Bacteria Based Self-Healing Concrete: A review

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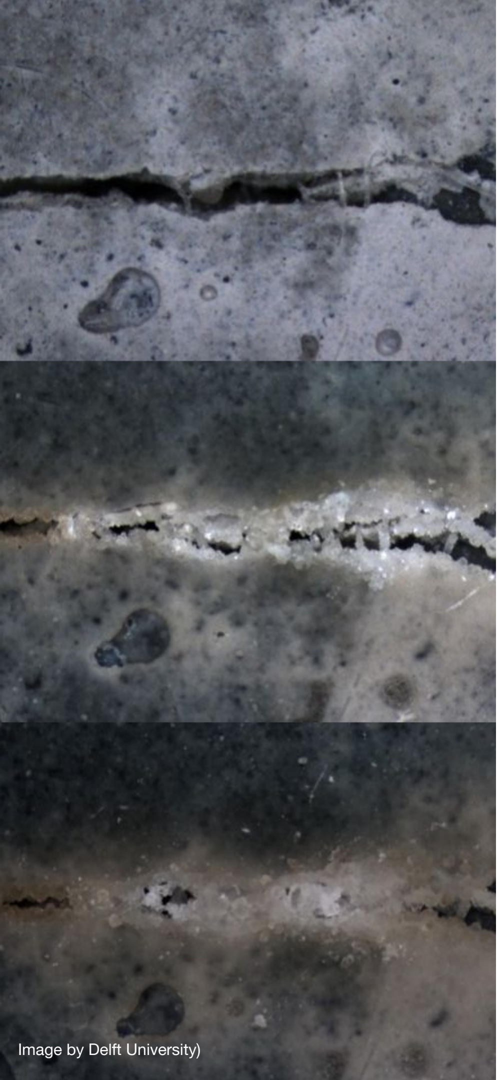


Image by Delft University)

Repairing Cracks in Concrete

- Bacteria precipitate calcium carbonate

Definition: Lightweight aggregates are construction materials with bulk density (weight of soil in given volume) lower than common construction aggregates (e.g. sand, gravel, crushed stone)

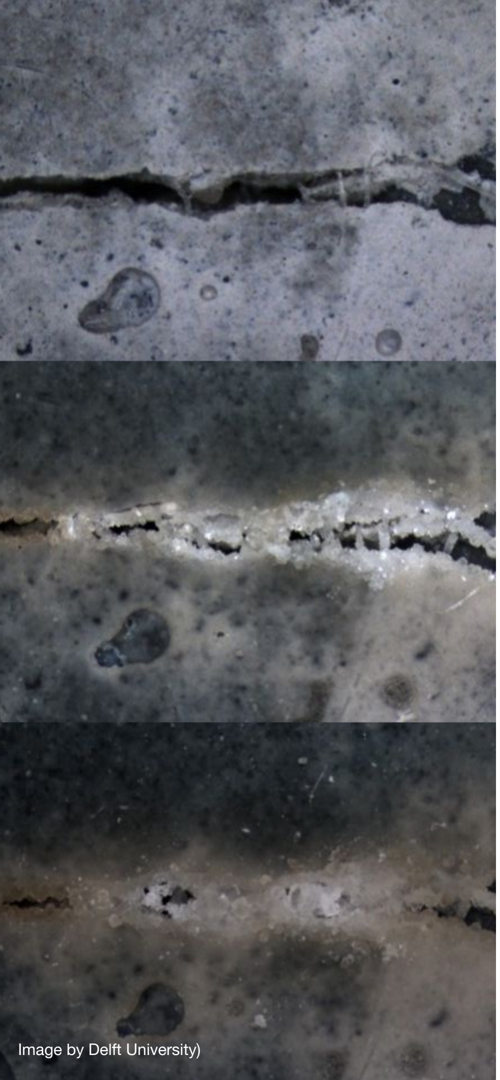


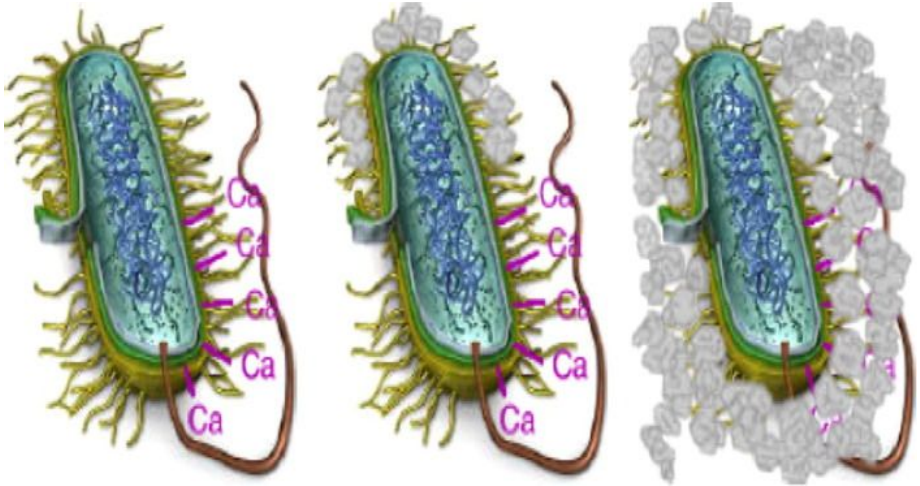
Image by Delft University)

