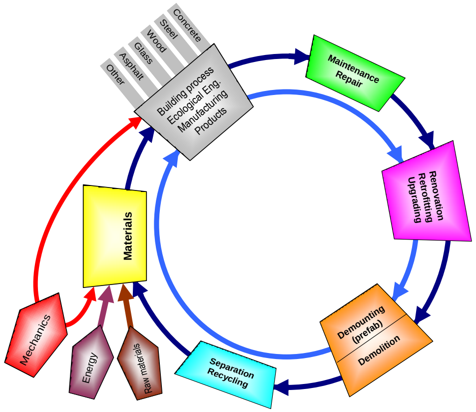
Seminar: Circulair bouwen - Beton als insipiratie

Groningen, 10 september 2015



Historie van duurzame innovatie in beton

K.(Klaas) van Breugel

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TU Delft, The Netherlands

Pantheon - Rome

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Het Pantheon in Rome

Het Pantheon, gebouwd door keizer Augustus (27 BC - 14 AD)

Het geheim van het Pantheon (2000 jaar oud)

- ❑ Goede architectuur?
- ❑ Goed constructief ontwerp?
- ❑ Goede materiaalkeuze?
- ❑ Goede uitvoering?
- ❑ Goed bouwmanagement?
- ❑ Goede bouwvoorschriften?
  - Voorschrijvend bouwvoorschrift (VBC, Eurocode)
  - Prestatiegericht bouwvoorschrift

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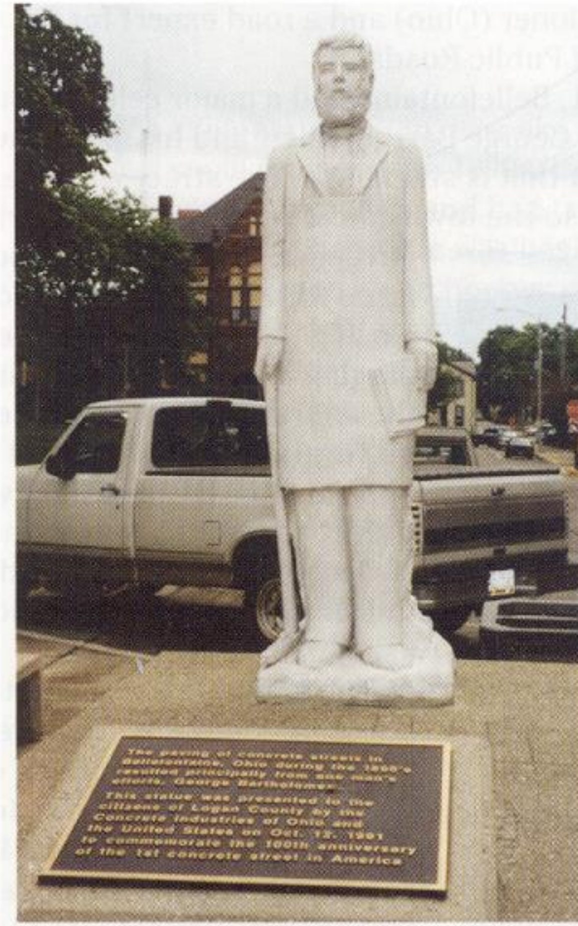
Duurzaam betonnen wegdek

The oldest concrete street in the United States as it appears now



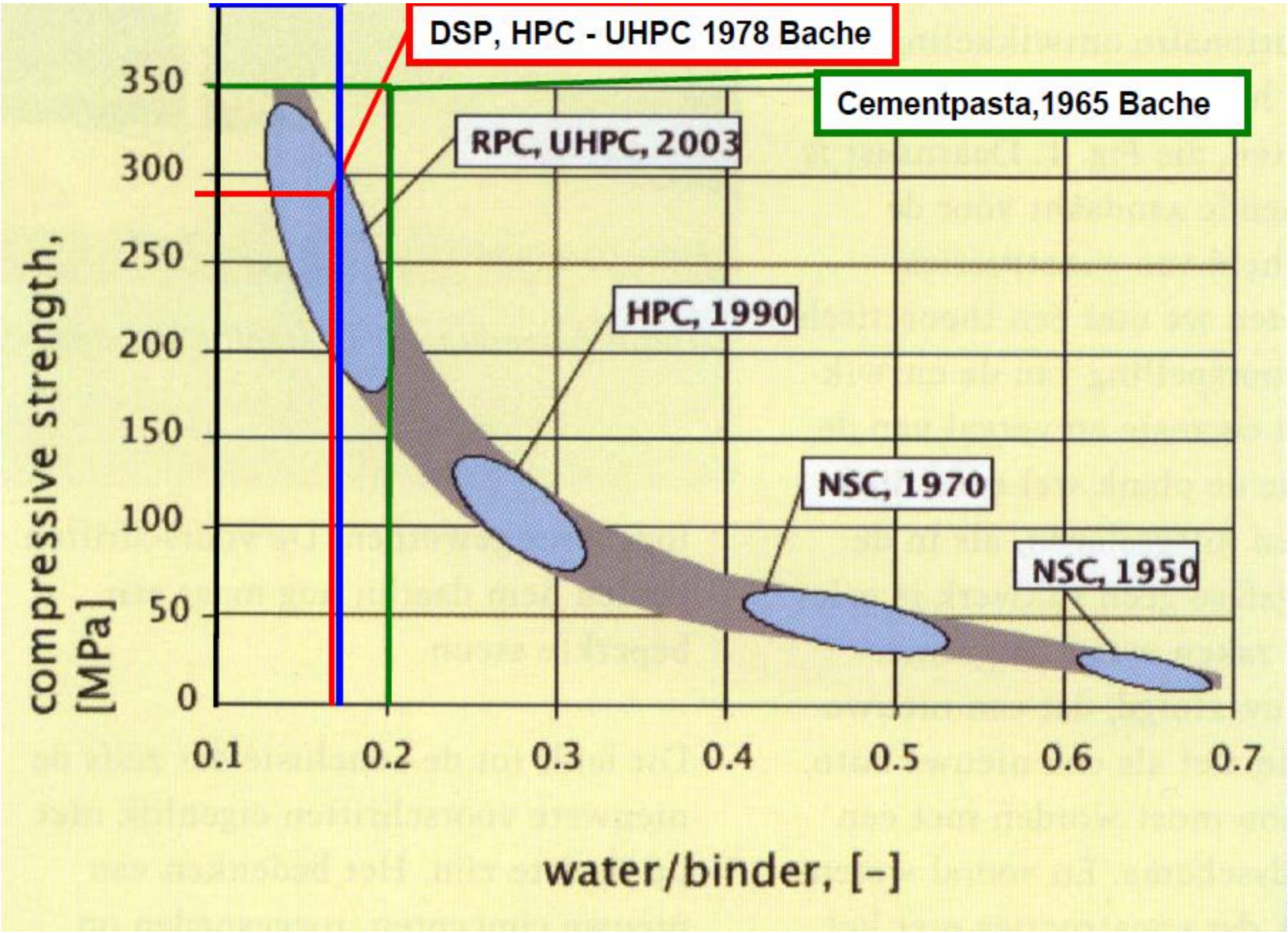
Town of Bellefontaine, State of Ohio, USA, 1891

George Bartholomew

Drijvende krachten achter innovaties

Vraagkant	**Antwoord**
• Verbeteren prestaties cement (sterkte)	Maaltechnologie (ca. 1940)
• Procesbeheersing tijdens de bouw	Verhardingsbeheersystemen
• Reduceren milieubelasting cement (1 ton Portland cement 0.8 ton CO_2)	Cementvervangende poeders (slag, vliegas, kalksteenmeel, geo-polymeren)
• Schaarste toeslagmaterialen	Verwerking afval/reststoffen Recycling beton/metstelwerk
• Arbeidsomstandigheden	Ontwikkeling zelfverdichtend beton
• Bijzondere architectuur	(Ultra) hoge sterkte beton
• Verlengen levensduur	Zelf-herstellend beton
• ICT-ontwikkeling & gebrek arbeiders	3D printen

