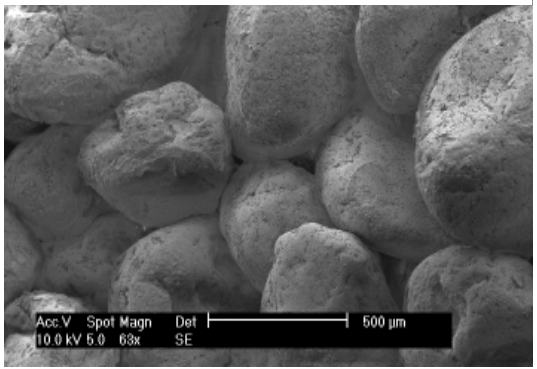




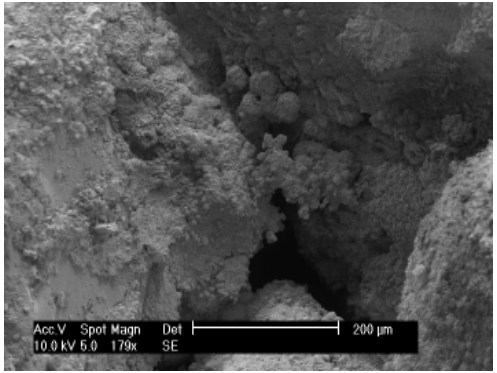
Cheng, L., Cord-Ruwisch, R., and Shahin, M. A. (2013). "Cementation of sand soil by microbial induced calcite precipitation at various degrees of saturation." *Canadian Geotechnical Journal*, 50(1), 81-90.