Repairing Cracks in Concrete

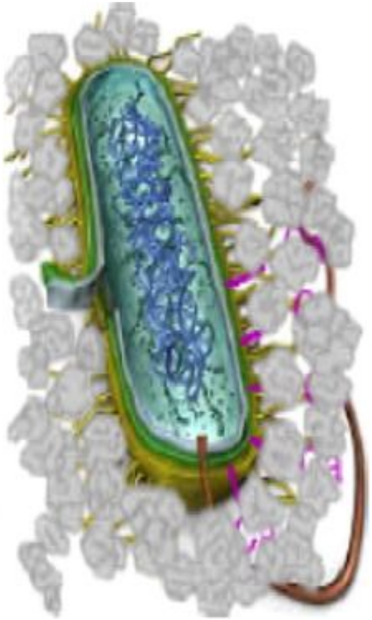
- Lightweight aggregates are efficient carriers for self-healing bacteria
    - Increases structural durability
- Promising results in remediating cracks in early stages

Repairing Cracks in Concrete

- **Objective of study:** Review properties of concrete which vary with addition of bacteria and the types of bacteria used for calcium carbonate precipitation



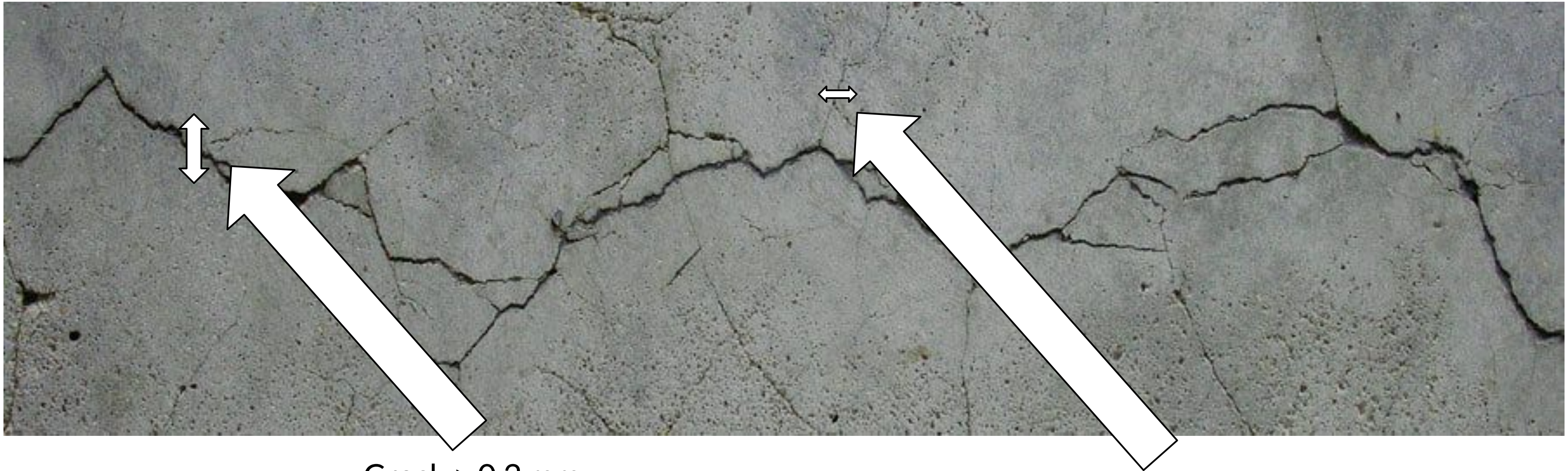
Repairing Cracks in Concrete



- Figure represents possible self-healing mechanism by application of cementitious materials in concrete

Definition: Cementitious materials are building materials mixed with a liquid, such as water, to form a plastic paste, to which an aggregate is added

Self Healing Approach

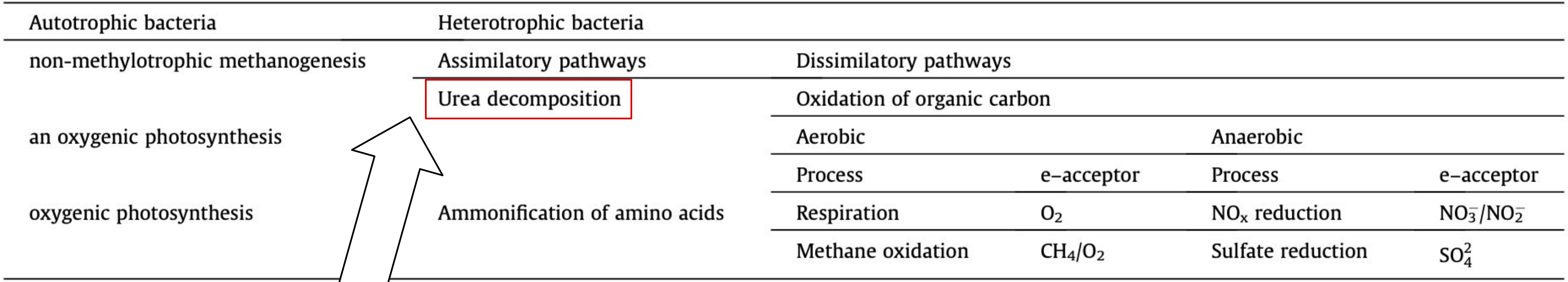


Crack > 0.2 mm

Crack < 0.2 mm

pH of concrete is very alkaline → bacteria need to withstand that!

Self Healing Approach



Autotrophic bacteria	Heterotrophic bacteria				
non-methylotrophic methanogenesis	Assimilatory pathways	Dissimilatory pathways			
	Urea decomposition	Oxidation of organic carbon			
an oxygenic photosynthesis		Aerobic		Anaerobic	
		Process	e–acceptor	Process	e–acceptor
oxygenic photosynthesis	Ammonification of amino acids	Respiration	O_2	NO_x reduction	NO_3^-/NO_2^-
		Methane oxidation	CH_4/O_2	Sulfate reduction	SO_4^2

Main focus of today’s presentation

Self Healing Approach

1. Bacillus subtilis
2. Bacillus aerius
3. Bacillus megaterium
4. Bacillus sphaericus
5. Sporosarcina pasteurii

Can precipitate at a high pH.