Ontwikkeling betonsterkte



NSC: Normal strength concrete

High Strength Concrete: 50-100 MPa;

Very **HSC**: 100-150 MPa;

Ultra **HSC**: > 200 MPa

RPC: Reactive powder concrete

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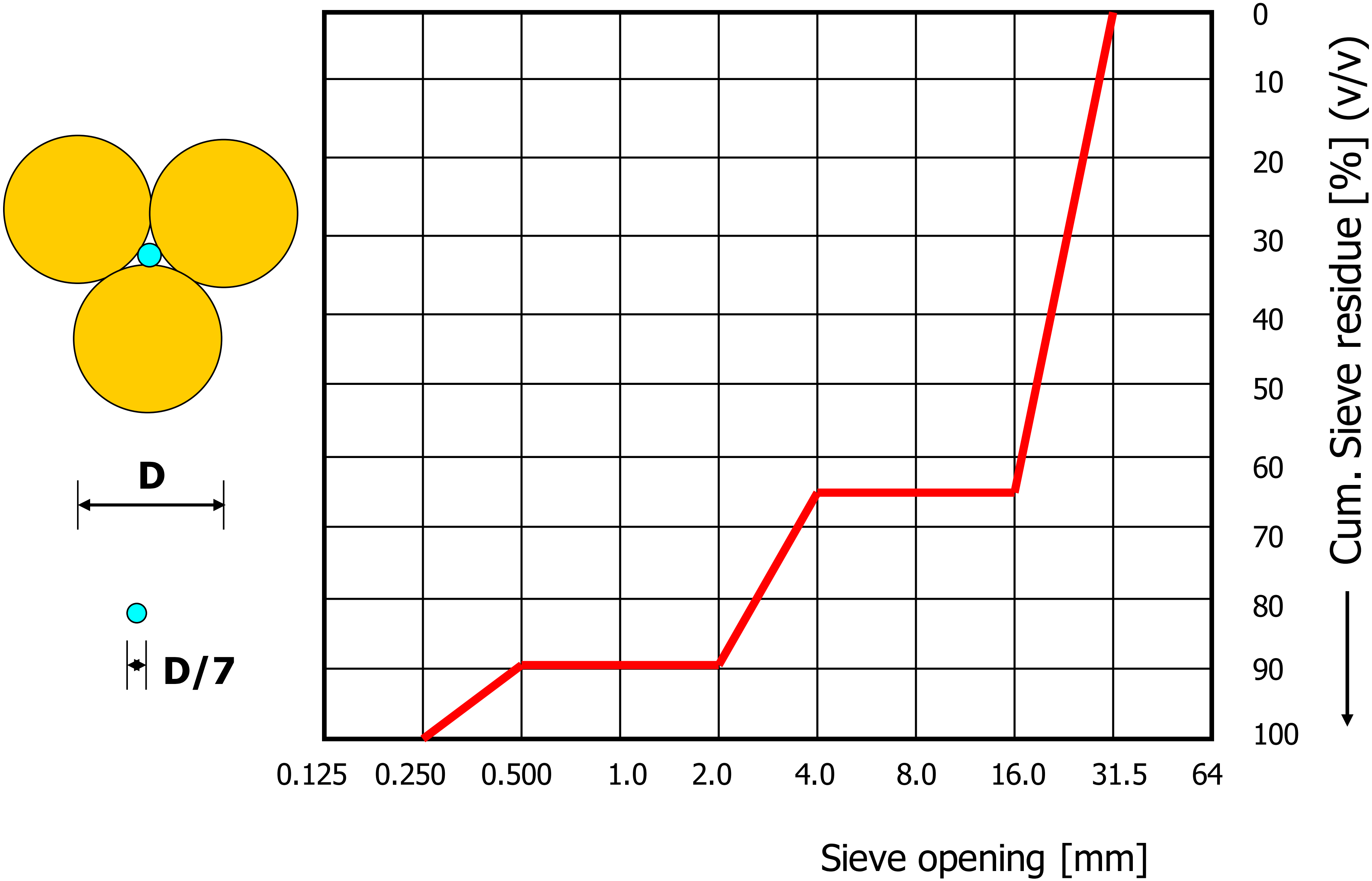
Belangrijkste sterkteparameters

- Korrelpakking toeslagmateriaal
- Korrelpakking cement en fijne poeders (silica fume)

