Self-healing concrete
Autogenous and bio-enhanced crack-healing

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Self-healing concrete

1. Introduction: type of cracks and mechanisms of crack-healing

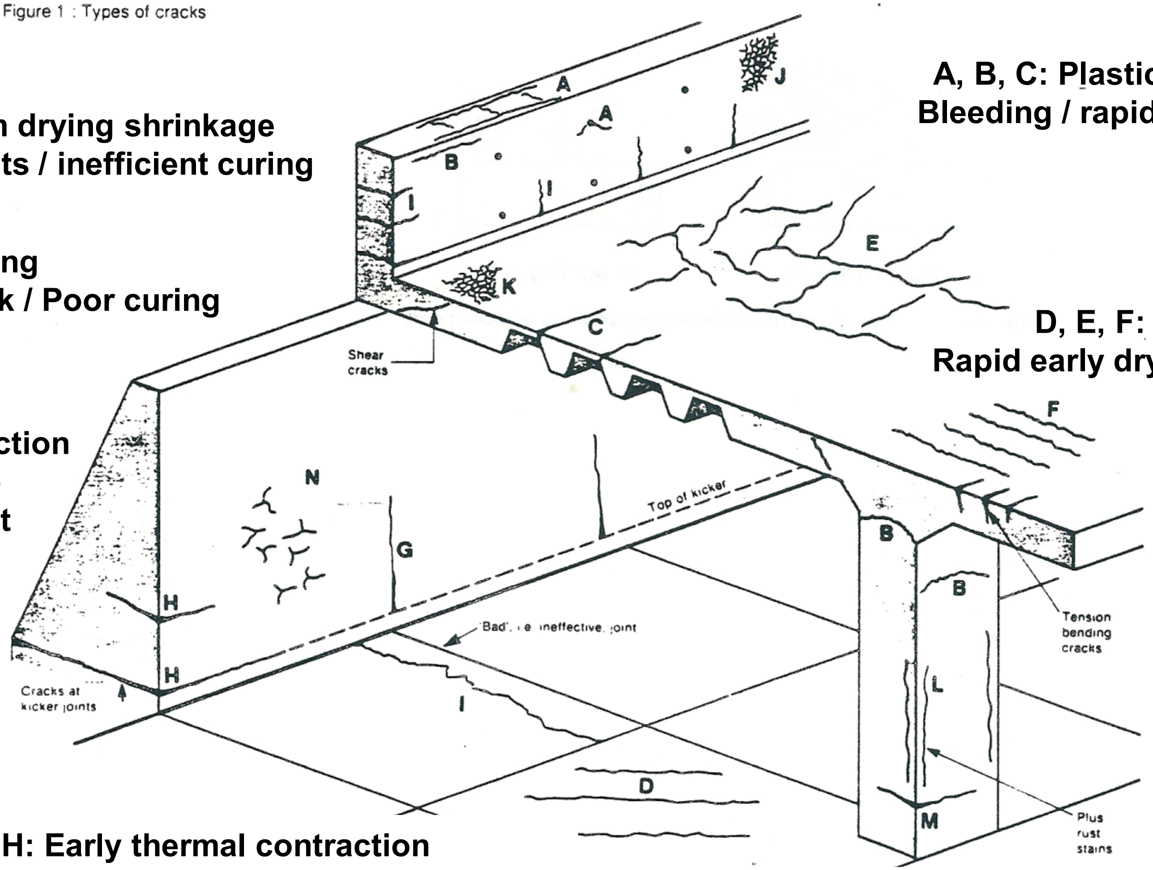
2. Importance of controlling crack-width in watertight constructions

3. Bio-based crack-healing in practice

Type of cracks and mechanisms of crack-healing

→ Concrete mix design *and* proper construction practice

Figure 1 : Types of cracks



I: Long term drying shrinkage
Inefficient joints / inefficient curing

J, K: Crazing
Impermeable formwork / Poor curing

N: Alkali-aggregate reaction
Reactive aggregate
+ high alkali cement

A, B, C: Plastic settlement
Bleeding / rapid early drying

D, E, F: Plastic shrinkage
Rapid early drying / steel near surface

G, H: Early thermal contraction
Excess heat generation / temperature gradients

L, M: Corrosion of reinforcement
Lack of cover / poor quality concrete

(Source: Concrete Society 1992 TR22 Non-structural cracks in concrete, modified after Betoniek May 1991)

Non-load-induced cracking:

Influenced by:

1. The **shrinkage** potential (volume reduction) of the concrete mixture and
2. The **degree of restraint** the element is experiencing

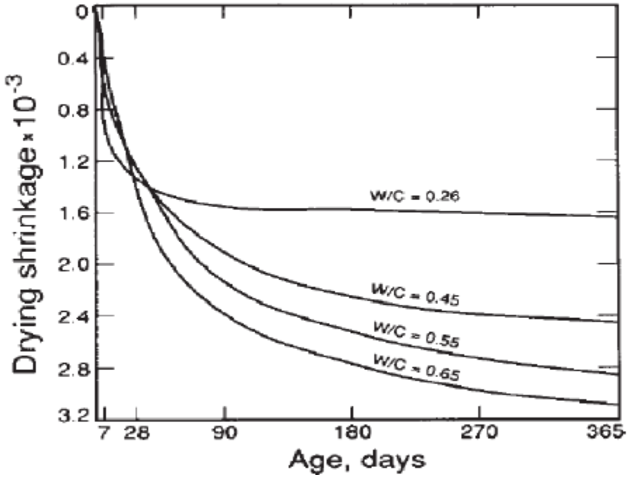
Shrinkage due to loss of water from the concrete matrix:

1. **Plastic shrinkage** in concrete **before hardening** (**evaporation**, absorption, rate of bleeding)
2. **Autogenous shrinkage** → volume decrease due to **chemical reactions** during cement hydration, (before and during hardening) specifically at very low w/c ratios
3. **Drying shrinkage** in concrete **after hardening** (loss of adsorbed capillary water: internal neg. pressure)
4. **Thermal contraction** → temp rise due to cement hydration (expansion) followed by volume reduction due to cooling to ambient temp

<u>Non-load</u>-induced cracking:

Plastic shrinkage cracks can extend throughout the entire thickness of the slab

https://concretesupplyco.com/6-concrete-cracks/



Autogenous + drying shrinkage depends on the ratio of water to cementitious materials content, volume of fine pores (dense microstructure!), aggregate content, and total water content.

https://www.researchgate.net/publication/277734494

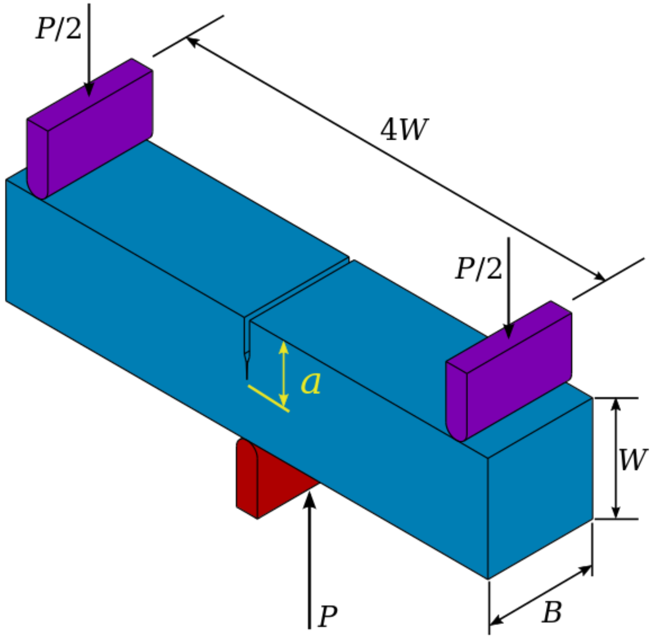
Early thermal contraction cracks on the side of a water storage reservoir. Temp rise due to cement hydration (expansion) followed by restrained volume reduction due to cooling down.

https://www.researchgate.net/publication/332063869

Load-induced cracking:

Concrete cracks caused by **(over)loading** → (over)load due to **compressive, tensile or bending load**

https://www.myrenovationspecialist.com/concrete-cracks/



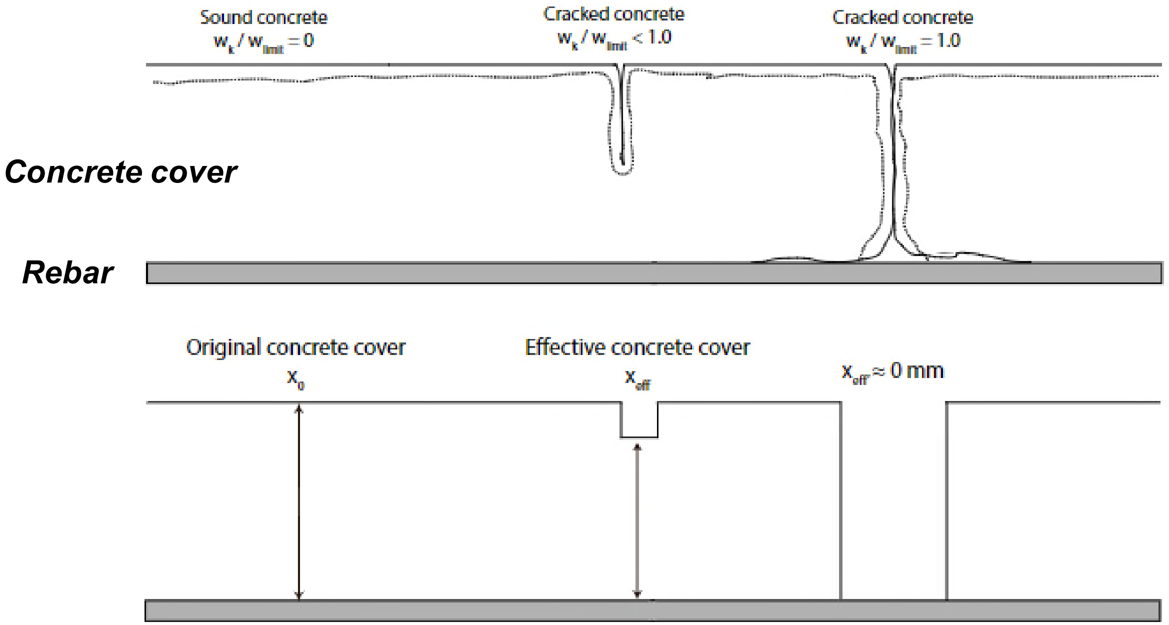
https://www.wikiwand.com/en/Three-point_flexural_test

https://concretesupplyco.com/6-concrete-cracks/

Type of cracks

Consequences for durability and water tightness

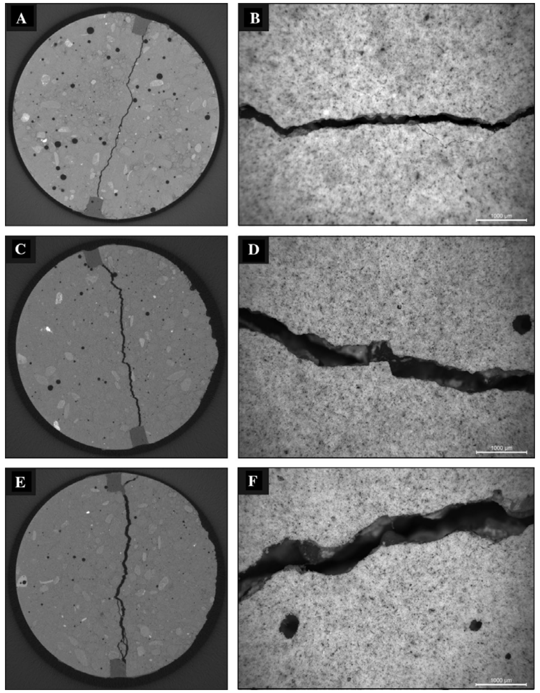
Type 1: surface cracks



Chloride ingress for sound and cracked concrete using effective cover depth (Pacheco Farías, 2015)

Affect durability

Type 2: through-going cracks



Affect durability and water tightness

Type of cracks and mechanisms of crack-healing

Consequences for durability

Type 1: surface cracks

Durability of e.g. (marine) structures

Moss growth and freeze/thaw damage

Type of cracks and mechanisms of crack-healing

Consequences for water tightness and durability

Type 2: through-going cracks

https://www.researchgate.net/publication/332063869

Durability and water tightness of structures

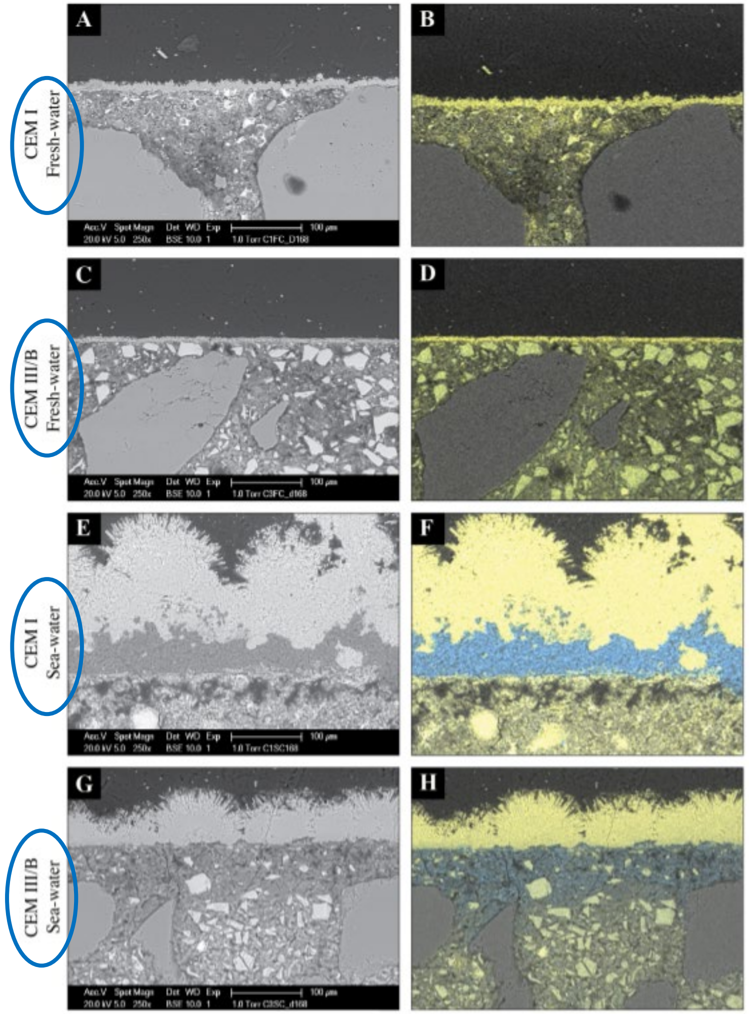
Type of cracks and mechanisms of crack-healing

Consequences for water tightness and durability

→ Autogenous healing ***MAY*** **result in closure of < 0.2 mm wide cracks**

→ **Autogenous healing capacity depends on many variables, e.g.:**

- **Clinker content**
- **Blaine fineness of cement**
- **Cement type**
- **Age of cracking**
- **W/C ratio**
- **pH and quality crack ingress water**
- **Water flow rate**



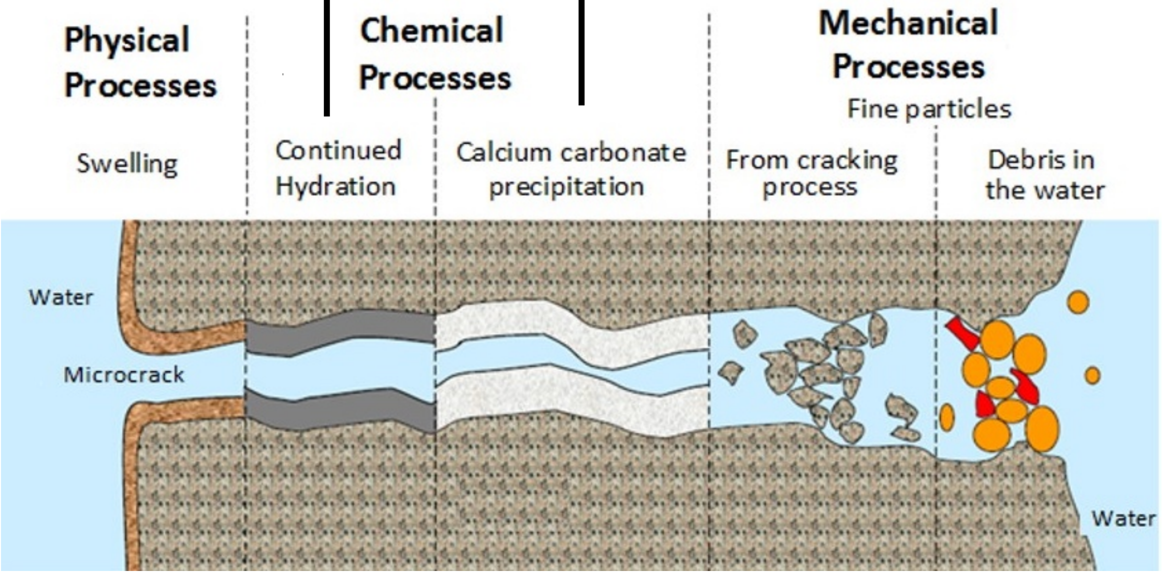
Palin et al. 2015 Cement and Concrete Research

Mechanisms of crack-healing

Autogenous self-healing: the crack-healing capacity of the concrete itself

Largely depending on **amount of non-hydrated cement particles (size!)** still present at crack surface (age of concrete and type/amount of cement used)

Depends on availability of Ca^{2+} and OH^- ions and CO_2: **$Ca(OH)_2$** + CO_2 → $CaCO_3$