Urealysis to convert urea into concrete, as seen in Bacillus Sphaericus

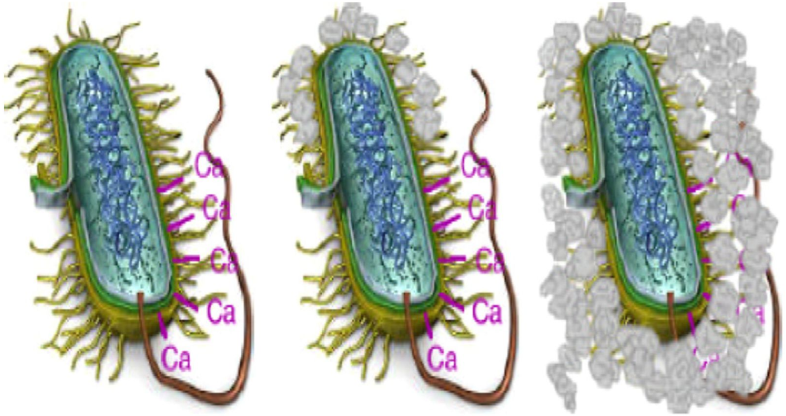
Self Healing Approach*

1. $\underbrace{CO(NH_2)_2}_{\text{urea}} + H_2O \rightarrow \underbrace{NH_2COOH}_{\text{intermediate acid}} + NH_3$	Adding water to urea breaks it down into an intermediate acid and ammonia.
2. $NH_2COOH + H_2O \rightarrow \underbrace{NH_3}_{\text{ammonia}} + \underbrace{H_2CO_3}_{\text{carbonic acid}}$	Adding more water breaks the acid down into more ammonia and carbonic acid.
3. $H_2CO_3 \leftrightarrow HCO_3^- + H^+$	Carbonic acid is in equilibrium with bicarbonate and H+ ions.
4. $2\,NH_3 + 2\,H_2O \leftrightarrow 2\,NH_4^+ + 2\,OH^-$	Ammonia is in equilibrium with ammonium and OH- ions.
5. $HCO_3^- + H^+ + 2\,NH_4^+ + 2\,OH^- \leftrightarrow \underbrace{CO_3^{2-}}_{\text{carbonate ion}} + 2\,NH_4^+ + 2\,H_2O$	Carbonic acid is in equilibrium with the carbonate ion and water. The ammonium ion spectates.
C1. $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$	In the cell, adding the calcium ion to the carbonate ion makes calcium carbonate.

Urealysis to convert urea into concrete, as seen in Bacillus Sphaericus

* requires the bacterium to have the enzyme bacterial urease.

Self Healing Approach



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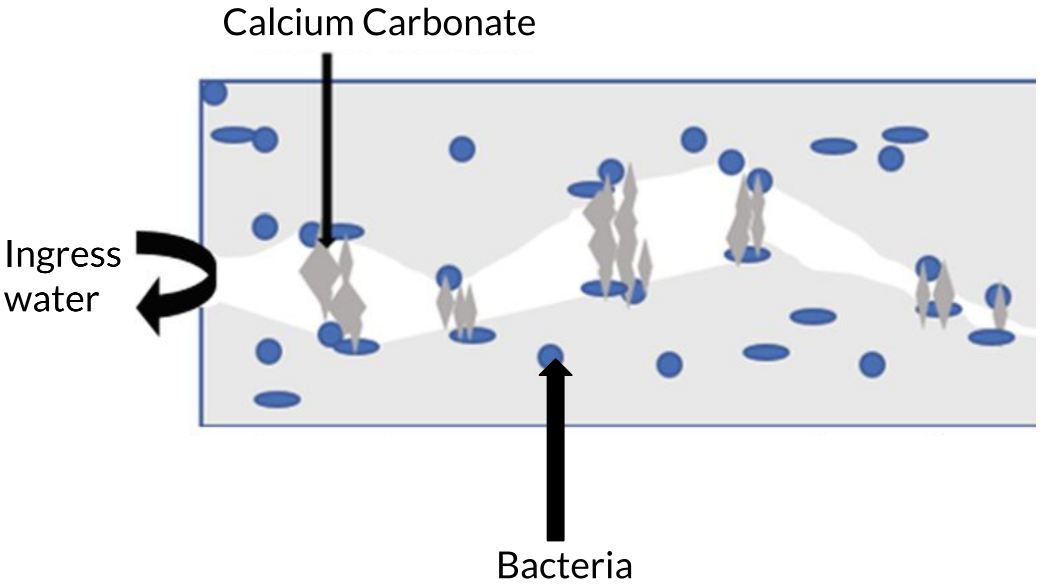
Self Healing Approach