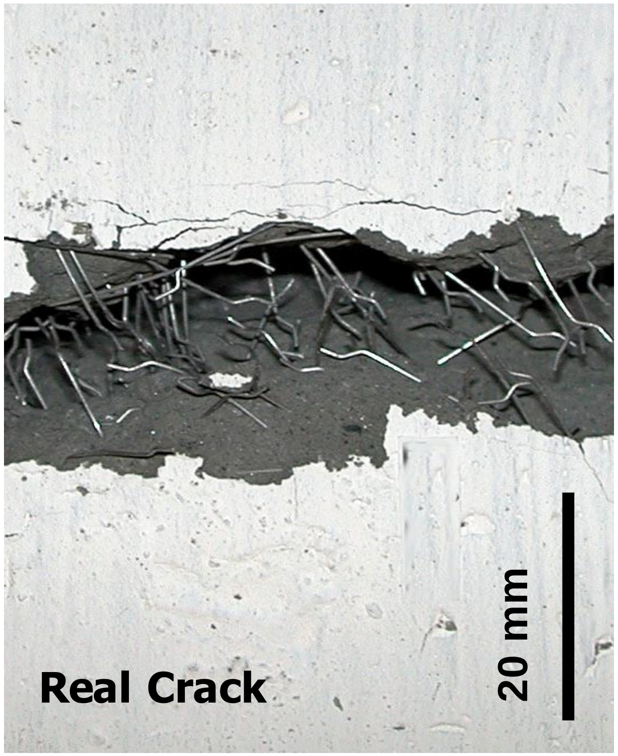
"Gap-graded" particle size distribution



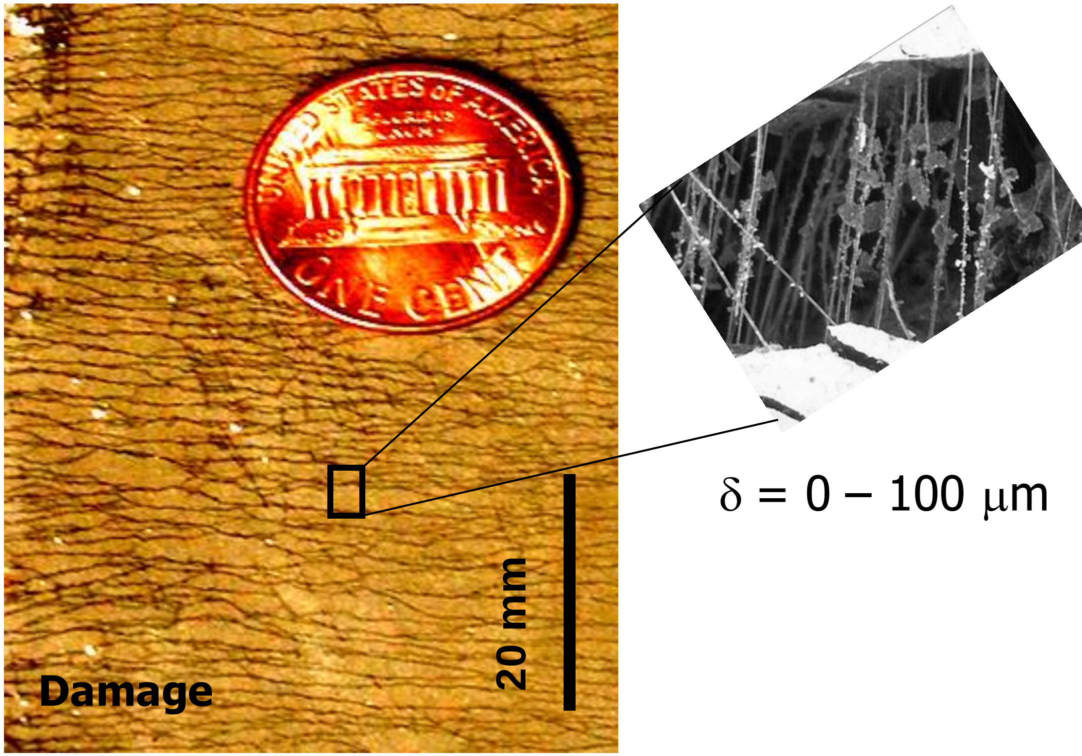
Belangrijkste sterkteparameters

- Korrelpakking toeslagmateriaal
- Korrelpakking cement en fijne poeders (silica fume)
- Fijnheid cement (fijn, dan snel 28-daagse sterkte)
- Type cement (klinkersamenstelling: C_3S, C_2S, C_3A, C_4AF)
- Water/bindmiddelfactor ((super)plasticeerders)
- Vezels (voor hoge treksterkte en taaiheid)

Scheuren in vezelversterkte mortel en in Engineered Cementitious Composite (ECC)



‘Normaal’ vezelbeton



“Engineered Cementitious Composite”

Bendable concrete

Engineered Cementitious Composite (ECC)

Invented by Victor Li (USA)
Strain capacity: 3 – 7 %

Krishna, Civil Feeds, 2012

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- Vezels (voor hoge treksterkte en taaiheid)
- Temperatuur (hoge verhardingstemperatuur, lagere eindsterkte)

Inventarisatie gedrag brugdekken in USA

Before 1930

- Slow strength development
- Blaine surface: 180 m^2/kg
- C_3S content: < 30%

1930 – 1950

- Structures (bridge decks) built after 1930 **less** durable than those built before 1930
- Blaine increased from 180 m^2/kg up to 300 m^2/kg (Construction and building technology as before 1930!)

Mehta & Burrow, 2001

Inventarisatie gedrag brugdekken in USA

1950 – 1980

- Structures (bridge decks) after 1940 had many durability problems
- Fineness increased to 400 m^2/kg
- C_3S content increased to > 60%
- Low w/c ratio: denser concrete, but higher proneness to cracking!

1980 to present

- Use of high-range water-reducing admixtures
- w/c ratio as low as 0.17
- Increased risk of early age cracking
- 29 bridges: Cracking in 44 MPa bridges twice that of 31 MPa bridges

Mehta & Burrow, 2001

Oorzaken geringere prestatie in recente bouw

Wensen

1. Sneller bouwen (economisch motief)
   - Fijner cement
   - Hoger C_3S-gehalte
2. Hogere sterkte (lagere w/b factor)
3. Lager cementgehalte (sustainability motief)

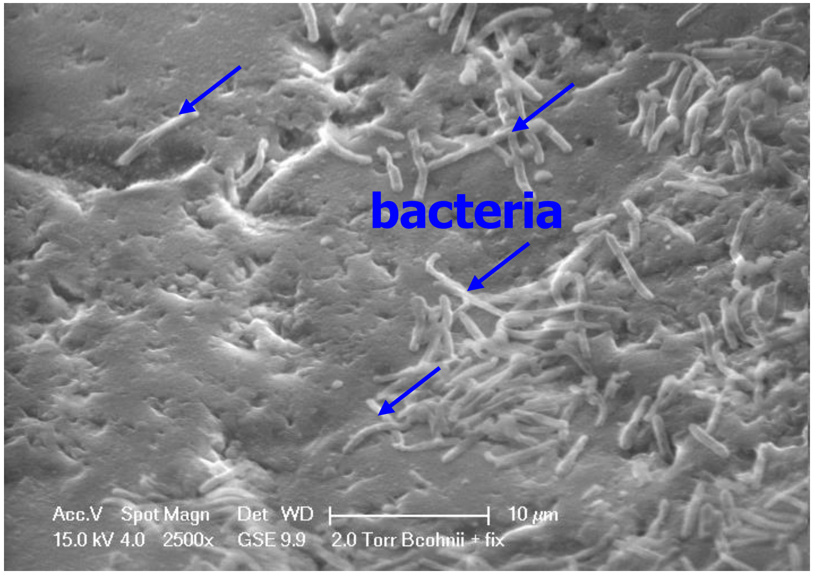
Consequenties

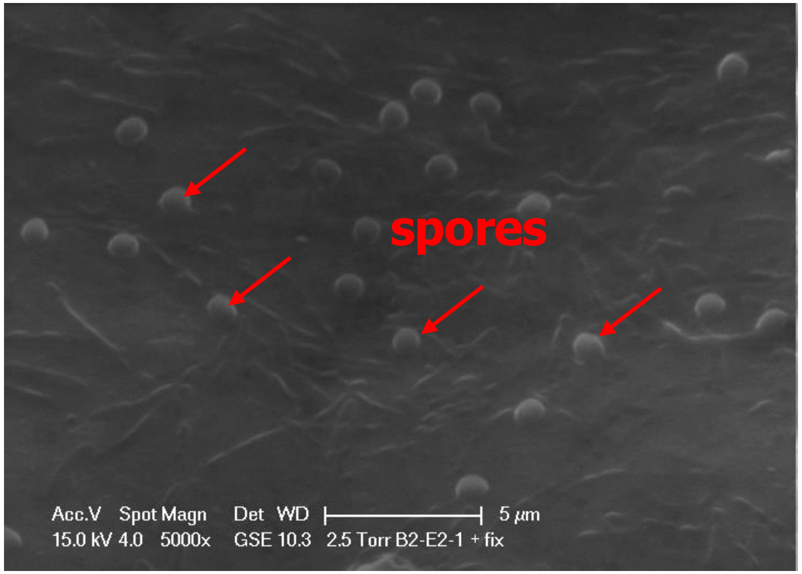
Ad 1: Grotere temperatuurspanningen tijdens verharding
Grotere kans op (micro)scheurvorming

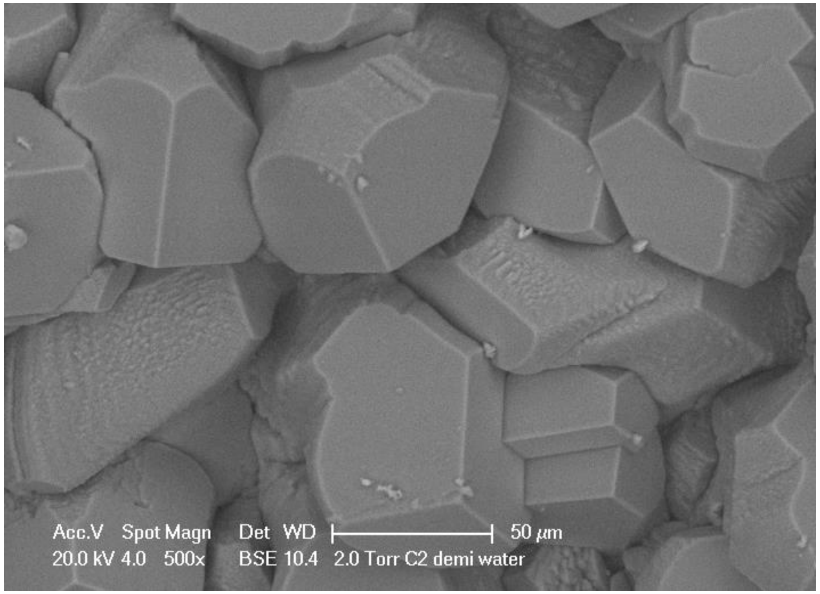
Ad 2: Meer autogene/verhardingskrimp ⟶ scheurgevoeliger