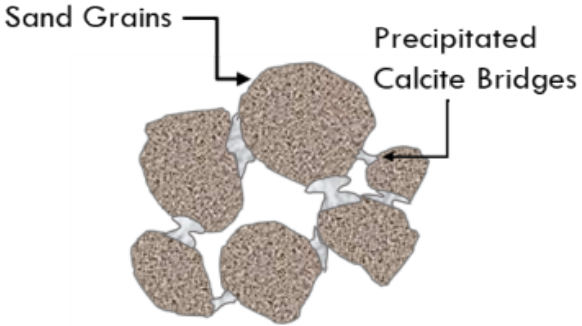
Degree of Saturation

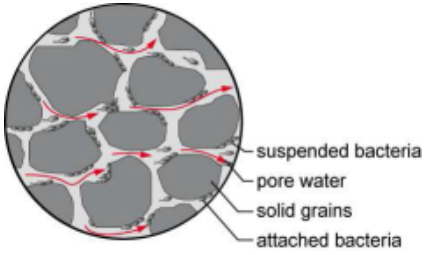
Low degree of saturation

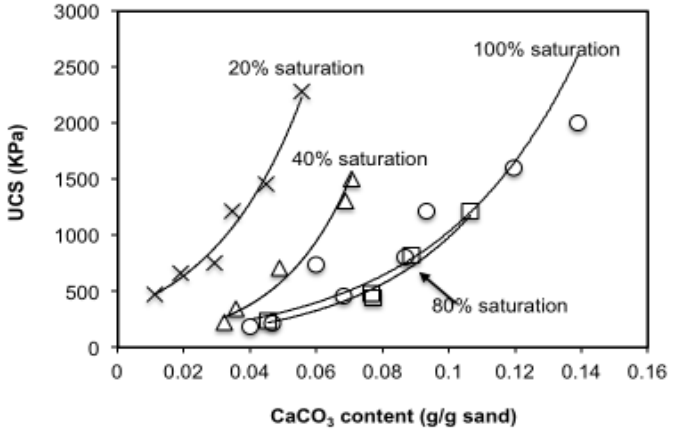


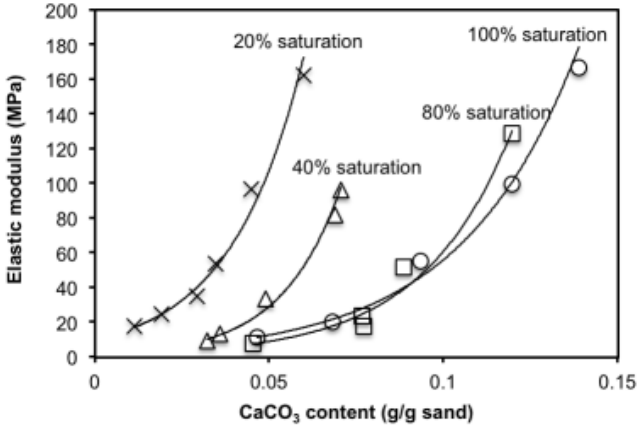
High degree of saturation





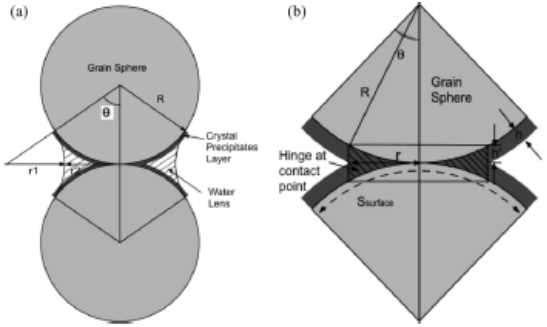


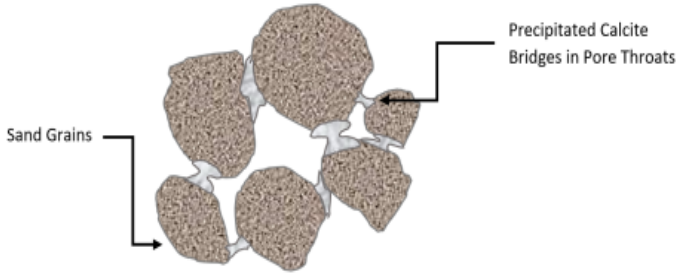


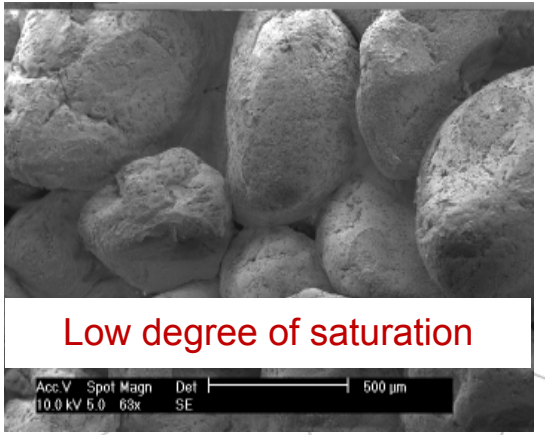


Cheng, L., Cord-Ruwisch, R., and Shahin, M. A. (2013). "Cementation of sand soil by microbial induced calcite precipitation at various degrees of saturation." *Canadian Geotechnical Journal*, 50(1), 81-90.

Degree of Saturation





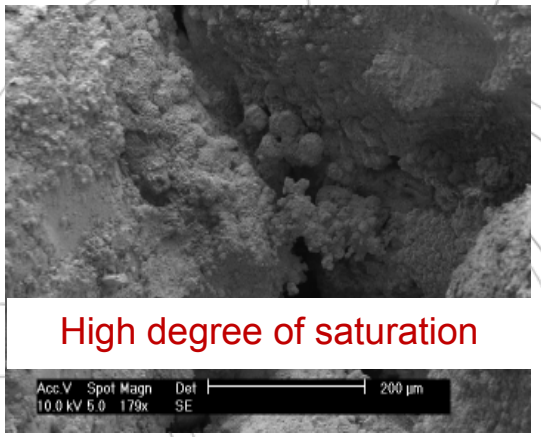


Low degree of saturation

$$V_{hinges} = \frac{6V_{soil}}{5.66R^3}\left[2\pi r^2 h' - (2\pi/3)h'^2(3\sqrt{(R+h)^2 - R^2} - h')\right]$$

$$h = \frac{\left(\frac{m_{crystals} \times V_{soil}}{\rho_{crystals}}\right)\left(\frac{V_{void} \times S}{2\pi R^3[1/\cos\theta - 1]^2[1-(2\pi/2-\theta)\tan\theta}\right)}{2\pi(R+h)^2[R-(R+h)\cos\theta]}$$

$$h' = R - \sqrt{R^2 - r^2}$$

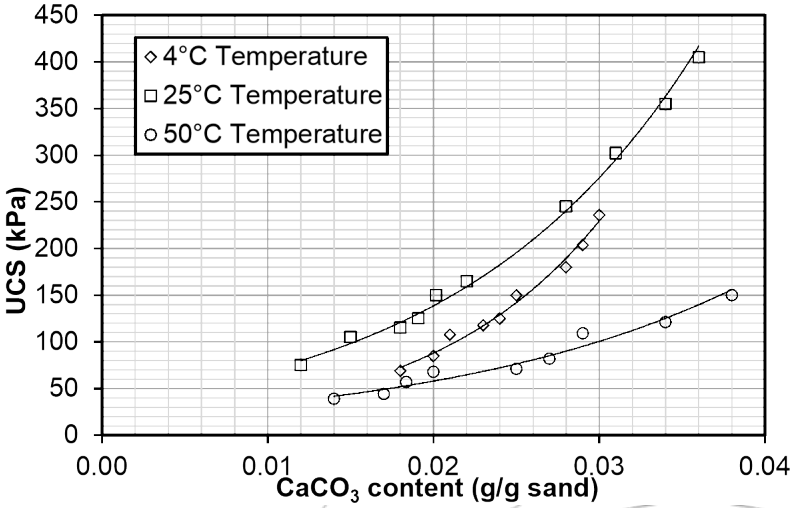


High degree of saturation

Cheng, L., Cord-Ruwisch, R., and Shahin, M. A. (2013). "Cementation of sand soil by microbial induced calcite precipitation at various degrees of saturation." *Canadian Geotechnical Journal.*, 50(1), 81-90.

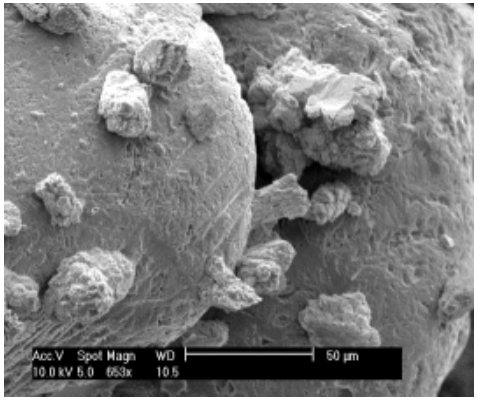
Degree of Temperature

- UCS increases with the increase of the amount of calcite content, for all weather conditions.
- MICP is more efficient for normal weather than cold and hot weather conditions, and cold weather is better for MICP treatment than hot weather.

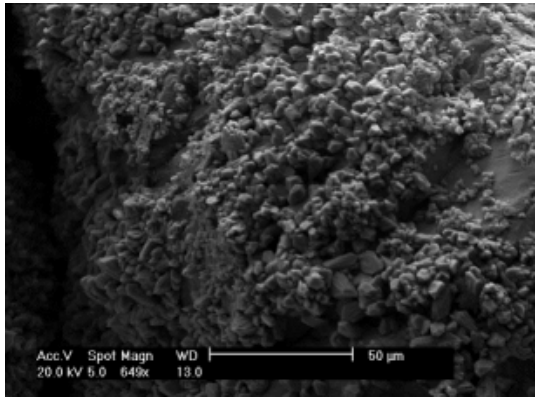


Cheng, L., Shahin, M. A., and Mujah, D. (2016). "Influence of key environmental conditions on microbially induced cementation for soil stabilization." ASCE, *Journal of Geotechnical & Geoenvironmental Engineering*, 143(1), 04016083.