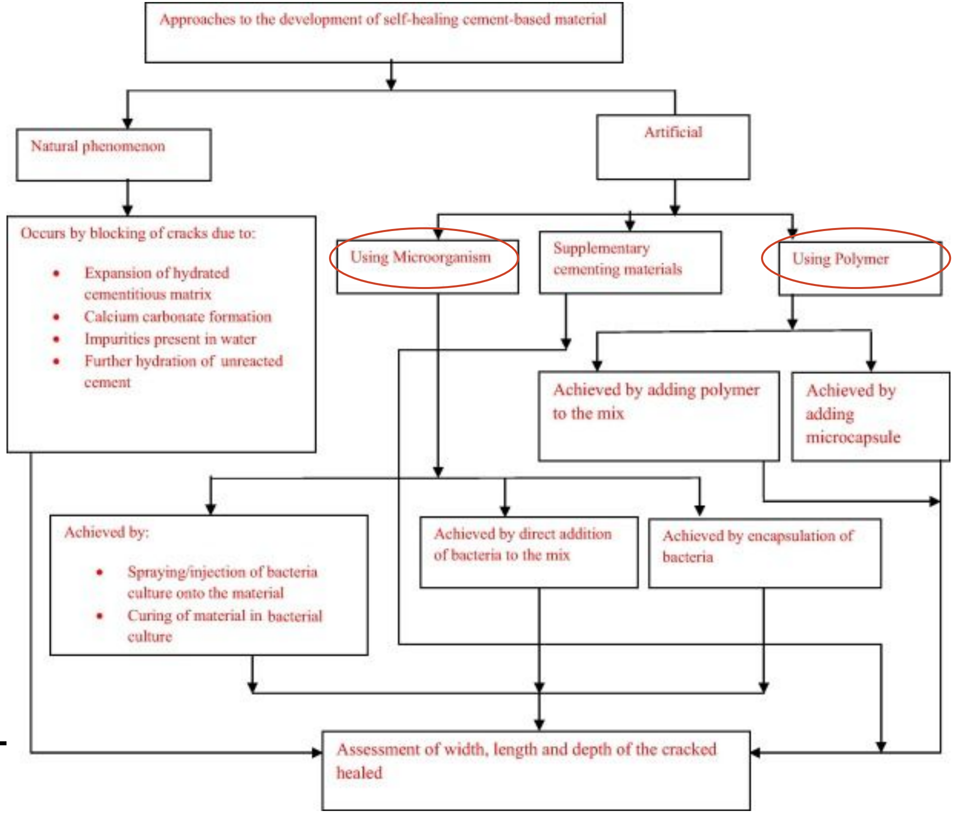


Urealysis to convert urea into concrete, as seen in Bacillus Sphaericus

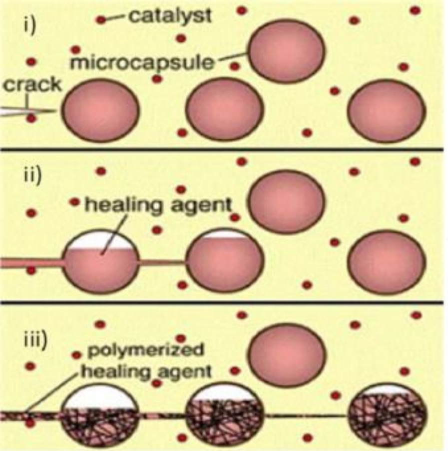
Applying Healing Agents to the Concrete

3 primary methods for incorporating healing agents:

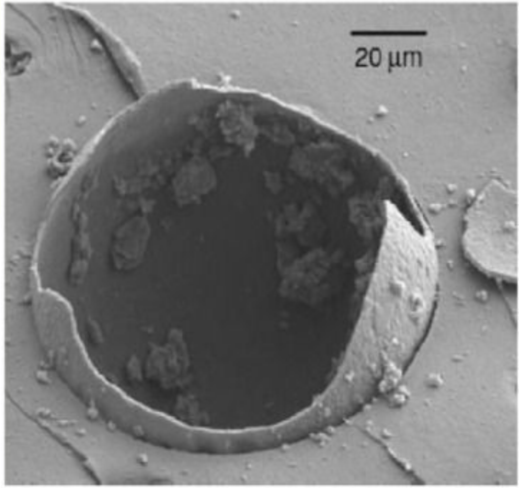
- Micro-encapsulation
- Bacteria direct application
- Bacteria and encapsulation



Micro-Encapsulation



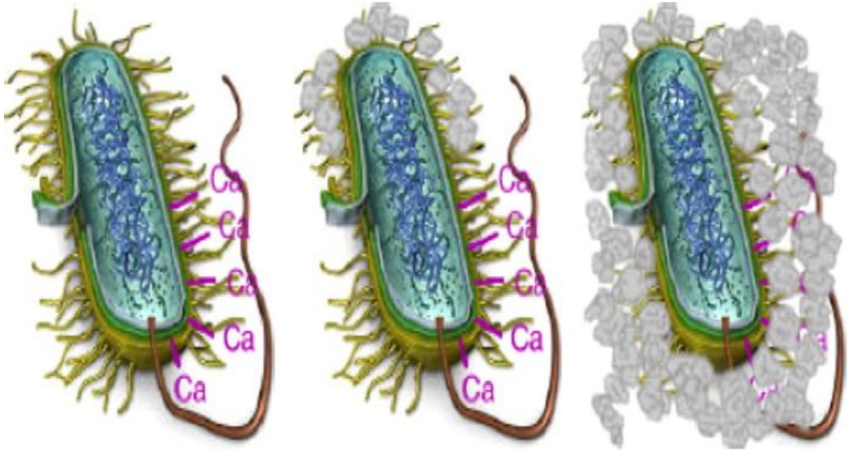
(a)