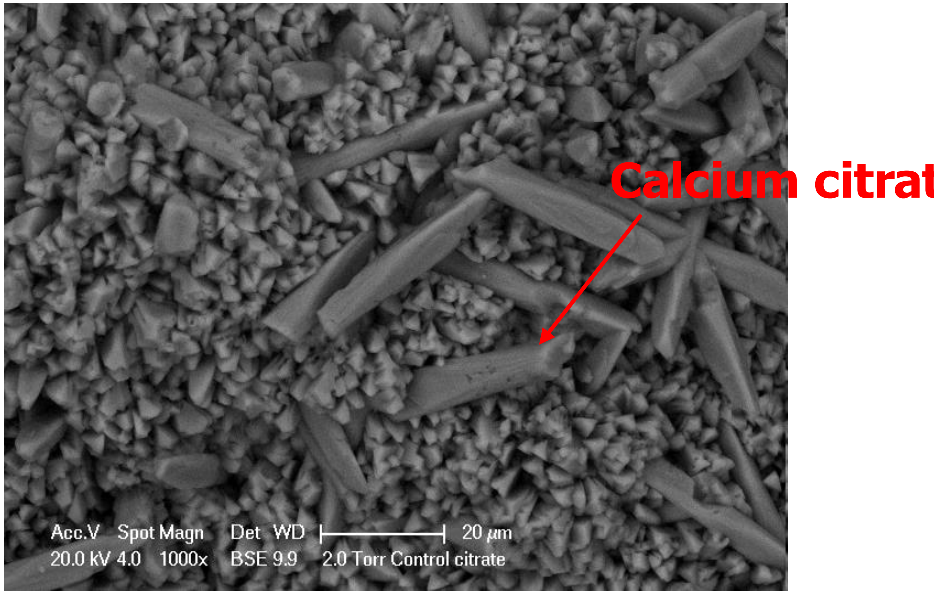
Ad 2: Afnemend vermogen tot zelfherstel van (micro)scheuren
Geringere weerstand tegen indringen agressieve stoffen (Cl)