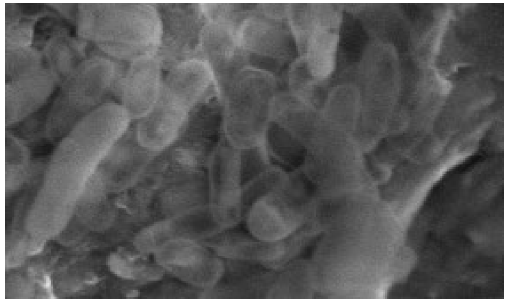


Main mechanisms producing **autogenous self-healing** of cementitious materials

(From: M. De Rooij, K. Van Tittelboom, N. De Belie, E. Schlangen, Self-Healing Phenomena in Cement-Based Materials, Springer, Dordrecht, The Netherlands 2013)

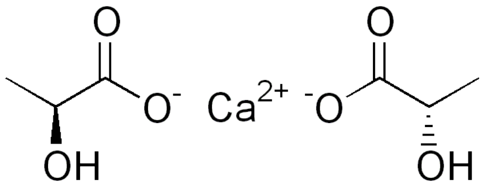
Mechanisms of crack-healing

Admixture ‘added’ (<u>autonomous</u>) self-healing



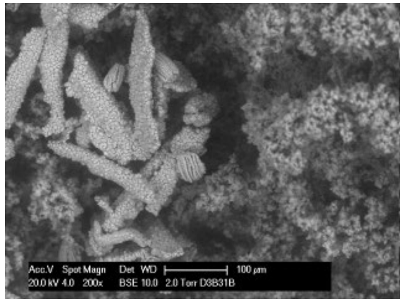
Bacteria

+



Calcium lactate

→



Limestone

Autonomous:
e.g. bacteria- induced self-healing

Occurs in natural limestone- and sand stone structures

Self-healing bacteria-based concrete:

Limestone production by bacteria
in alkaline environments

Bacteria: convert organics into CO_2

$$Ca(C_3H_5O_3)_2 + 6\ O_2 \rightarrow CaCO_3 + 5\ CO_2 + 5\ H_2O$$

$$5\ CO_2 + 5Ca(OH)_2 \rightarrow 5CaCO_3$$

$Ca(OH)_2$

pH 10-12

→ Two components required: bacteria + nutrients

Autonomous:
e.g. Bacteria-induced self-healing

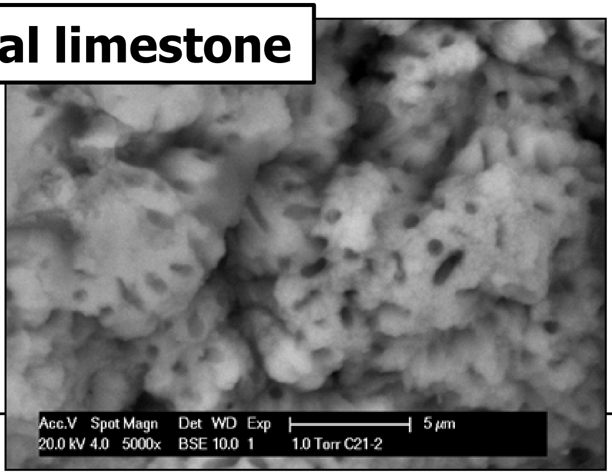
1. **Oxygen consumption:** → Reduce risk of steel corrosion

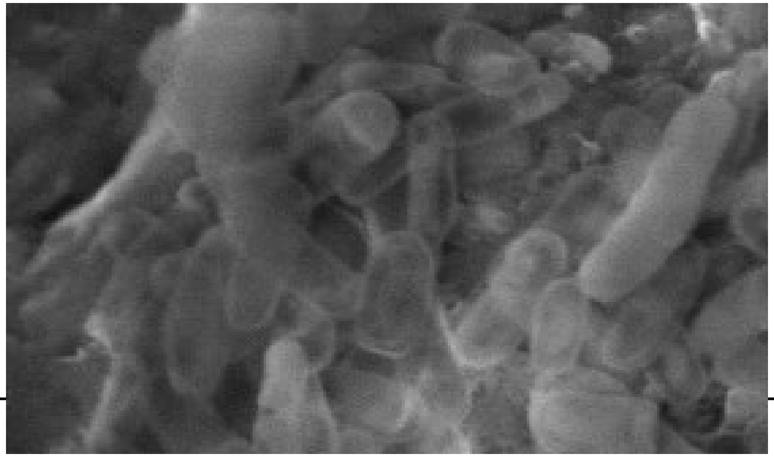
2. **Limestone formation:** → Improving water tightness / reduced Cl^- ingress

3. “ → Porosity decrease / density increase

↓ Improved damage / wear resistance

Bacterial limestone





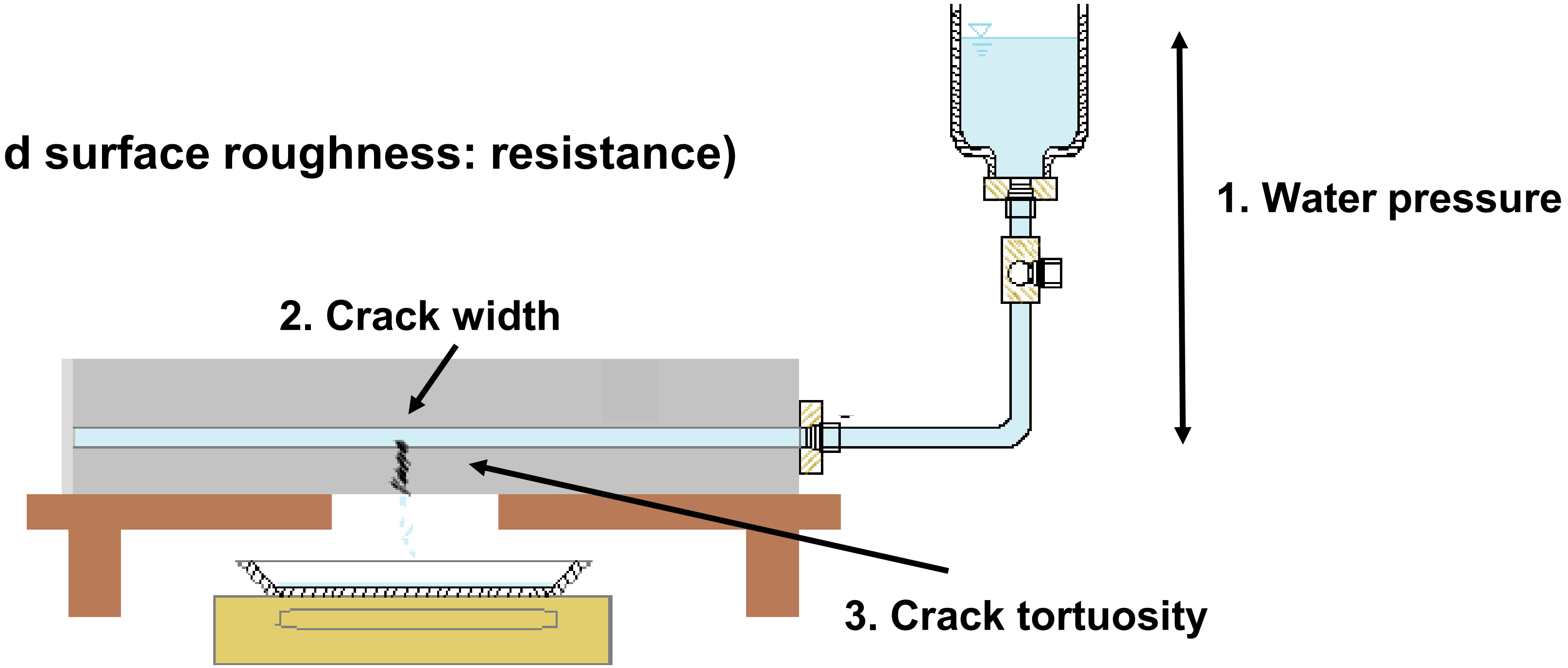
2 μm

The importance of <u>limiting crack width</u>
specifically in (water carrying) through-going cracks:

→ Limitation of water flow

Water flow predominantly determined by:

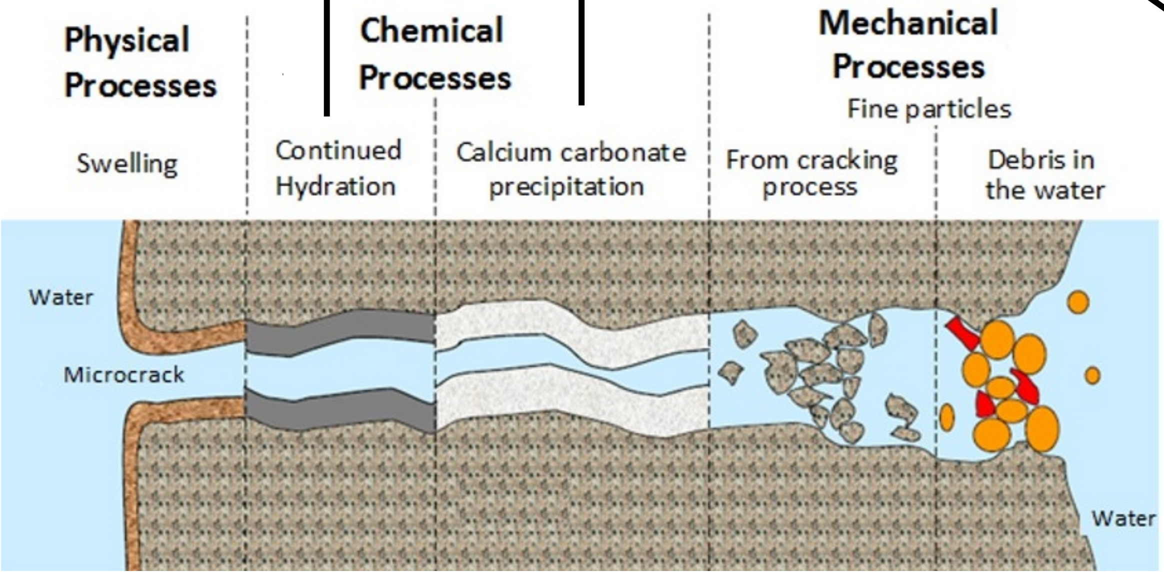
1. Water pressure
2. Crack width
3. Crack tortuosity (length and surface roughness: resistance)