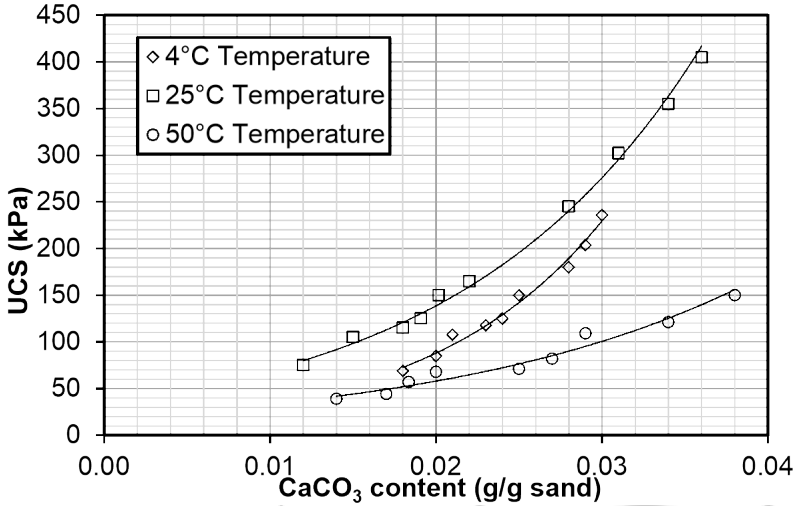
Degree of Temperature



Normal weather (25°C)



Hot weather (50°C)

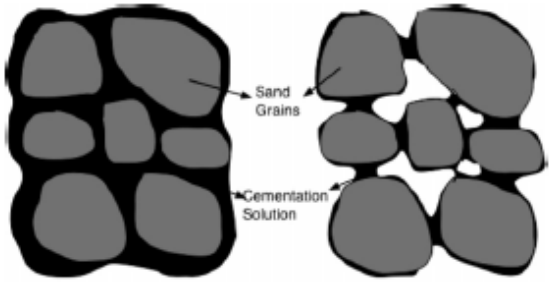


- At 50°C, the rate of calcite growth is faster than that at 25°C leading to small size crystals.
- At 4°C the rate of calcite growth is slower than that of 25°C also leading to small size crystals.

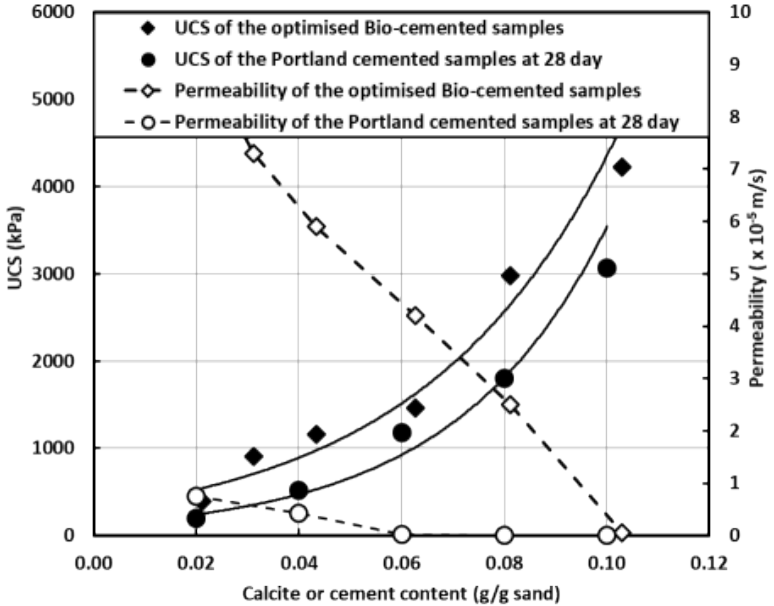
Cheng, L., Shahin, M. A., and Mujah, D. (2016). "Influence of key environmental conditions on microbially induced cementation for soil stabilization." ASCE, *Journal of Geotechnical & Geoenvironmental Engineering*, 143(1), 04016083.

Soil Permeability

- MICP has a tendency of decreasing permeability of treated soils with the increase of produced calcite but it retains sufficient soil permeability compared to OPC treated soils.



OPC-cementation Bio-cementation



Mujah, D., Cheng, L., and Shahin, M. A. “Microstructural and geo-mechanical study on bio-cemented sand for optimization of MICP process” *Journal of Materials in Civil Engineering*, 31(4), 04019025(1-10).

Soil Healing and Self-healing

Damaged bio-cemented sample (UCS = 790 kPa)

Bio-healed sample (UCS = 710 kPa) (strength regain = 90%)