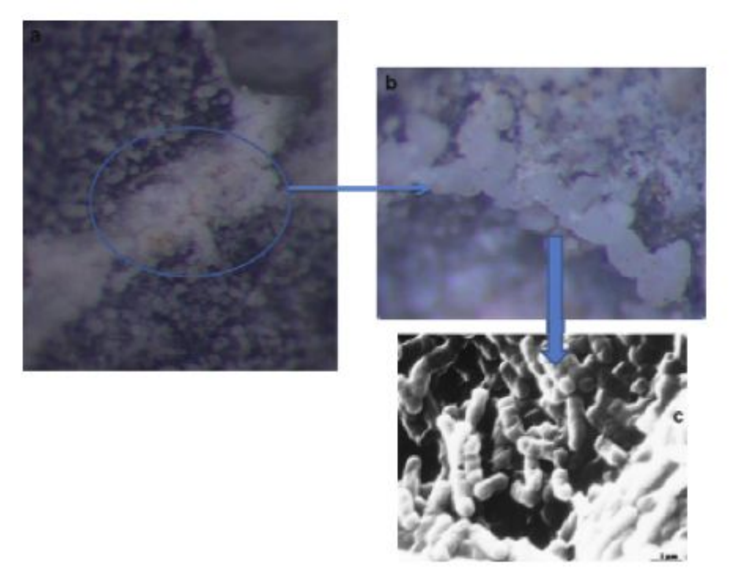
(b)

- Capsule Materials:
  - sodium silicate liquid , Zemac-400 powder, urea, ammonium chloride, resorcinol, Formaldehyde solution, commercial polyurethane (PU) prepolymer, and Desmodur L 75
- Once capsule is ruptured, healing agent is released to react with the catalyst and promote self healing
- Primary reaction is urealysis producing carbonate ions that react to form calcium carbonate

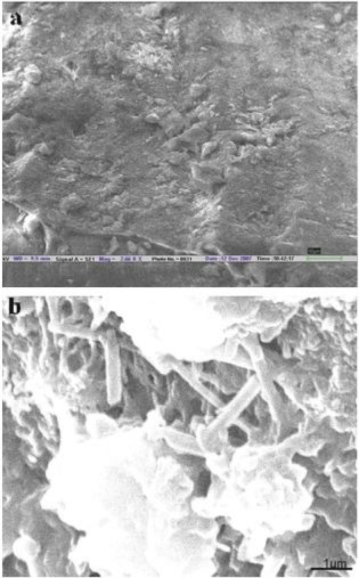
Bacteria Direct Application



- Bacterial cultures are mixed directly with cement mortar before pouring/setting
- Bacteria mediate the precipitation of minerals through **Biologically Induced Mineralization** (BIM)
  - negative charge of cell wall attracts Ca 2+ cations necessary for the precipitation of Calcium Carbonate
- Bacteria serve as nucleation sites for mineral deposition
- Faster rate of mineralization than inorganic mineralization



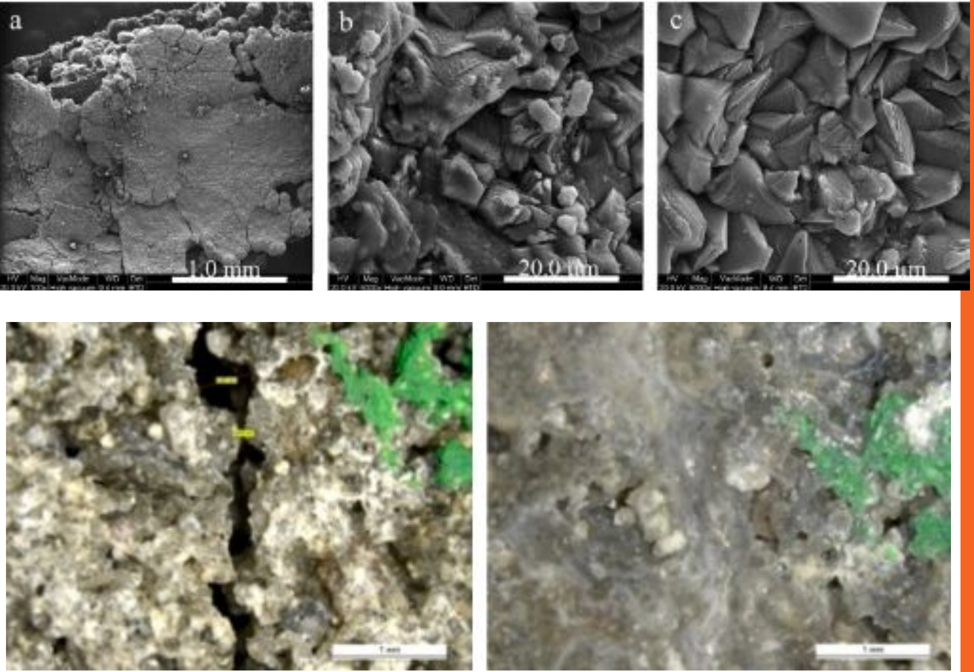
1) Microscopic image of: (a) crack remediated area, (b) enlarged portion of image a and (c) Electron micrograph showing bacteria embedded in crack remediated area.



2) matrix of cement mortar prepared without bacteria, vs a sample with a remediated crack, showing calcite crystals Bacillus sp. CT-5

*Figures from V. Achal, A. Mukerjee, M.S. Reddy
Biogenic treatment improves the durability and remediates the cracks of concrete structures
Constr. Build. Mater., 48 (2013), pp. 1-5