Crack self-healing capacity is to a major extend affected by water flow

Largely depending on amount of non-hydrated cement particles still present (age of concrete and type/amount of cement used)

Depends on availability of Ca^{2+} and OH^- ions and CO_2: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3$



Water soluble:
too high water flow will flush out $Ca(OH)_2$

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Crack self-healing capacity is to a major extend affected by water flow

Bacteria convert nutrients to limestone:

$$Ca(C_3H_5O_3)_2 + 6\ O_2 \rightarrow CaCO_3 + 5\ CO_2 + 5\ H_2O$$

$$CO_2 + 2(OH^-) \rightarrow CO_3^{2-} + H_2O$$

$$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3$$

$Ca(OH)_2$

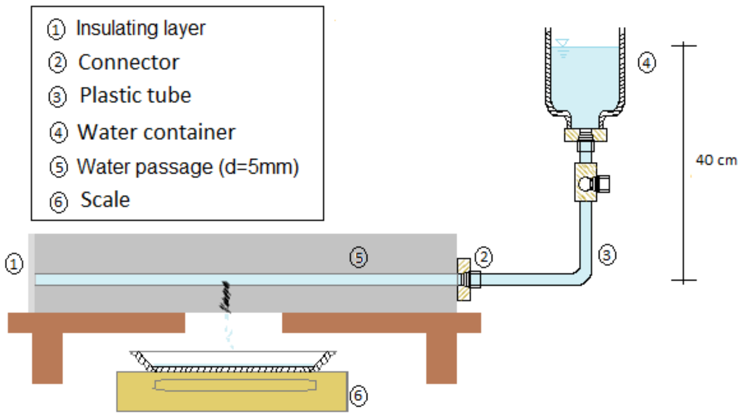
Water soluble:
<u>too high</u> water flow will flush out
$Ca(C_3H_5O_3)_2 + Ca(OH)_2$

Autonomous:
e.g. bacteria- induced self-healing

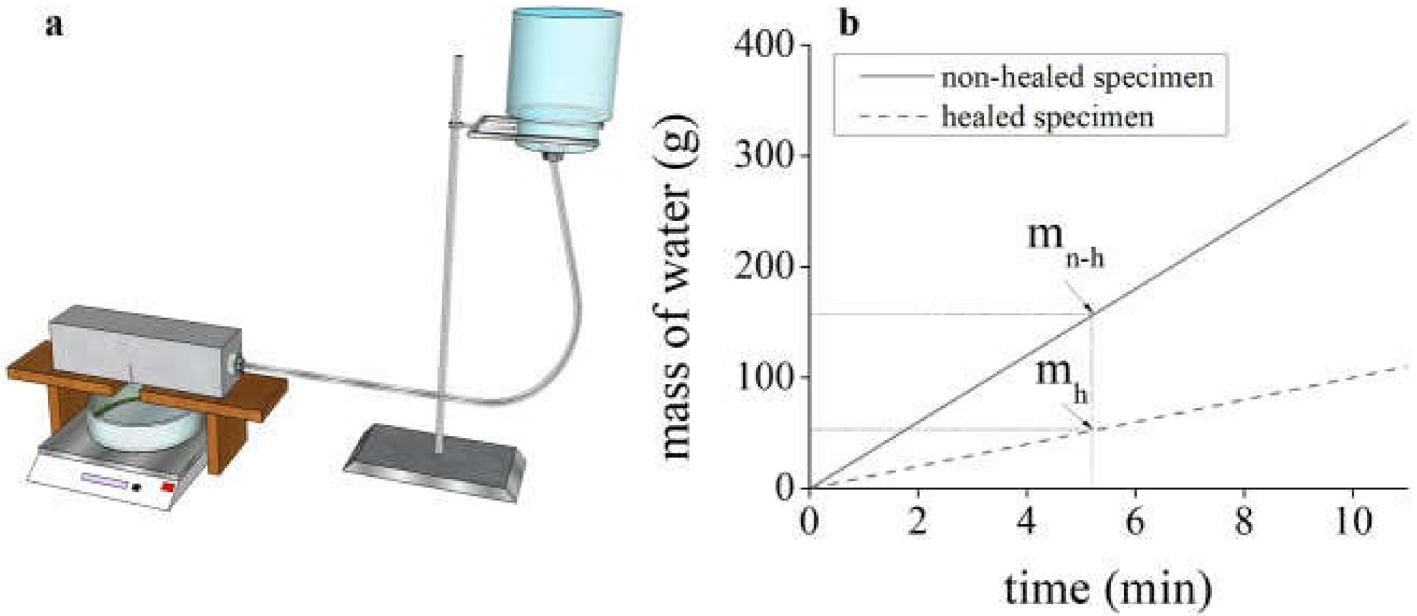
Methods of testing: evaluation of efficiency of self healing

Water permeability – regain of water tightness

→ Assessment of water flow through the specimen during a certain period



Type 1: Surface cracks

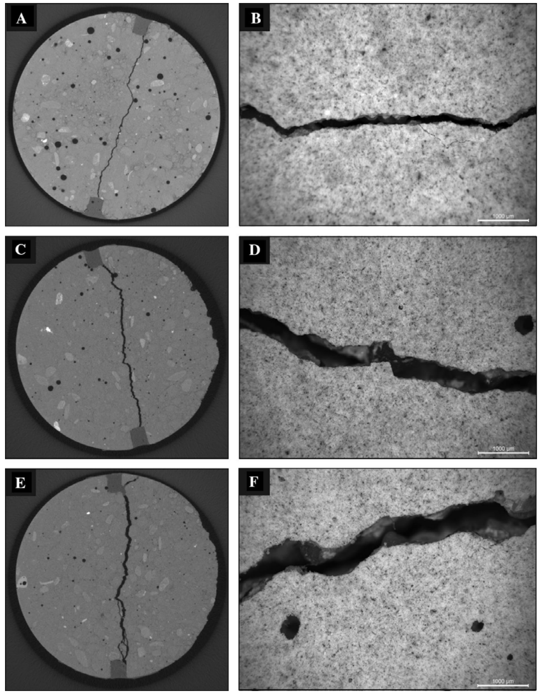


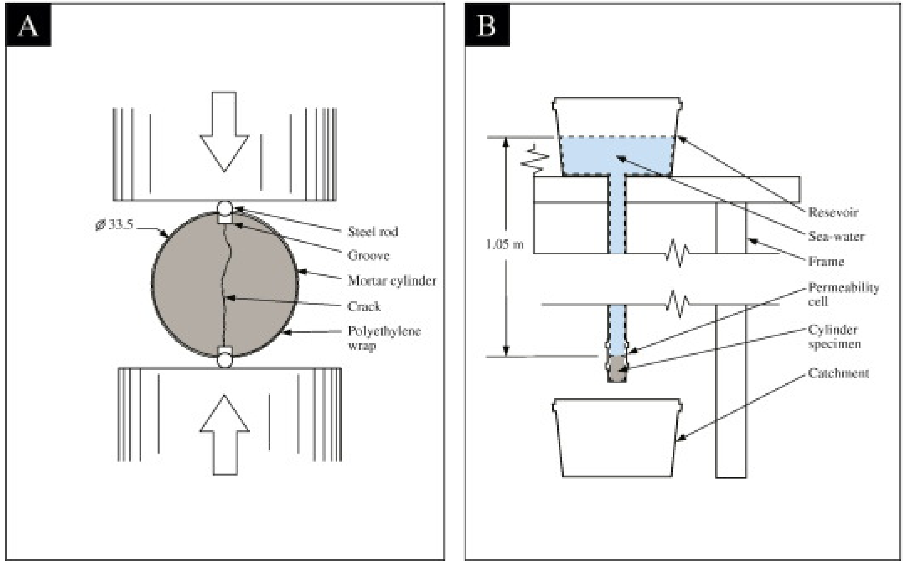
E. Tziviloglou et al (2014) Proceedings of the Int Conference on Ageing of Materials & Structures Delft 26 – 28 May 2014, The Netherlands