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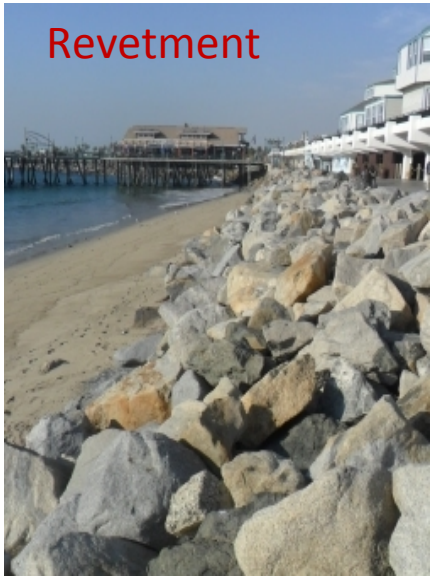
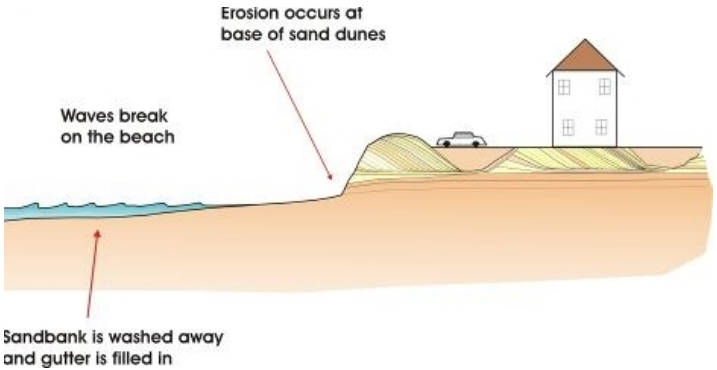
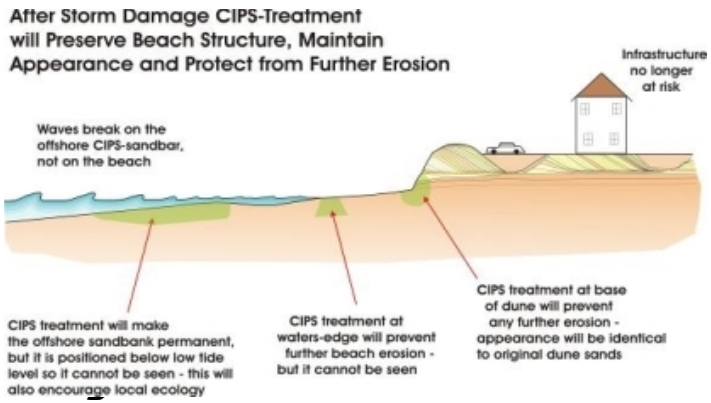
Soil Coastal Erosion

- Over 31,000 kilometres of Australian coastline is vulnerable to coastal erosion.
- Over $226 billion dollars of properties and infrastructure facilities are threatened.



Coastal Soil Erosion



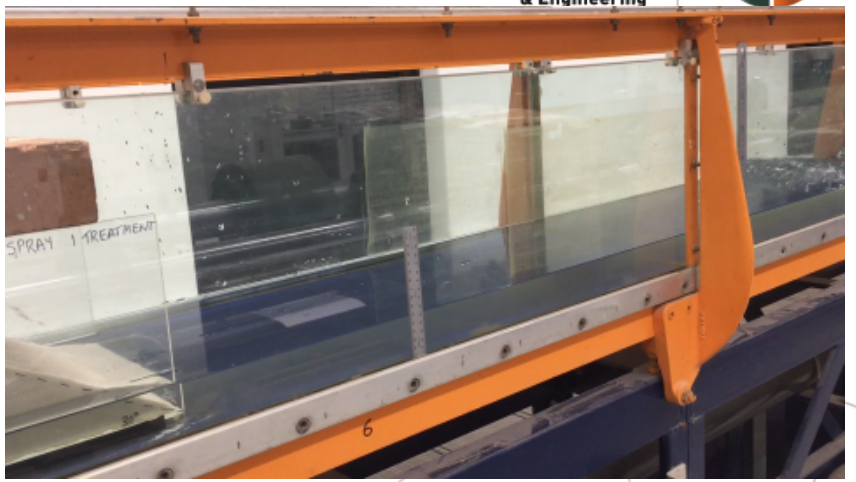


Ability of bacteria to survive for a long time in marine environment

Soil Coastal Erosion

Wave flume

Before wave application



After wave application

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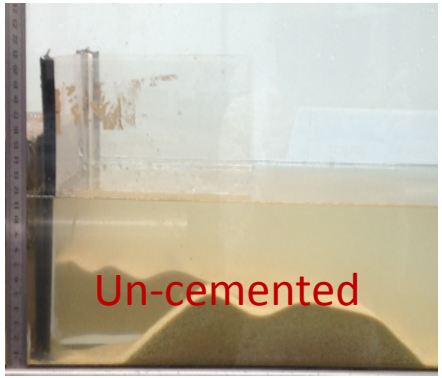
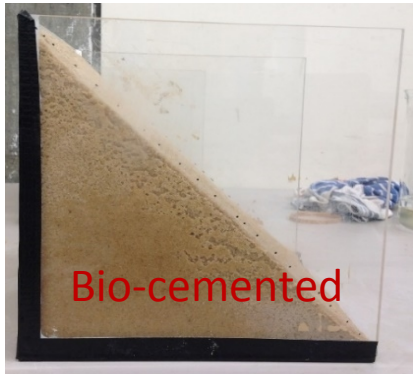
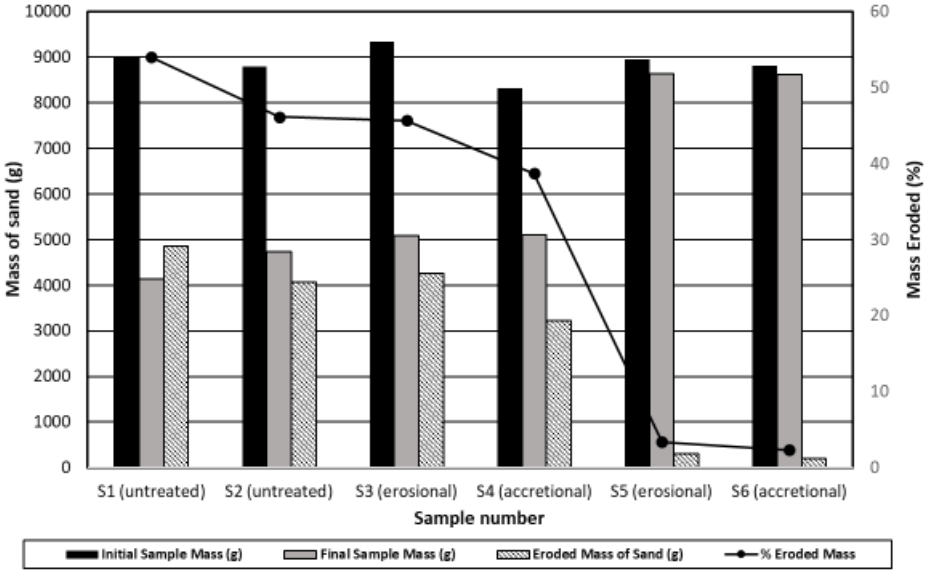
Soil Coastal Erosion