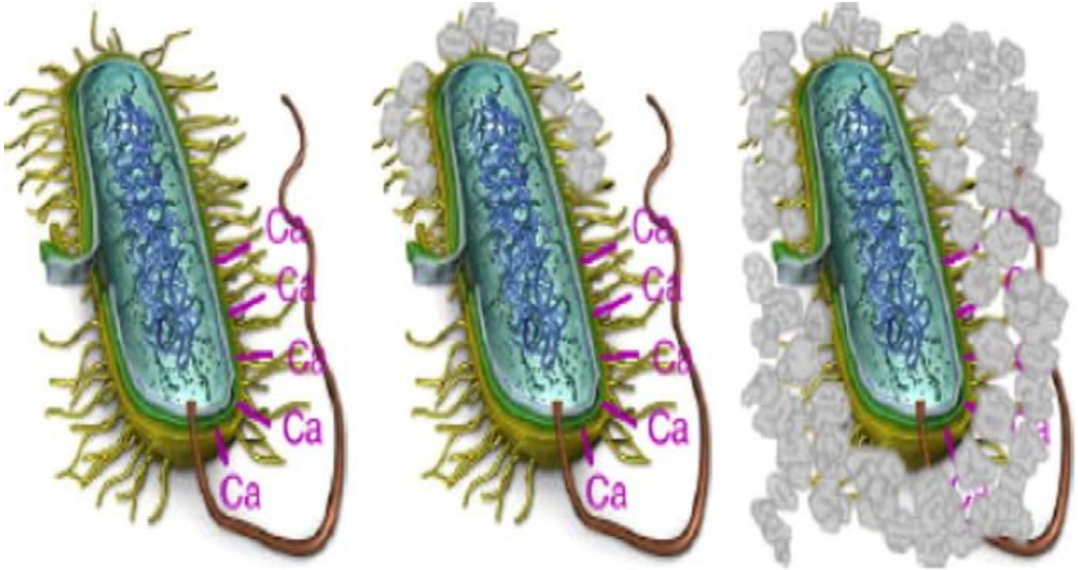
Bacteria and Encapsulation



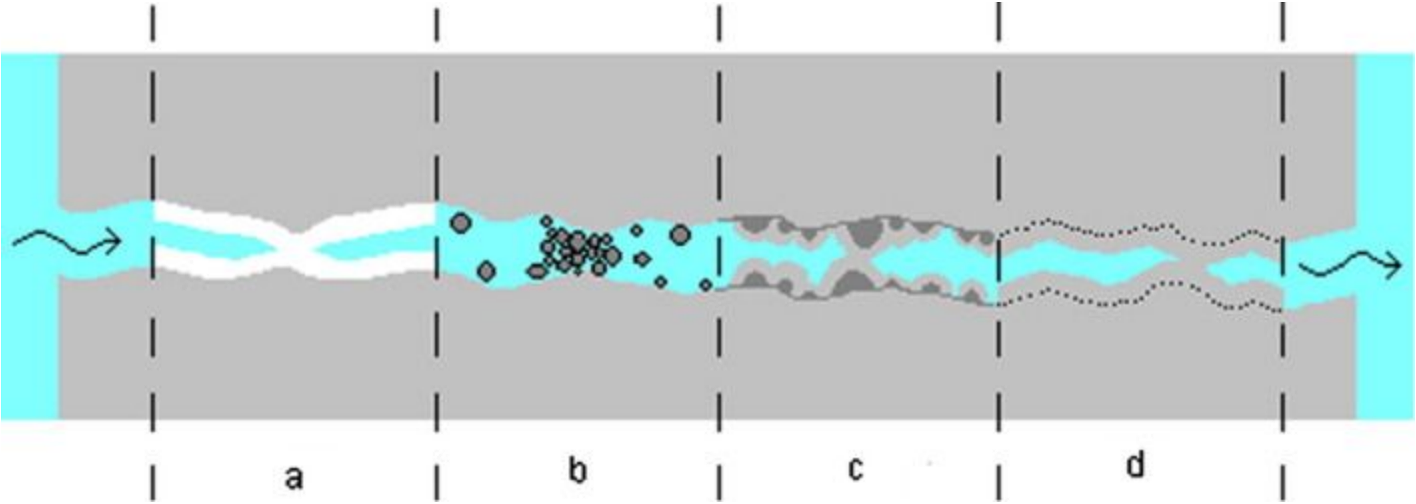
Figures from J.Y. Wang, D. Snoeck, S. Van Vlierberghe, W. Verstraete, N. De Belie
Application of hydrogel encapsulated carbonate precipitating bacteria for approaching a realistic self-healing in concrete
Constr. Build. Mater., 68 (2014), pp. 110-119

- Physical mechanism similar to micro-encapsulation
- Capsule protects bacteria from highly alkaline environment of concrete
  - Allows for the use of bacteria other than Bacillus sp which can withstand high pH
- Most modern methods utilize hydrogel capsules to enclose the bacteria

Formation of concrete



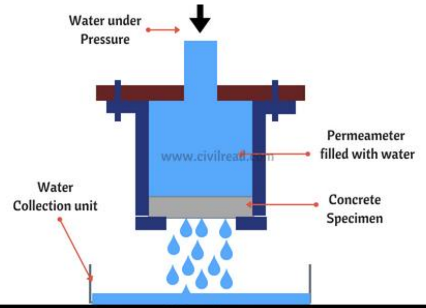
Hydration Kinetics



Compressive Strength

- Concrete must have high compressive strength
- Bacteria can increase strength by generating calcium carbonate
- Decreasing fly ash concentration → increased bacterial growth → increased calcium carbonate & compressive strength
- Variation in strength is also achieved by type of bacteria used and concentration of cells