Methods of testing: evaluation of efficiency of self healing

Water permeability – regain of water tightness

→ A rapid test delivering accurate and reliable crack permeability data

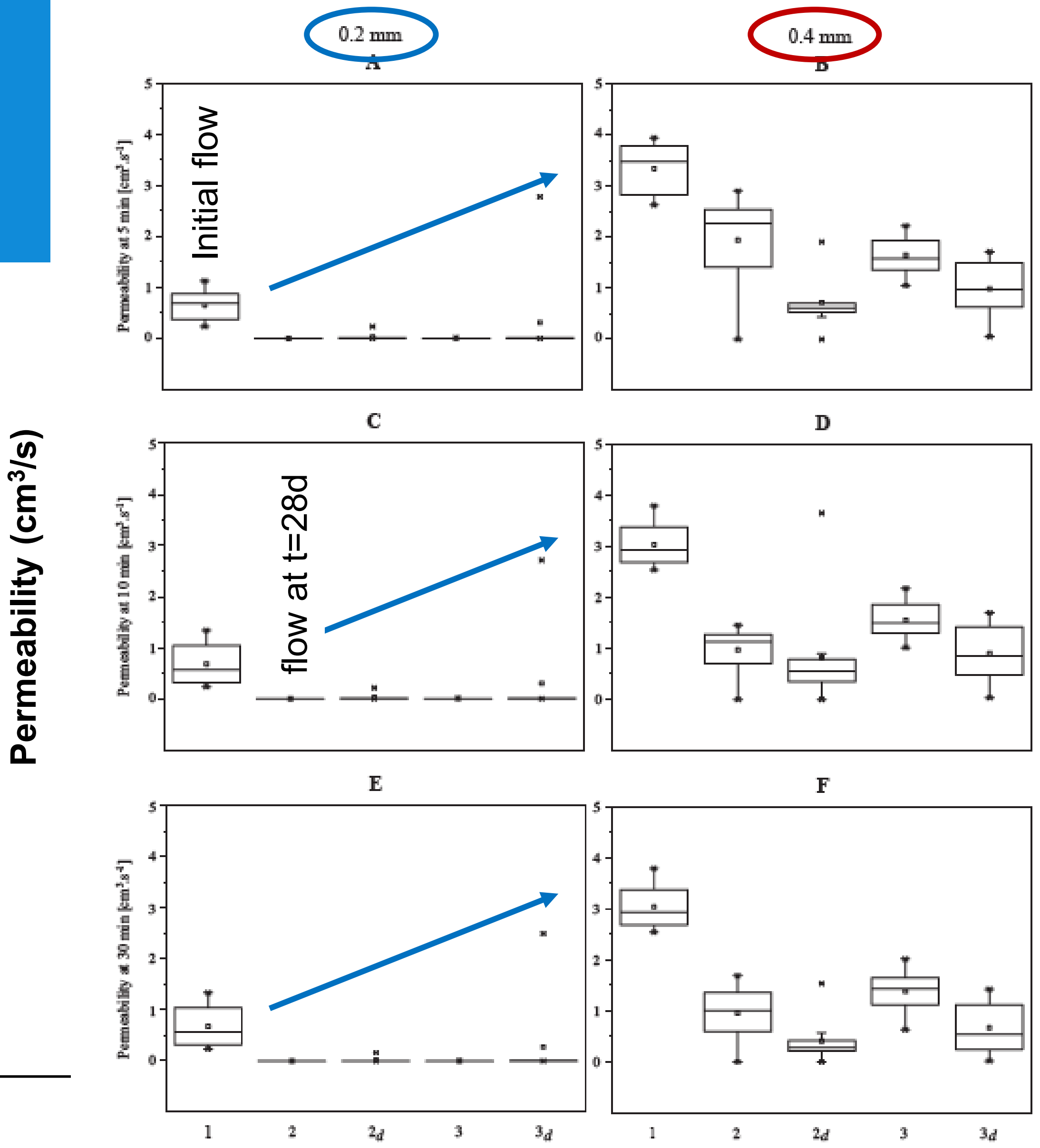




Type 2: through going cracks

Palin et al (2016 and 2019) International Journal of Civil Engineering (2019) 17:645–652

Consequence of crack width for water flow



→ **Water flow increases exponentially with increasing crack width**

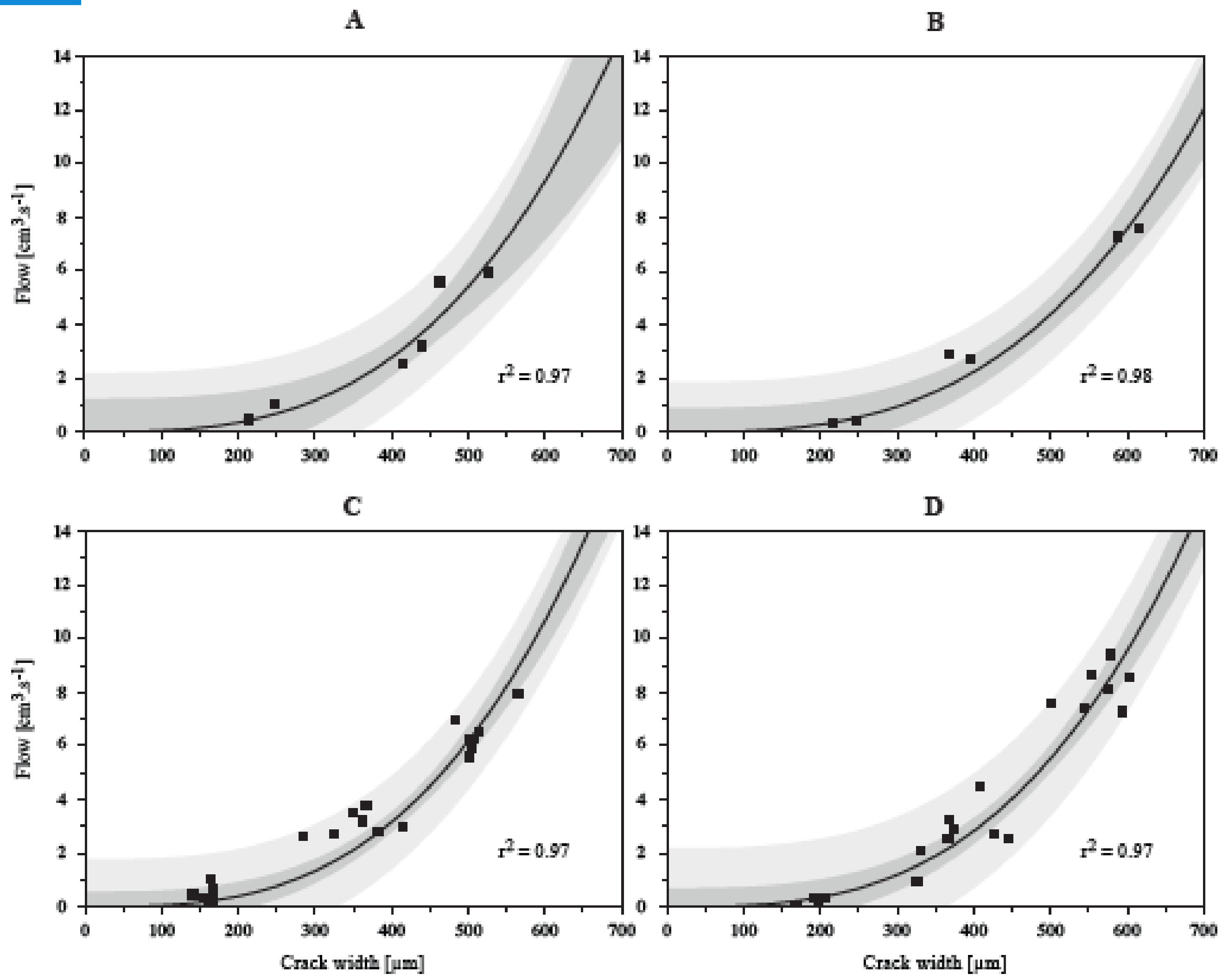
Initial water flow **before** autogenous self-healing:

→ **0.2 mm crack**: 0.7 ml/s
→ **0.4 mm crack:** 3.2 ml/s

Figure 3.4 Crack permeability data for series 1, 2 and 3 in the form of 6 box plot graphs. Graphs (A, C and E) show the permeability data for the 0.2 mm cracks after flowing the water for: (A) 5; (C) 10; and (E) 30 min. Graphs (B, D and F) show the permeability data for the 0.4 mm cracks after: (B) 5; (D) 10; and (F) 30 min. The first box plot to the left of each graph shows the initial permeability, second is the permeability of cracked specimens after 28 days submersion, third are the same specimens after drying, fourth is the permeability of cracked specimens after 56 days submersion, and fourth the same specimens after drying. Each box represents the permeability of 10 separate specimens. The square symbol of the boxes represents the mean permeability; the whiskers the minimum and maximum permeability values; and the top, middle and bottom lines the 75th, 50th and 25th percentiles ($x_{.75}$, $x_{.5}$ and $x_{.25}$), respectively.

D. Palin, H.M. Jonkers, V. Wiktor, Autogenous healing of sea-water exposed mortar: Quantification through a simple and rapid permeability test, Cement and Concrete Research, 84 (2016) 1-7.