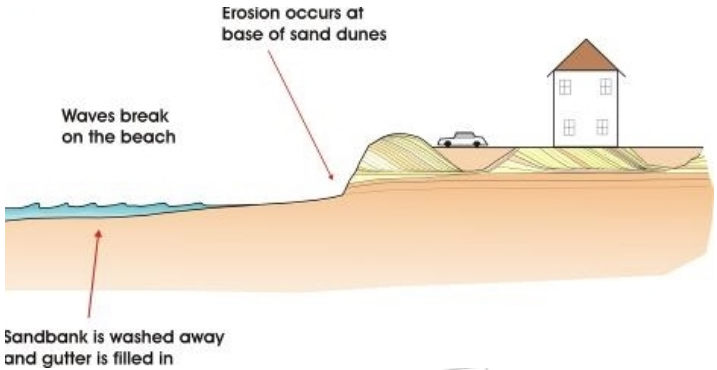
After wave application

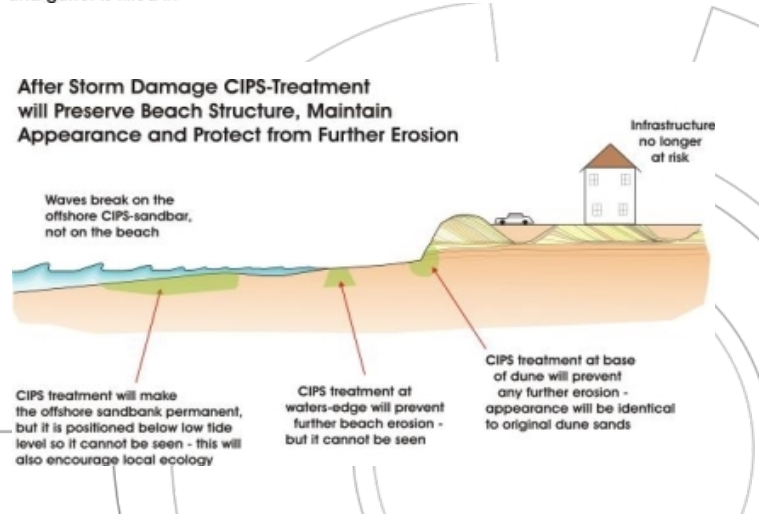


Shahin, M. A., Jamieson, K., and Cheng, L. (2020). “Microbial-induced carbonate precipitation for coastal erosion mitigation of sandy slopes” Geotechnique Letters, 10(3), 211-215.

Coastal Soil Erosion

- Feasibility of providing continuous source of calcium ions from seawater.
- Treatment by flushing is provided naturally via tidal wave action, leading to reduction in material and operation cost.





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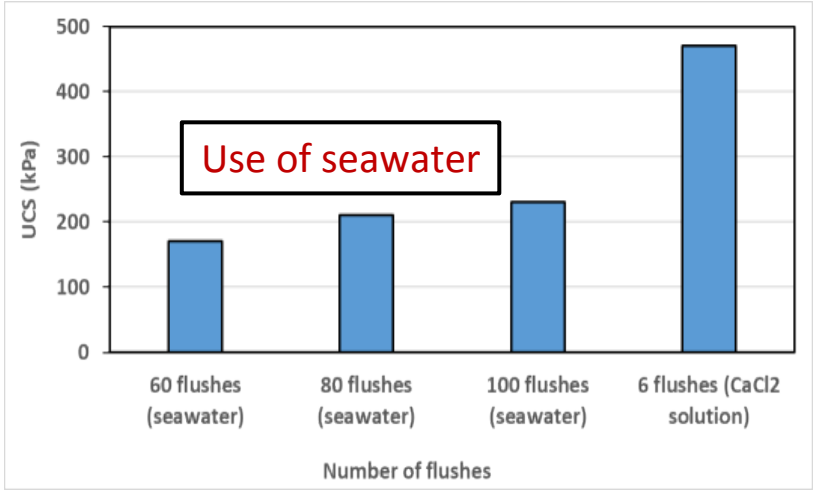
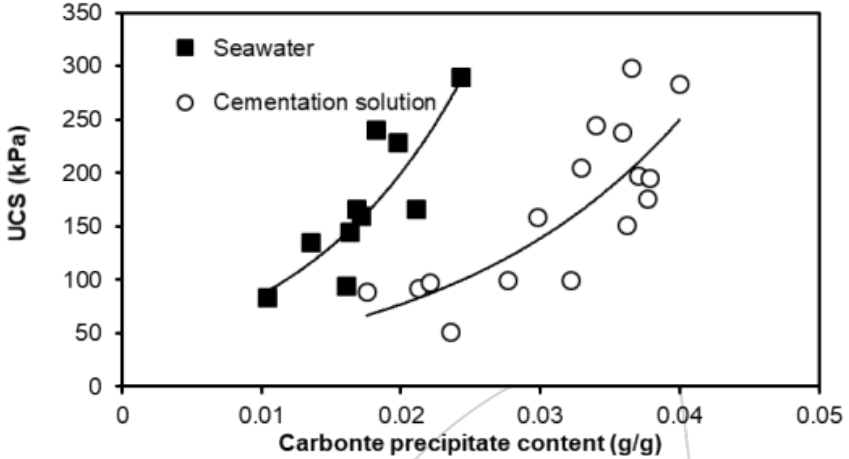
Soil Coastal Erosion





Cheng, L., Shahin, M. A., and Cord-Ruwisch, R. (2014). "Bio-cementation of sandy soil using microbial-induced carbonate precipitation (MICP) for marine environments." Géotechnique, 64(12), 1010-1013.