Zelfherstellend beton - Biobeton





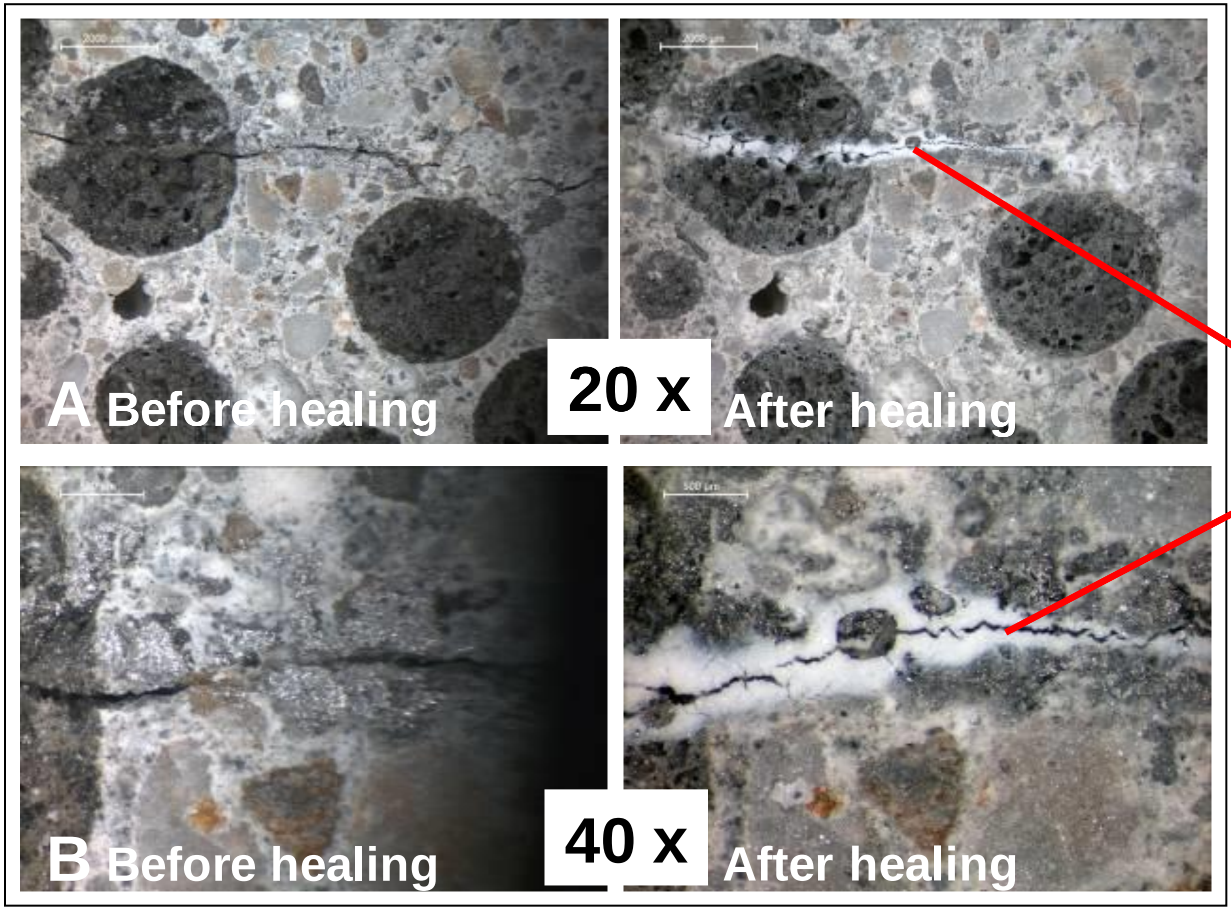




Thijssen, Microlab

Resultaten scheurheling – Traditioneel beton

Control specimens



Precipitate: No crack-sealing

0.15 mm crack width

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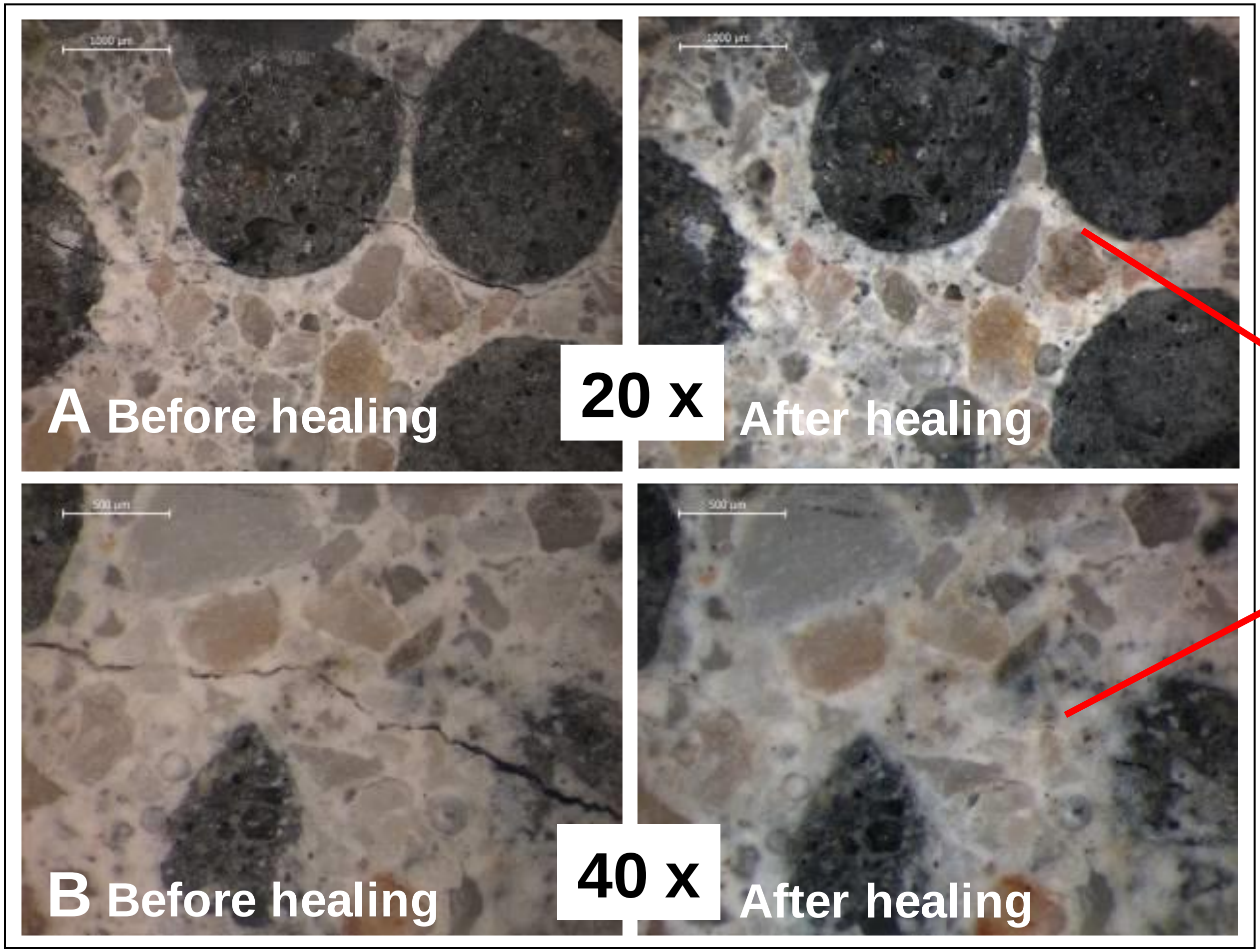
Resultaten scheurheling - Biobeton

Bacterial specimens



Perfect Crack-sealing

0.15 mm crack width

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Lichtgewicht beton - Misapor

Expanded glass

Key data

- watertight
- frost-resistant
- strength of over 10 N/mm^2
- dry density of only 950kg/m^3!
- necessary insulation performance is achieved with a construction thickness of as little as 40cm.
- **monolithic** exposed concrete structures without additional insulation
- Absolutely free of thermal bridges, of course, because just one **homogenous construction material** is used.

Woning van misapor-beton - Switzerland

Single family house in Trimmis, Switzerland | 2006 | Architecture: Lost, Basel

Beton – 3D printen – China - 4 verdiepingen

WinSun 3D-print appartement en villa, Shanghai

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Waarde infrastructuur van Nederland

Fysieke infrastructuur bedraagt ca. 50% van het nationale kapitaal!

Category	Value [€]	%-age of national wealth [%]
Infrastructure	$312\ 10^9$	8
Houses	$975\ 10^9$	25
Industrial buildings	$382\ 10^9$	10
Permanent capital goods	$156\ 10^9$	4
Total	$1825\ 10^9$	47

Note: National wealth of The Netherlands estimated at € $3800\ 10^9$ (2009)

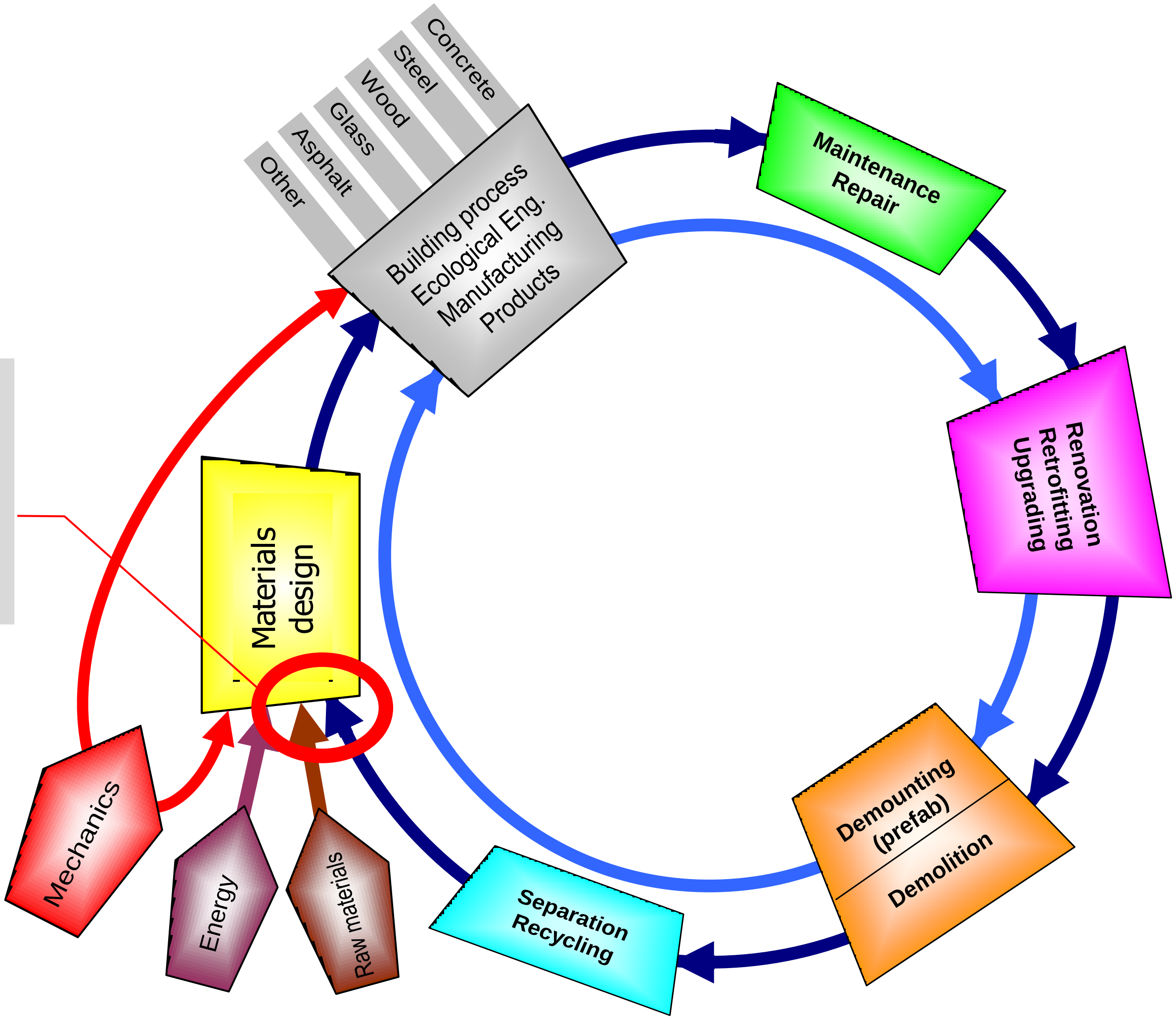
De Haan, 2009

Materiaalcyclus in bouw en onderwijs

Hoe houd ik de keten schoon?

- Opname afval!
- Recycling!