Consequence of crack width for water flow



→ **Water flow increases exponentially with increasing crack width**

→ Observed values (symbols) against predicted values

<u>too high</u> water flow will flush out $Ca(C_3H_5O_3)_2 + Ca(OH)_2$ (autogenous + autonomous healing)

Figure 4.2 Observed values plotted against predicted values for: (A) the unmodified test whose cracks were analysed through CT; (B) the modified test whose cracks were analysed through CT; (C) the unmodified test whose cracks were analysed through stereomicroscope; and (D) the modified test whose cracks were analysed through stereomicroscope. Symbols represent the observed values; lines represent the predicted values; the darker shaded areas flanking the lines represent the 95% confidence intervals, and the lighter areas flanking those the 95% prediction intervals. The R-squared (r^2) values for the models are also indicated.

D. Palin, H.M. Jonkers, V. Wiktor, Autogenous healing of sea-water exposed mortar: Quantification through a simple and rapid permeability test, Cement and Concrete Research, 84 (2016) 1-7.

Conclusions:

1. Through-going cracks: water flow rate strongly affects autogenous + autonomous healing efficiency
→ less concern (risk) for surface (non-through-going) cracks

2. Limit initial crack width as much as possible to increase self-healing efficiency
of particularly through-going cracks

2A. Decrease thermal expansion/shrinkage (mix design, e.g. low clinker, retarder; practice, e.g. cooling)

2B. Decrease plastic shrinkage (mix design, e.g. limit water content; practice, avoid water loss, e.g. apply sufficient cover during setting)

2C. Decrease autogenous + drying shrinkage (mix design, e.g. increase aggregate/paste ratio, decrease w/c ratio, decrease volume of fines, reduce surface tension of water within the pores; practice, avoid water loss → e.g. apply *effective* curing)

3. Make sure that mix design and construction practice (execution) are compatible:
80% of insufficient quality due to mistakes during placement and aftercare construction!

Bio-based (autonomous) healing in practice

Monitoring techniques for assessment of self-healing outdoors structures:

'Healing agent'

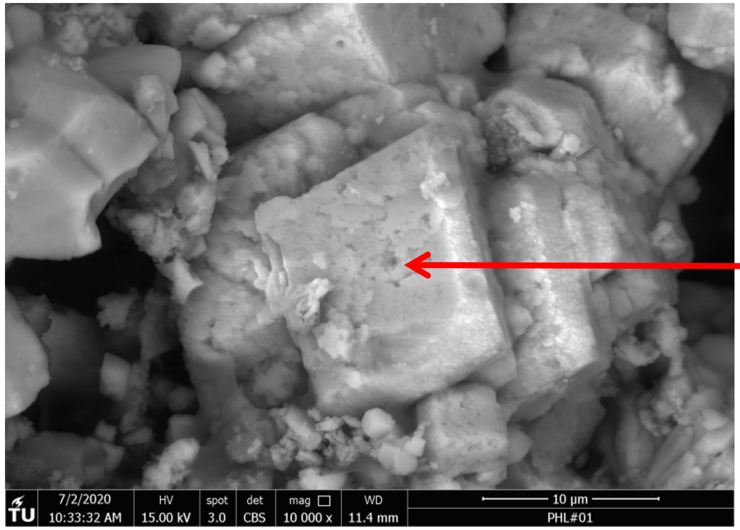
→ Visual crack width + closure determination
→ Water tightness (water flow)
→ Surface permeability using Karsten Tube Penetration Test

Mors & Jonkers (2019) RILEM Technical Letters 4: 138-144

Bio-based (autonomous) healing in practice

Monitoring techniques for assessment of self-healing outdoors structures:

Determining bacteria-driven limestone formation: electron microscopic analysis crack flow water

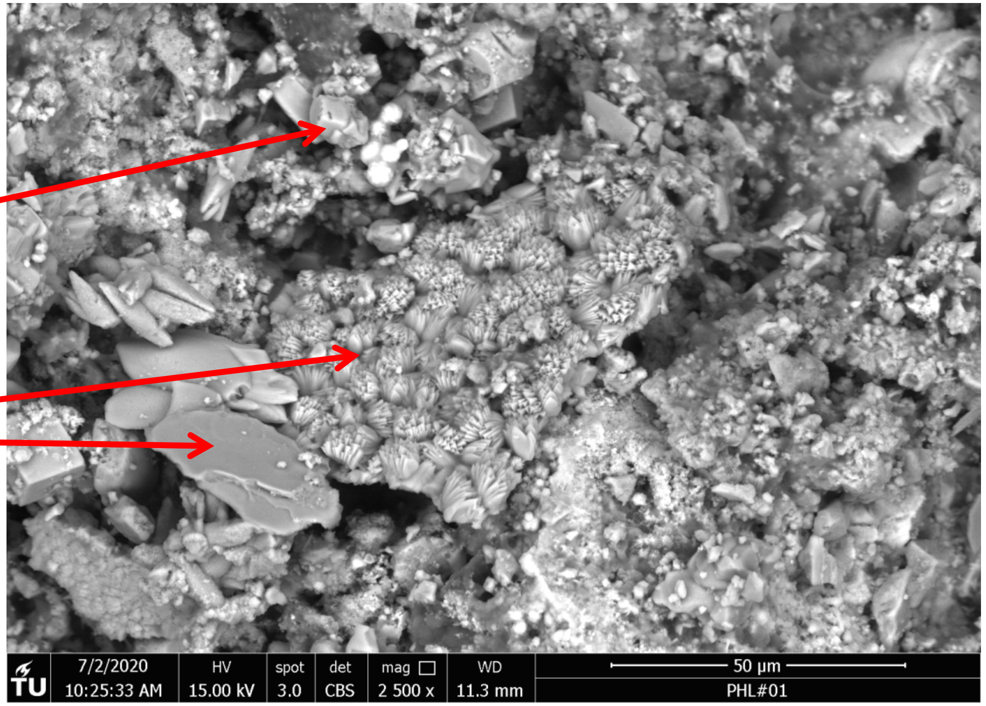


Magnification: 10 000x

Bacteria-imprints in calcite crystals

Limestone (calcite) crystals

Massive formation of calcite crystals

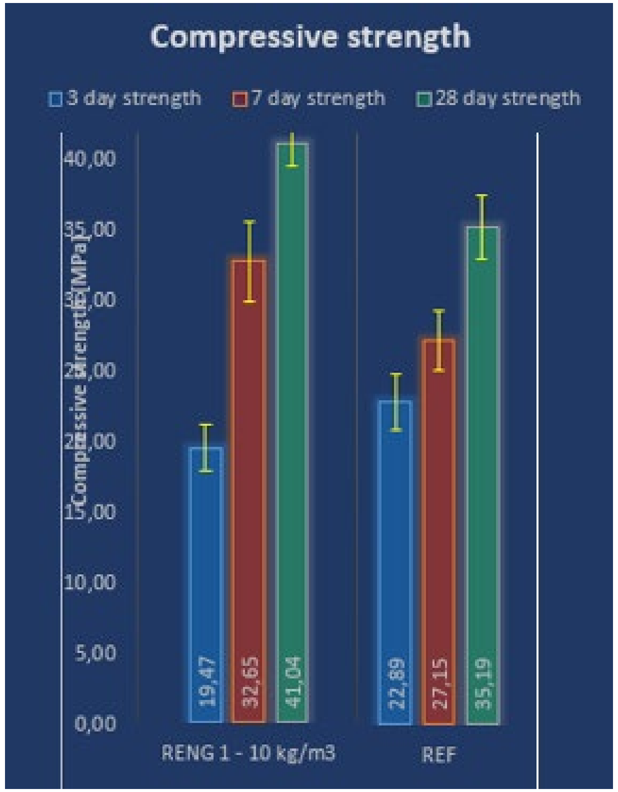


Magnification 2500x

Healing agent triple function:

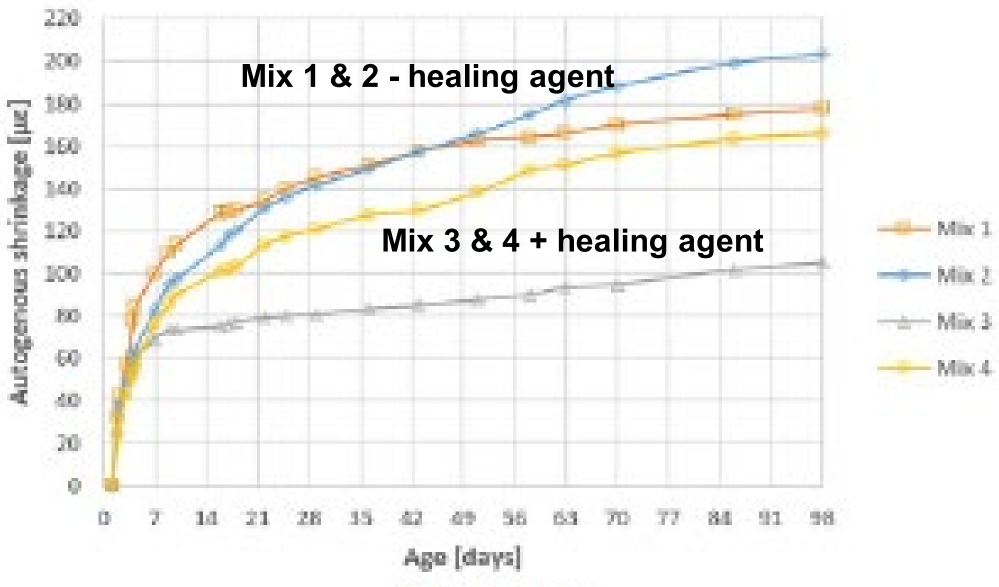
1. Mild retarder (thermal expansion/contraction reducer)

2. Autogenous shrinkage reducer



Mild retarder

MSc thesis Martin Megalla



(b) Three months.