The efficiency of generated calcite using seawater (low calcium concentration) is higher than that of highly-concentrated commercial calcium chloride

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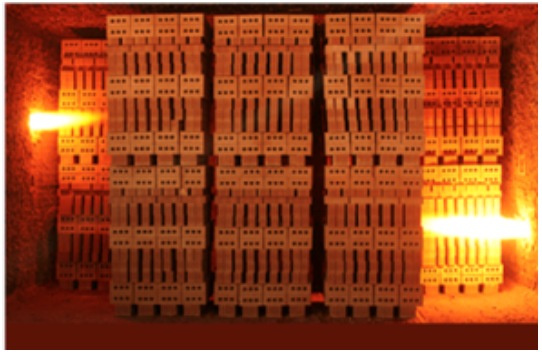
Production of Bio-Bricks

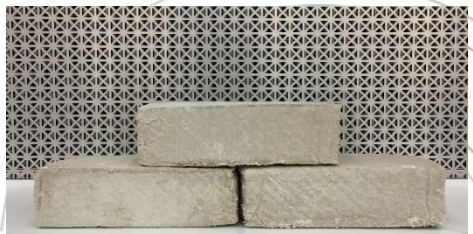


Fired-clay bricks

OPC bricks

Prepare sand bio-brick

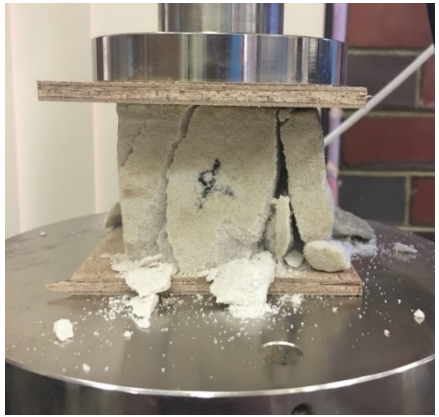
Bio-treatment by submergence



Final product (bio-bricks)

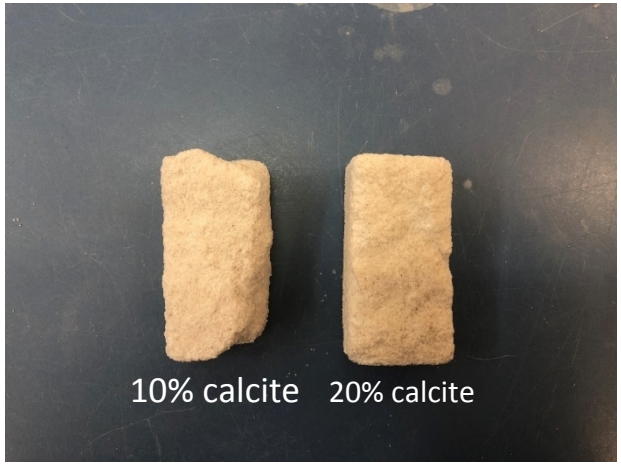
Production of Bio-Bricks

- Compressive strength.
- Durability: salt attack resistance & freezing-thawing resistance .
- Fire resistance: UCS at 200°C, 400°C, 600°C.



Compressive strength

UCS = 5.6 MPa at 20% calcite content



Salt attack samples after 8 cycles

Fire resistance

200°C

400°C

600°C

Cheng, L., Kobayashi, T., Shahin, M. A. (2020). "Microbially induced calcite precipitation for production of "bio-bricks" treated at partial saturation condition" Construction and Building Materials, 231, 117095(1-9).

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Geothermal Energy

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Soil Thermal Conductivity

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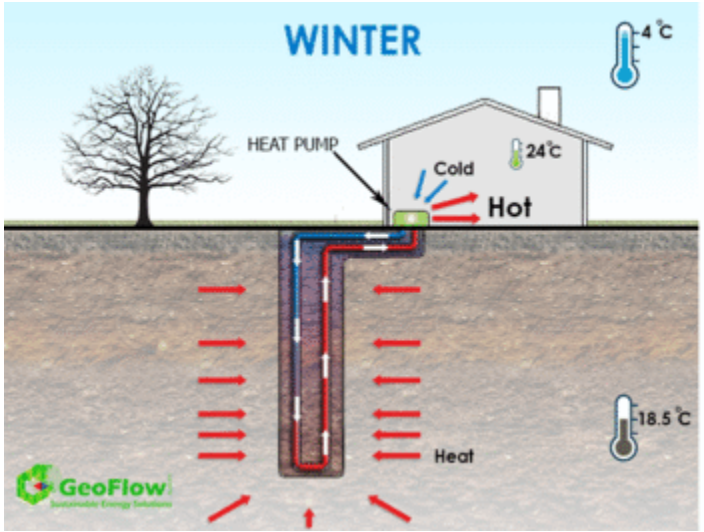