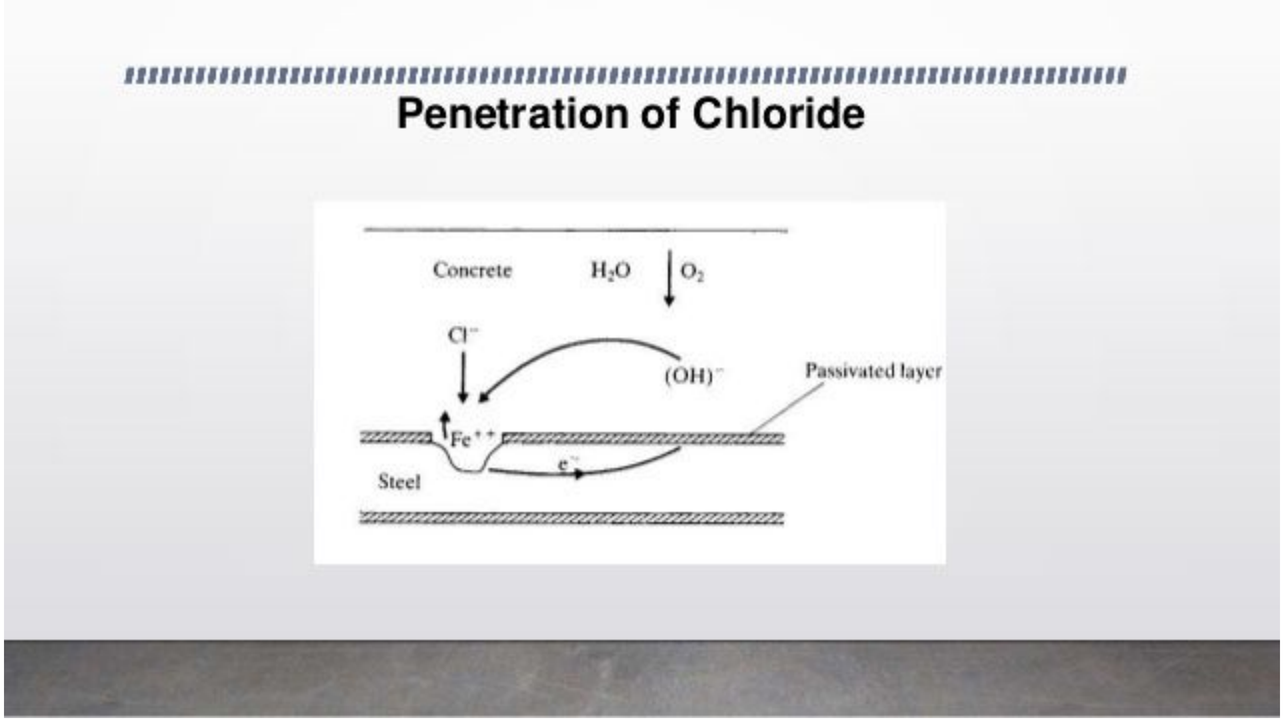
Water permeability



Water Permeability by Pressure test

- Bacteria decrease the ingress water permeability of concrete by building up calcium carbonate in pores
- Decrease in permeability means the concrete is more durable under high pressure and extreme conditions, making it better construction material

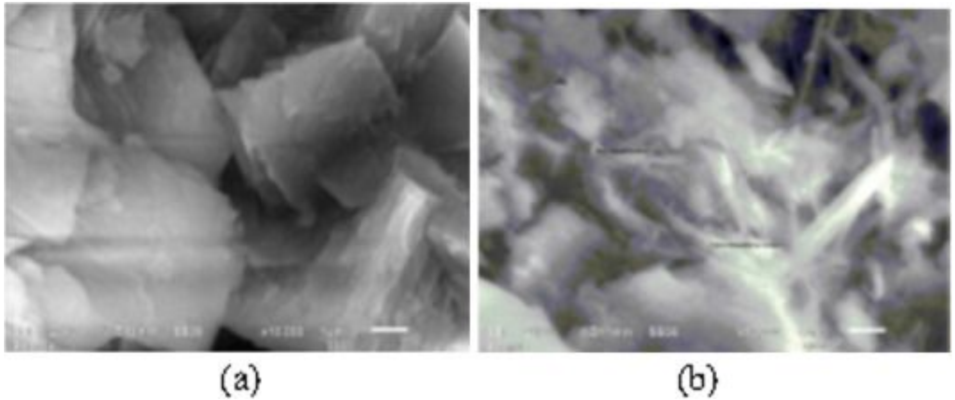
Chloride Ion Permeability



Penetration of Chloride

Microstructure

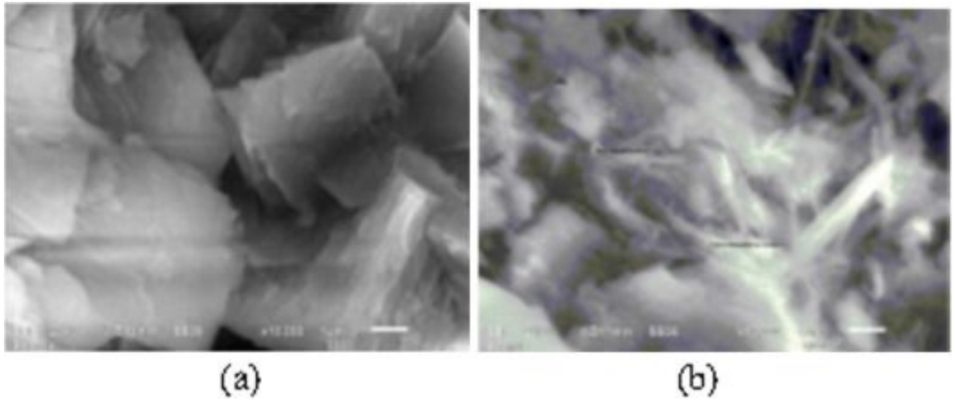
Definition: SEM analysis is a process that scans a solid inorganic sample with an electron beam to produce a magnified image