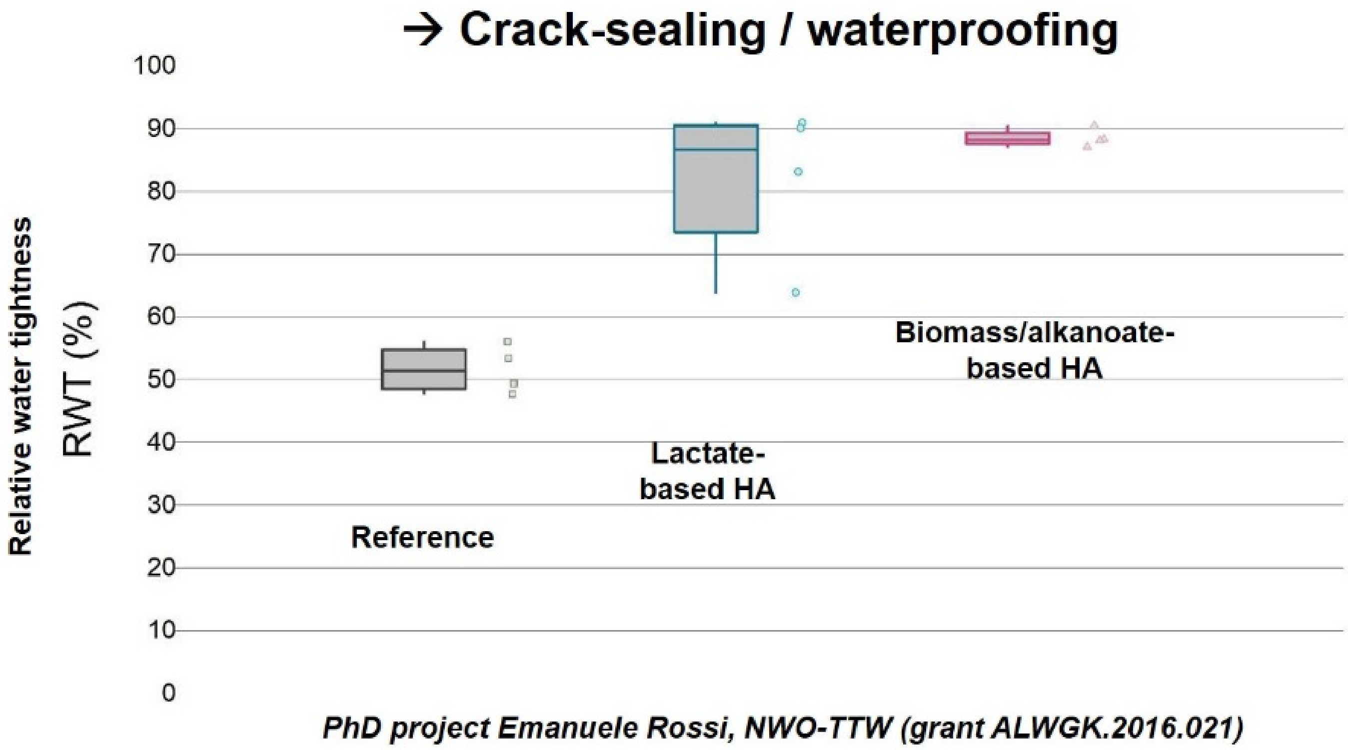
Figure 4.7: Autogenous shrinkage test results.

Autogenous shrinkage reducer

MSc thesis Youri van Zondag

Healing agent triple function:

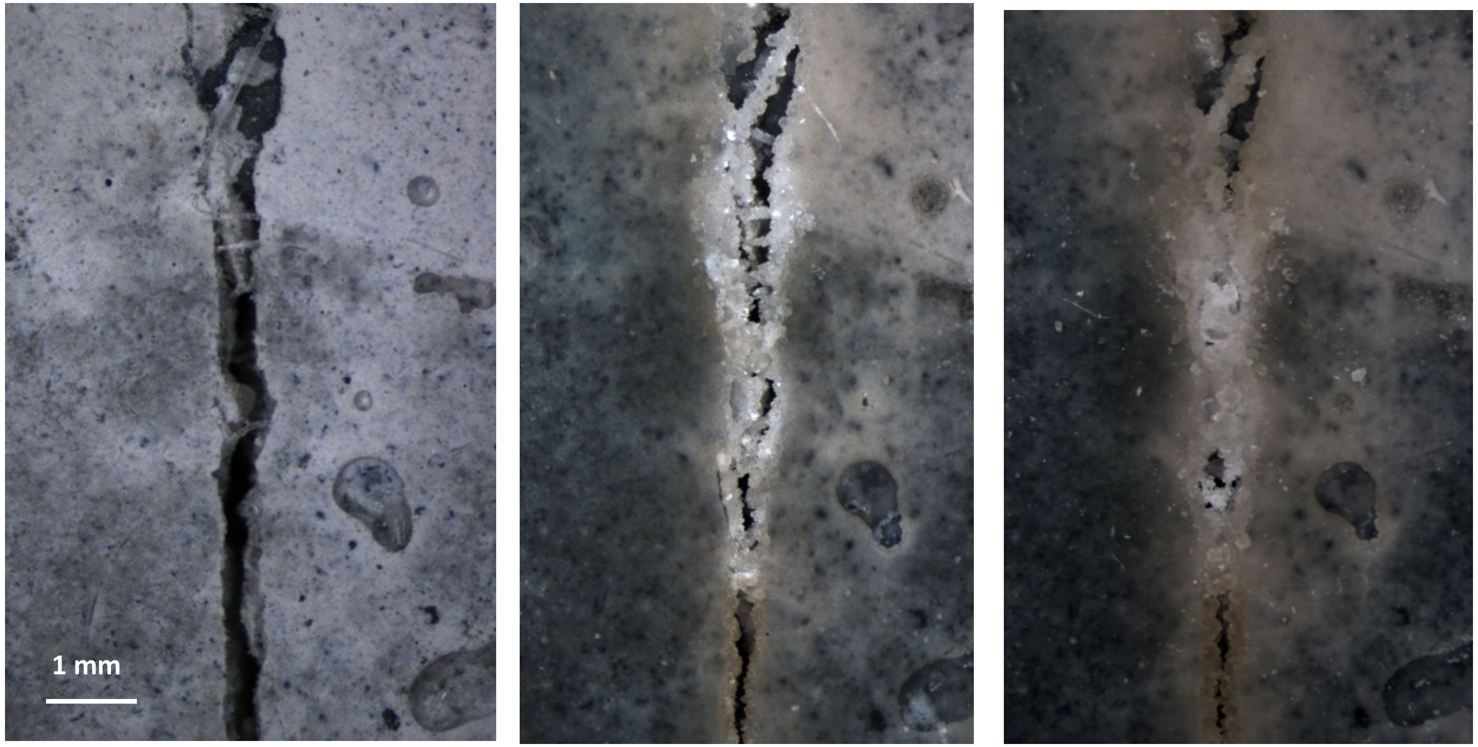
3. Enhanced (on top of autogenous) crack-healing capacity (limestone formation)