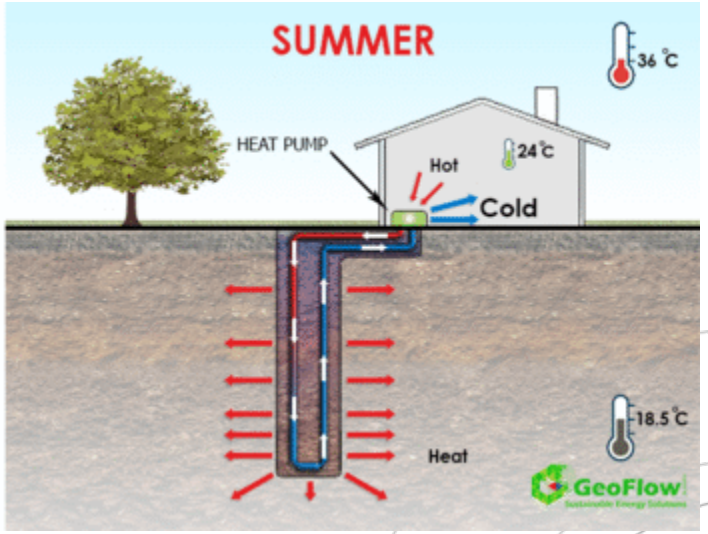

Geothermal Energy: Vertical Pipe Loop

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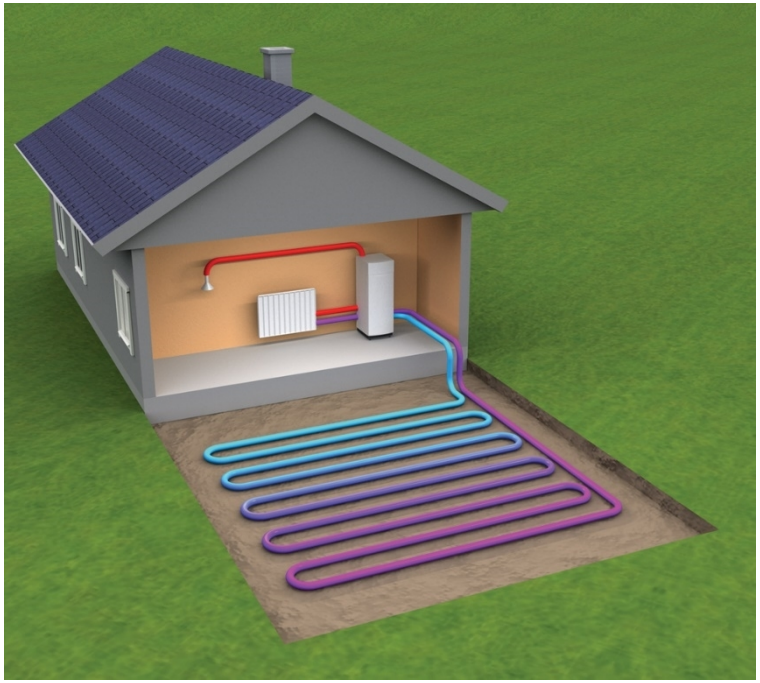
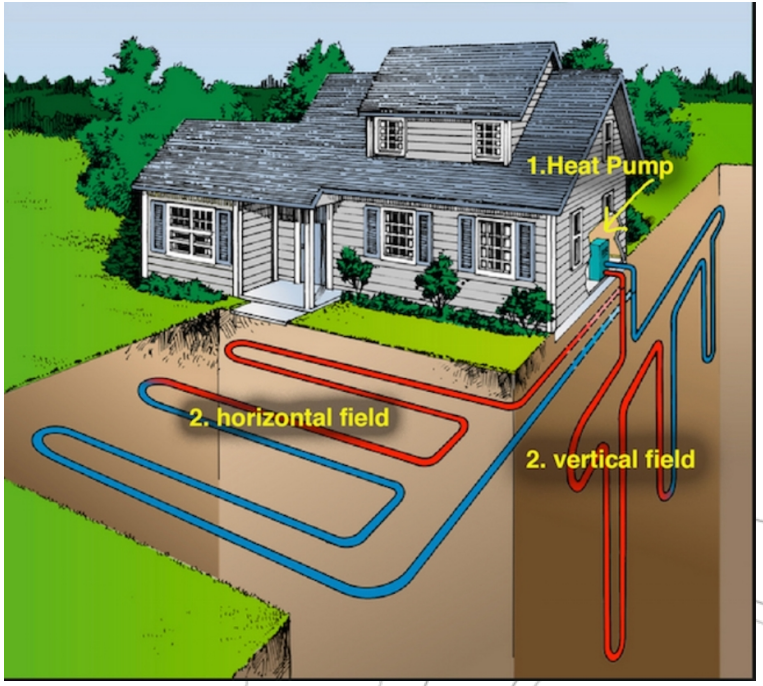
Soil Thermal Conductivity



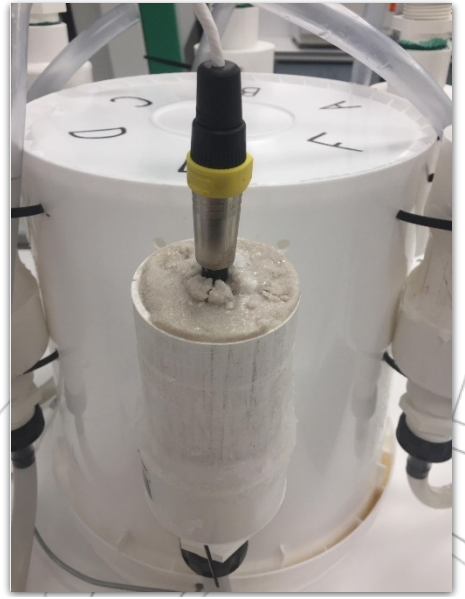
Horizontal Pipe Loop



Horizontal + Vertical Pipe Loops

Soil Thermal Conductivity

Sample Number	$CaCl_2$ Content (%)	$MgCl_2$ Content (%)
1	100	0
2	90	10
3	80	20
4	70	30
5	60	40
6	50	50
7	40	60
8	30	70
9	20	80
10	10	90
11	0	100