Electronisch materialen/ elementen paspoort



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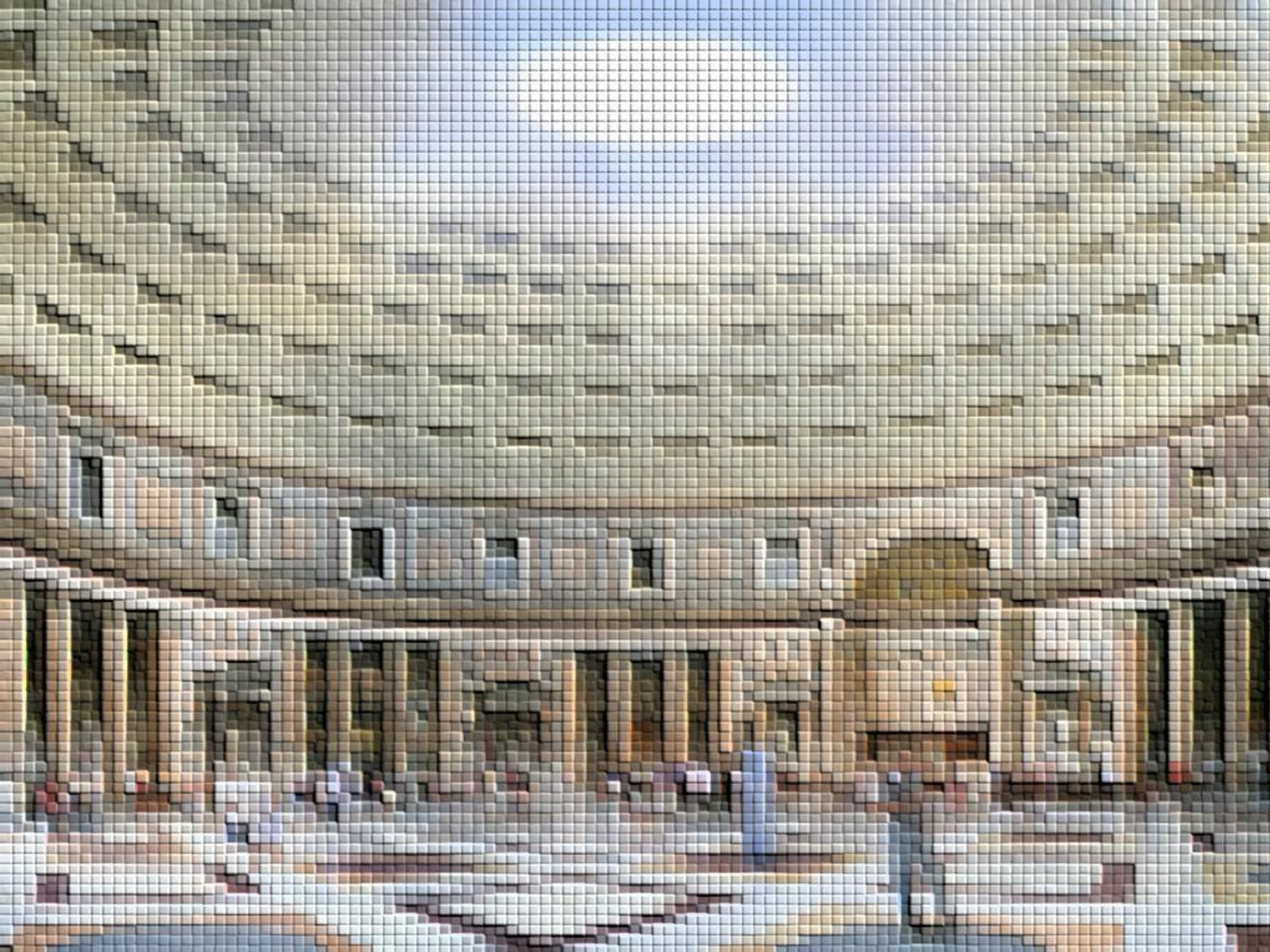
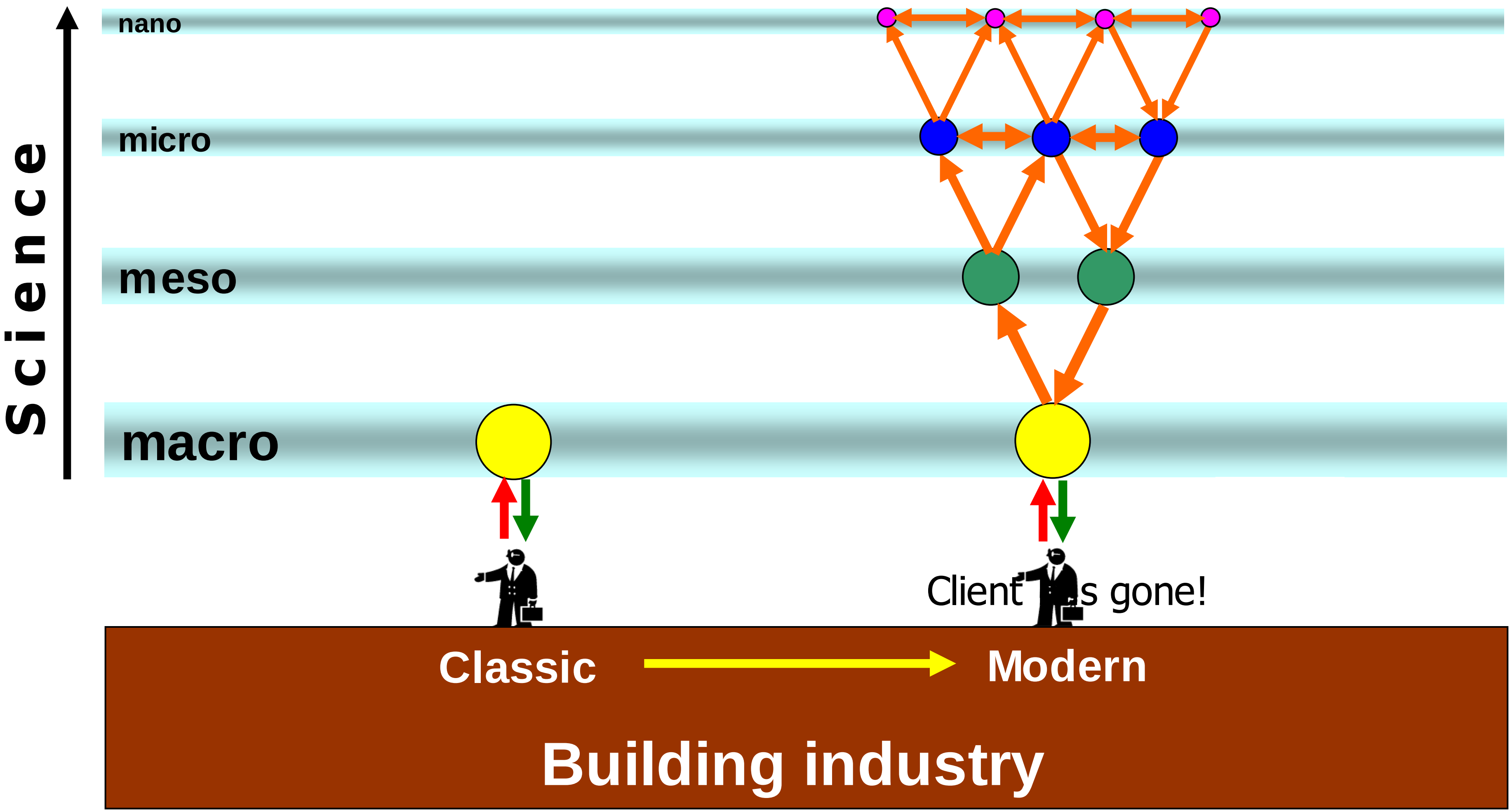


Misapor house - Switzerland

Holiday home in Sent, Switzerland | 2006 | Architect: Fries, Zurich

Implementation of research in innovation - Constraints



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Classic Building Codes

Code of Hammurabi (1750 BC)
"If a builder builds a house for someone, and does not construct it properly, and the house which he built falls in and kills its owner, then that builder shall be put to death".