Enhanced crack-healing

Quantification of self-healing

4th generation polymer-based healing agent

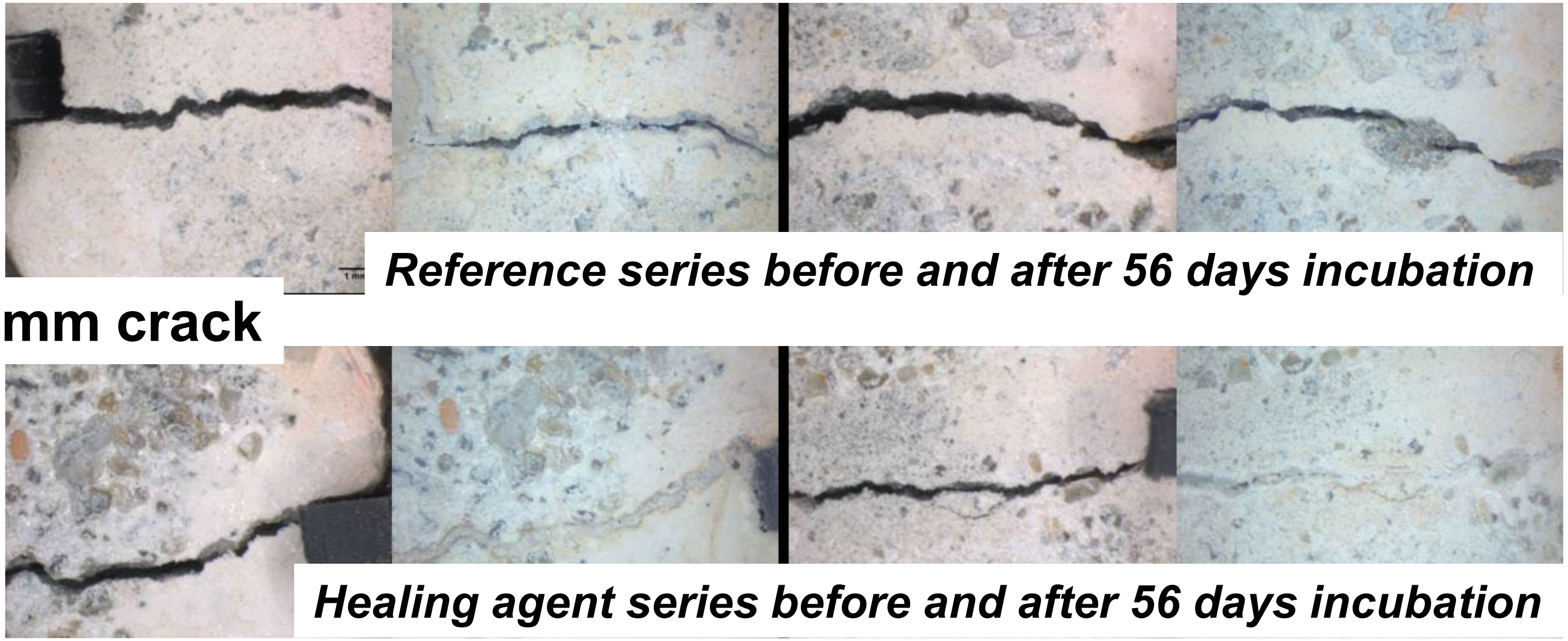


t=0 **t=24d** **t=58d**

Crack healing in water

Bacterial metabolically driven mineral formation

→ Crack-sealing



Reference series before and after 56 days incubation

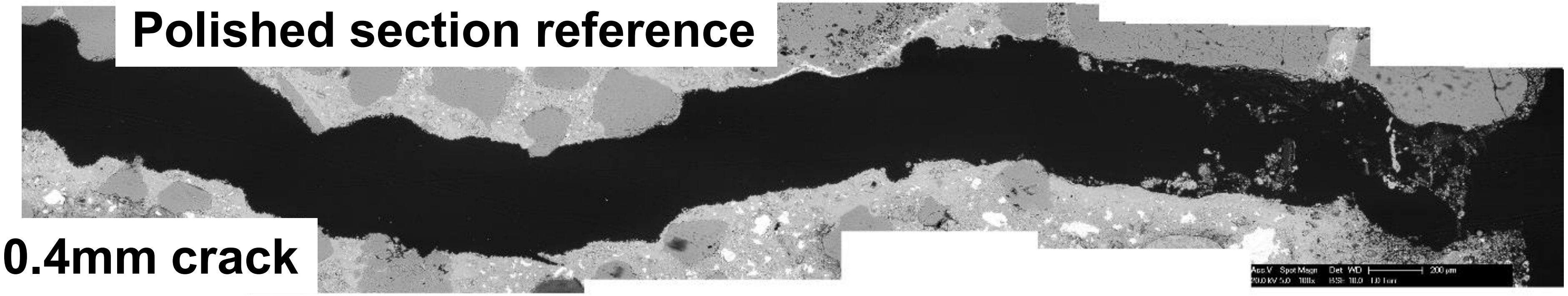
0.4mm crack

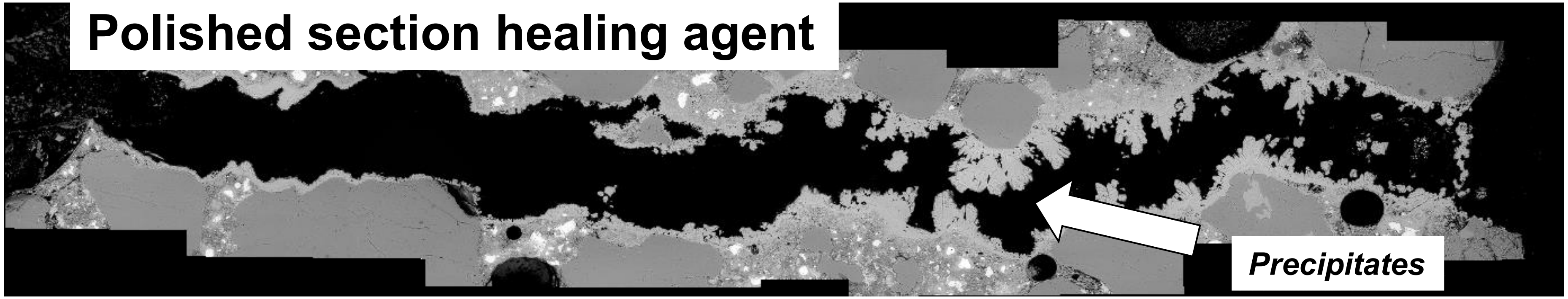
Healing agent series before and after 56 days incubation

Sample surface view

Bacterial metabolically driven mineral formation

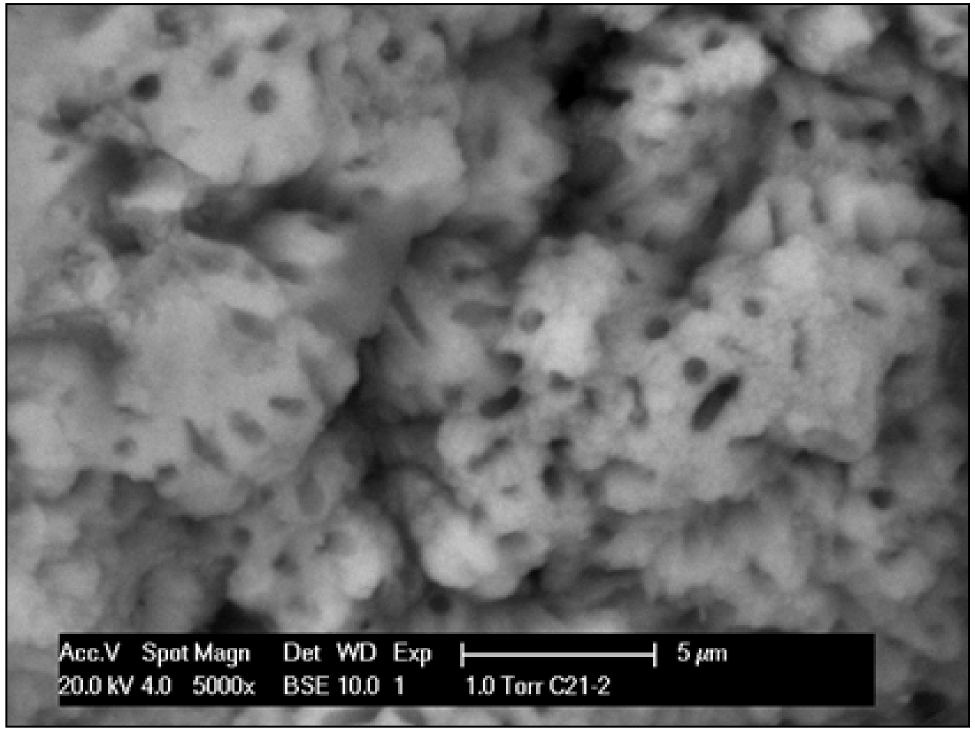
→ Crack-sealing



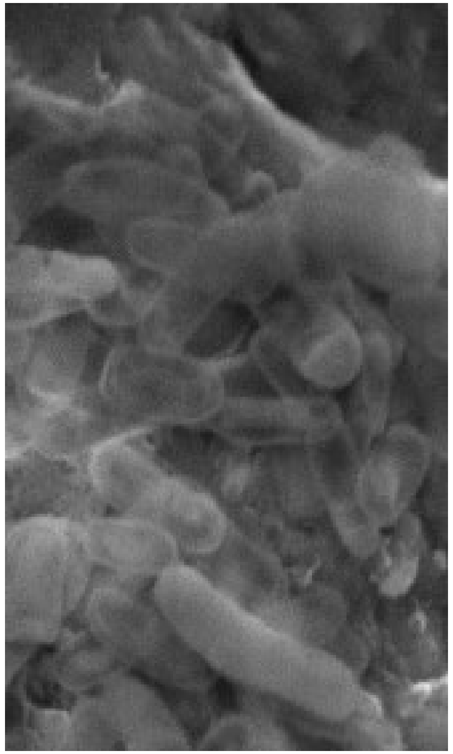


Cross sample (polished section) view

Bacterial metabolically driven mineral formation



Bacterial limestone



2 µm

Healing agent best practice

→ **Determine effectivity in demonstrator applications**

→ **Compare crack formation + crack healing in parts of structure with and without healing agent (similar mix design and execution practice)**


Simpelveld water reservoir

Hoogvliet water reservoir

Basilisk
self healing concrete

basiliskconcrete.com

Self-healing concrete products

Self Healing Agent

Basilisk self-healing agent for concrete mixtures

Self Healing Repair Mortar MR3

Basilisk self-healing repair mortar for existing concrete structures

Liquid Repair System ER7

Basilisk liquid repair solution