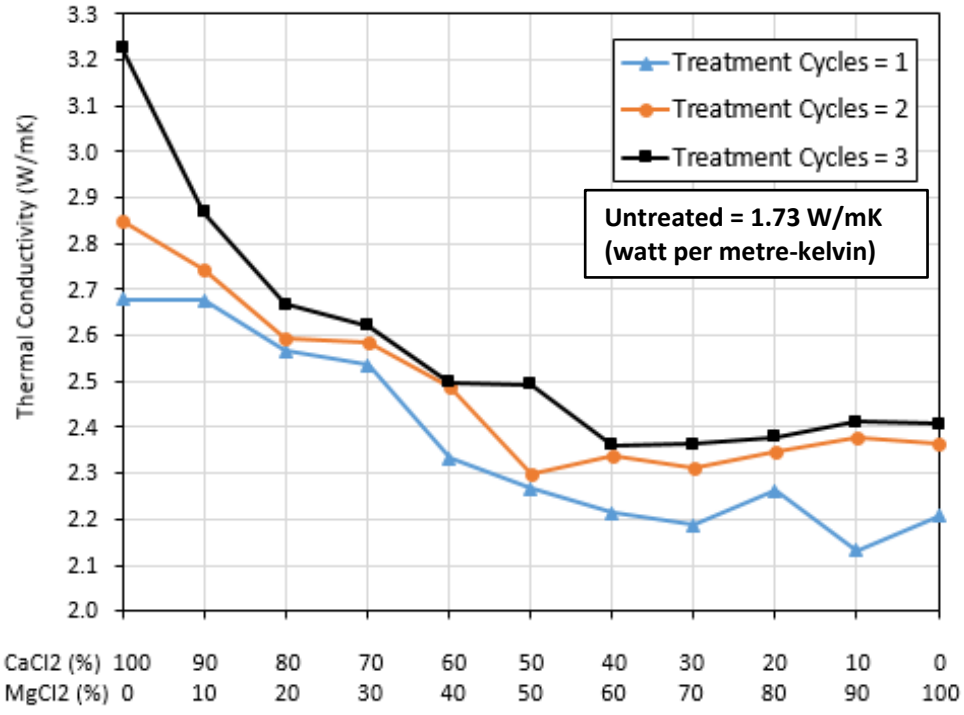
Thermal conductivity testing

Cheng, L., Afur, N., and Shahin, M. A. (2021). “Bio-cementation for improving soil thermal conductivity”, Sustainability, 13, 10238(1-12).

Soil Thermal Conductivity

- Cementation solution with 100% calcium chloride after 3 treatment cycles gives the best results.
- Almost two times improvement in thermal conductivity is achieved.

Cheng, L., Afur, N., and Shahin, M. A. (2021). “Bio-cementation for improving soil thermal conductivity”, Sustainability, 13, 10238(1-12).



Soil Thermal Conductivity

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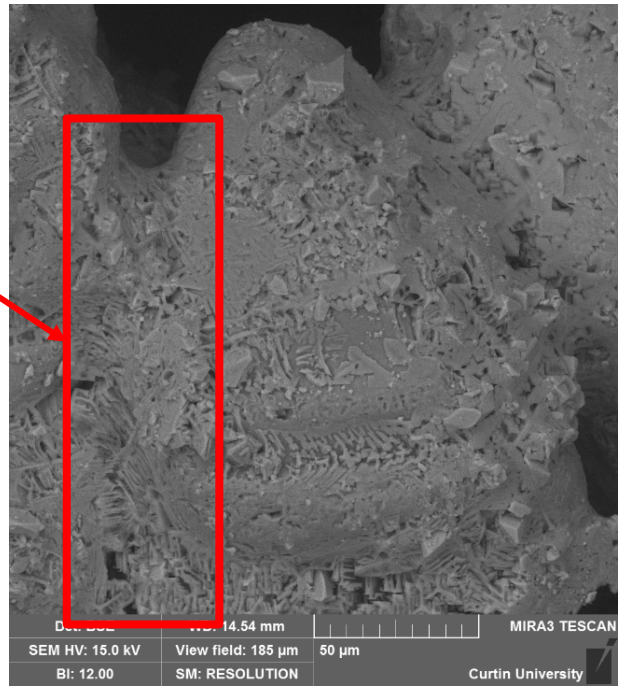
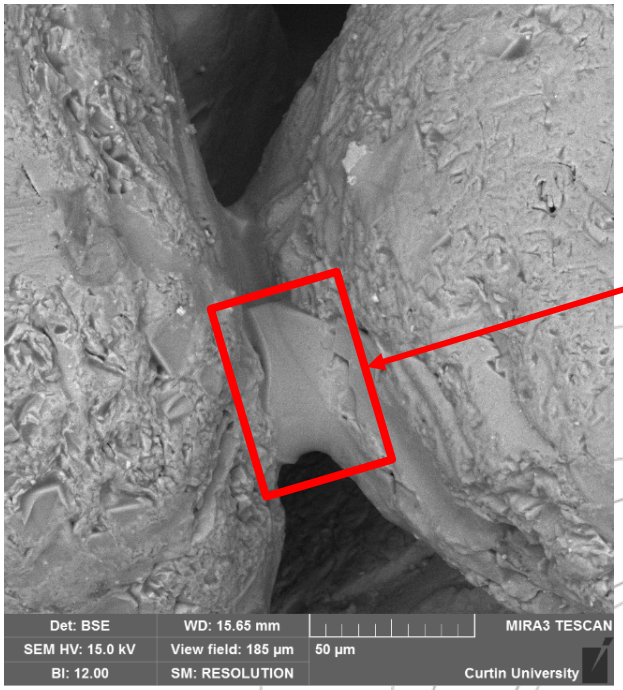
100% Calcium Chloride

100% Magnesium Chloride

Calcium carbonate





Magnesium carbonate

Organized by

Cheng, L., Afur, N., and Shahin, M. A. (2021). "Bio-cementation for improving soil thermal conductivity", Sustainability, 13, 10238(1-12).

Concluding Remarks

- Bio-cementation is a promising sustainable and eco-friendly technique that can be used for ground improvement and soil healing.
- Better bio-cementation treatment can be obtained for treatment at as low degree of saturation as 20% and normal weather condition (± 25^{o}C).
- Bio-cementation is a viable solution for control of coastal erosion, production of construction materials (bio-bricks) and improving soil conductivity in extraction of geothermal energy.
- Despite its success, bio-cementation still has some disadvantages related to its cost and field implementation, as well as treating fine soils (clay) but research is on-going to overcome such problems.

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