Deuteronomium 22: 8 (14th century BC)
"When you build a new house, you must build a railing around the edge of its flat roof. That way you will not be considered guilty of murder if someone falls from the roof".

These were Performance-Based building codes!

Vitruvius (born 80–70 BC, died 15 BC)

"Architectura"

Pont du Gard (Fr)

"Architectura" (10 books)

Originally (and preferably):

- Building process in the hands of 1 person
- The builder should know all aspects of the building process
- The building process was an "holistic" activity

Concession:

- Complexity of the building process forces to share responsibilities (introduction of certificates etc.)

Original perception of architecture

Architecture is the **art** and **science** of designing and constructing buildings and other physical structures for human shelter or use.

Please note!:

- "Architecture" = Art **+** Science
- Building is for human shelter or use

So:

- Architecture is(was) not just "beauty" or "aesthetics"
- Architecture was an activity "in the service of mankind"
- Building codes were largely performance(functional)-based

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Age of Enlightenment (1650s to 1780s)

In the Age of Enlightment (or Age of Reason):

- The visible world is "decomposed" (scientific approach)
- Farewell to the perception of holisticity

Art and Science of architecture become **divorced**

- The building process is decomposed (fragmented)
- From a decomposed reality we "create", or "engineer", a new reality
- Building codes are designed as rule books, strongly focusing on the properties of the 'building blocks' (**prescriptive codes**!)

Experiences with prescriptive codes

- Quality is more than following a rule book.
- The more detailed a rule book is, the more interfaces you create between individual "building blocks". This increases the risk of communication errors.
- The more stringent prescriptive codes are (in an attempt to ensure high quality), the less room is left for innovation.
- The separation of *art* and *science* of the building process further hampers innovation (suffering from lack of holistic/integral view).
- Prescriptive codes are less suitable for addressing sustainability issues ("new responsibilities").

Towards "corporate social responsibility" (MVO)

- Performance-based codes are potentially better suited to stimulate, or accommodate, innovation (integral view on the building process)

- Reducing the huge impact of the building process on the environment is a responsibility of the whole society. Performance-based codes are potentially better suited to "implement" these responsibilities in concrete structural designs.

- The promise that performance-based codes are better suited to promote innovation will **not** come true if the risk of innovation is not shared by **all stakeholders** in the building process.

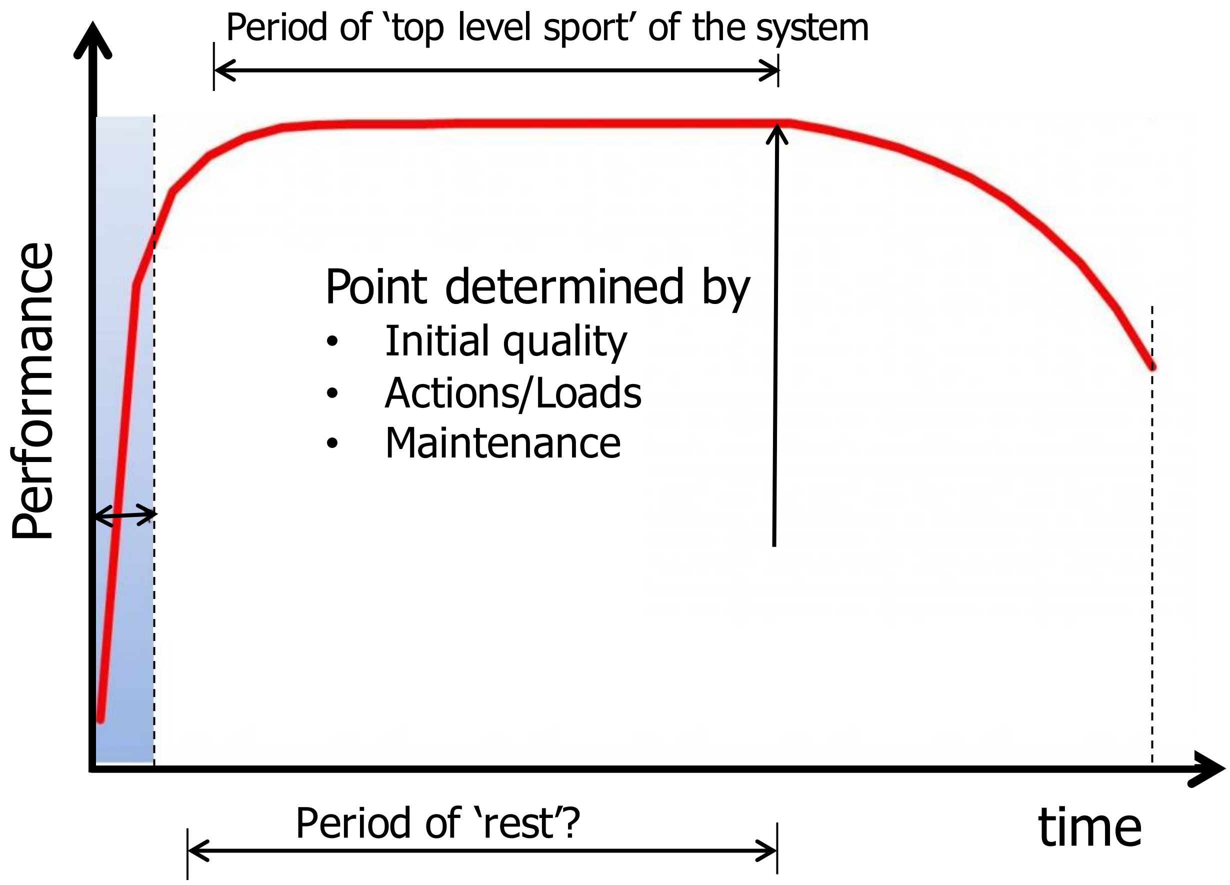
- Sharing of the risk of innovation presupposes **preparedness to communicate** details of the proposed innovation.

Where research comes in today

Fundamental research is needed for:

- Checking the suitability of alternative materials and design concepts for reducing the environmental impact of the building industry
- Developing reliable concepts for service life predictions and LCA's of structures made with traditional and alternative materials
- Design of new materials with predefined properties:
  - high performance
  - low environmental impact