Microstructure

- Calcite precipitation in mortar and concrete visualized

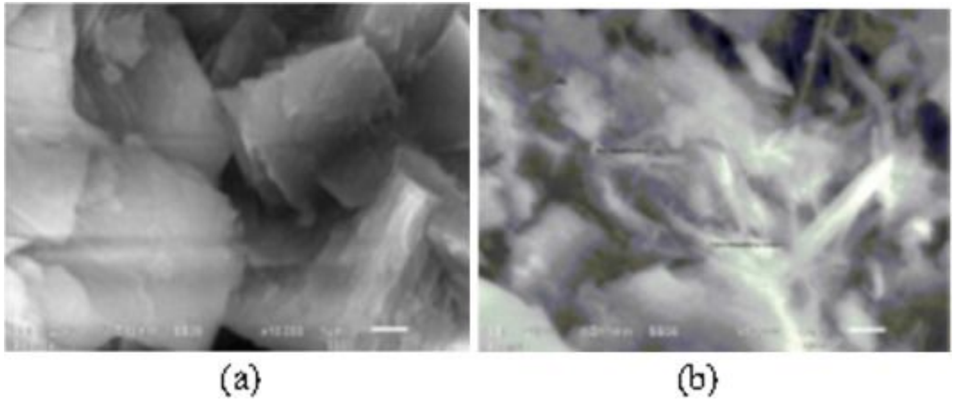
- Rod-shaped bacteria associated with calcite crystals



Microstructure

- SEM analysis shows different calcite crystals embedded with bacteria
- Deposition of calcium carbonate in concrete pores

control concrete

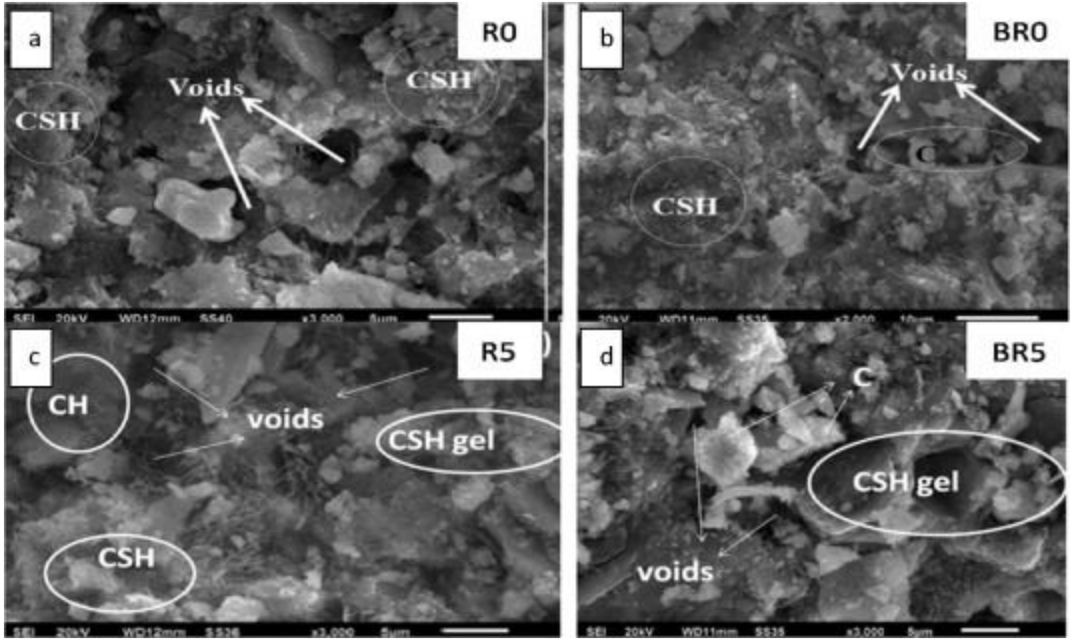


(a)

(b)

bacterial calcite precipitation in 10% silica fume concrete

Microstructure



normal concrete

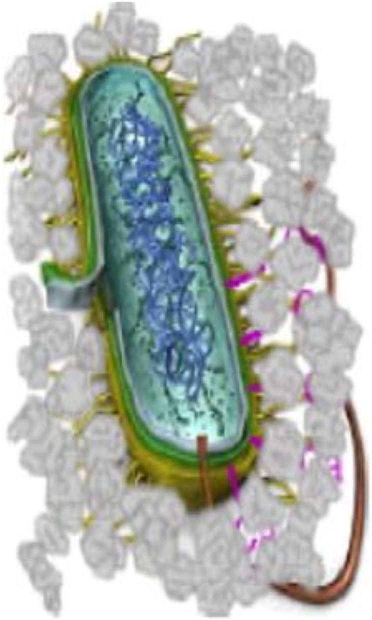
bacterial concrete

5% of RHA concrete

bacterial concrete with 5% RHA

Practical Applications

Conclusions



TLDR:

- → The creation of calcium carbonate through **urealysis** provides an eco friendly alternative to repair concrete
- → This method of crack repair has shown positive effects in the compressive strength of concrete

Strengths and limitations of the study:

- → Gave lots of statistics to back up the concept of having bacteria in concrete.
- → ***Very*** thorough.
- → Transition to large scale is daunting.
- → Assumes the reader is well versed in the bacterial concrete community as well as the concrete community in general.
- → Less than ideal amount of explanation on the ways of incorporating the bacteria into the concrete efficiently.

Discussion Questions

1. Where else could concrete made by urealysis be useful?
2. What other tests and indicators can be used to determine the strength and quality of concrete?
3. What problems could arise with the use of bacteria to facilitate a reaction?