Research for revealing hidden ageing issues



Portland cement: Basic chemical components

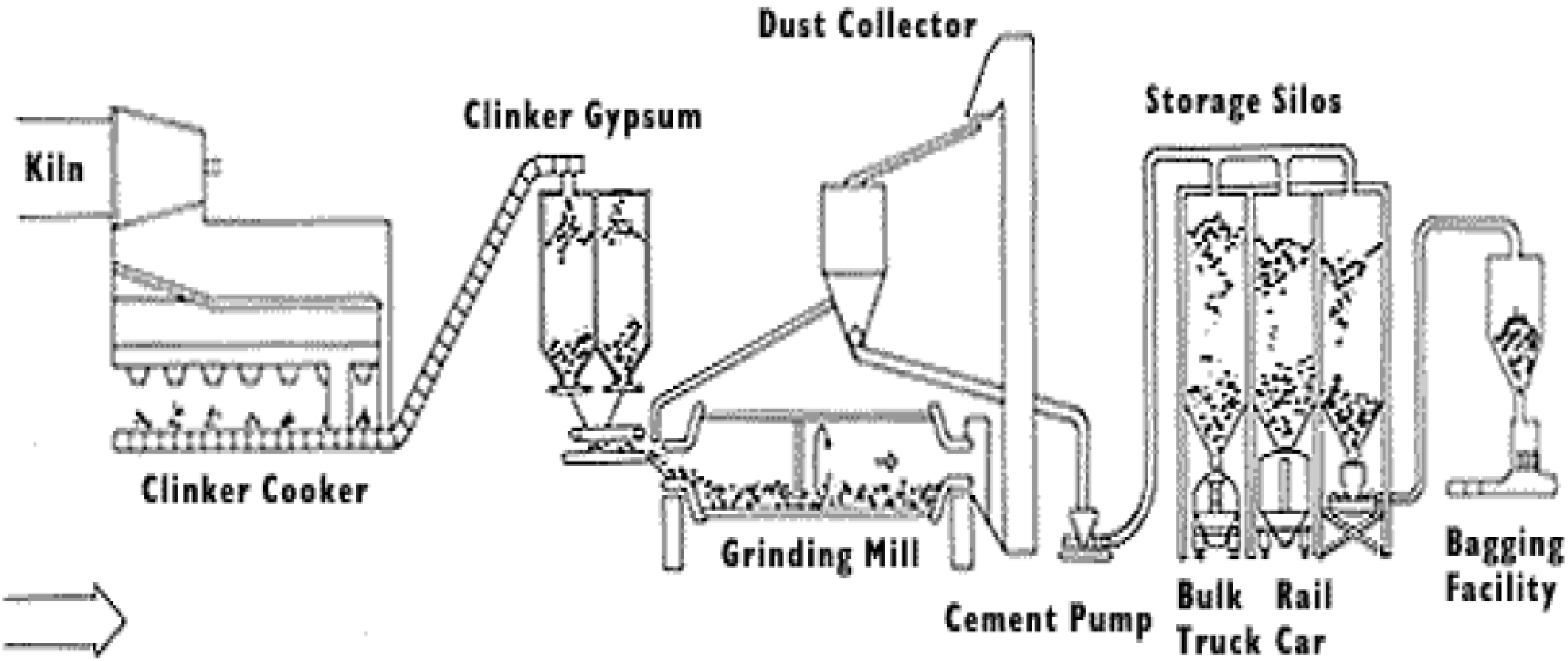
Basic chemical components of Portland cement:

- Calcium (Ca)
- Silicon (Si)
- Aluminum (Al)
- Iron (Fe)

Typical raw materials:

- Limestone ($CaCO_3$)
- Sand (SiO_2)
- Shale, Clay (SiO_2, Al_2O_3, Fe_2O_3)
- Iron Ore/Mill Shale (Fe_2O_3)

Portland cement – Production scheme



Once cooled, the clinker is ground with a small amount of gypsum.
It's now portland cement-ready to be bagged or shipped in bulk.

Cement and concrete - Facts

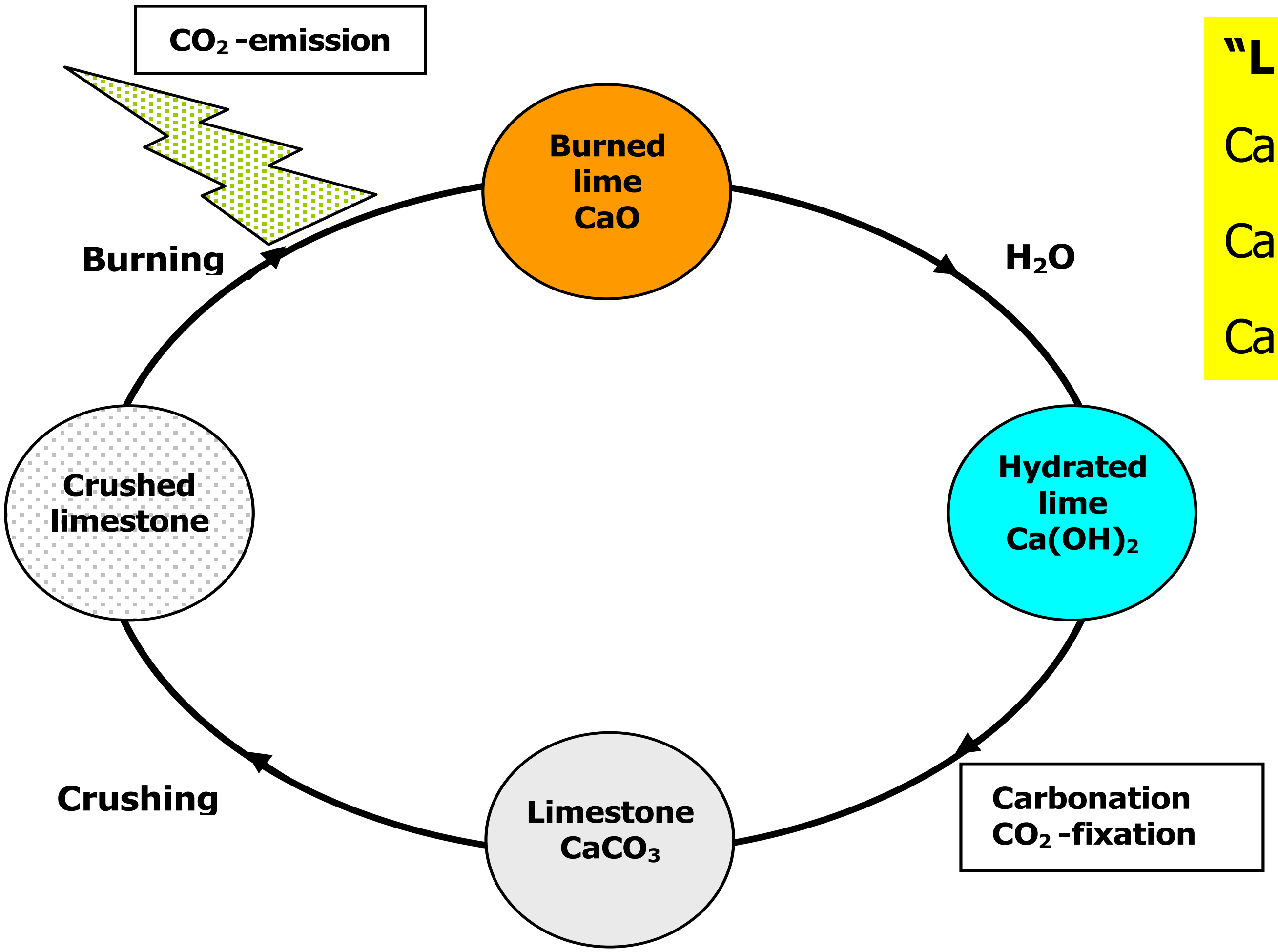
World Production cement (2001) : 1.6 billion tons
(Steel production : 900 million tons)

For each ton cement produced: 0.8 ton CO_2 is produced

- 0.525 ton from decalcination of limestone
- 0.335 ton from combustion of fuel in the kiln
- 0.05 ton from electricity

Per capita about 1 m^3 of concrete is used

De calcium hydroxide cyclus ("Lime cycle")



"Lime cycle"

$CaCO_3 \rightarrow CaO + CO_2$

$CaO + H_2O \rightarrow Ca(OH)_2$

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

CO_2 emission caused by cement production

Per ton cement:	0.8 ton CO_2
1 m^3 concrete contains about 350 kg cement (0.35 ton)	
Concrete consumption per capita:	1 m^3/y
Cement consumption per capita:	0.35 ton/y
Cement consumption world wide:	$6.99\ 10^9 \times 0.35 = 2.45\ 10^9$ ton
Cement-related CO_2 emission:	$0.8 \times 2.45\ 10^9 =$ **$1.96\ 10^9$** ton
Total CO_2 emission (2008, world wide):	**29.10^9** ton
Cement related CO_2 emission:	**6.8%**

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Ageing – Dutch perspective (II)

Potential savings by extending the service life of fixed capital goods

Total value fixed capital goods: € 1.825 10^9

Service life **X** [years]	Increase of service life [%]	Required expenses per year [€]	Savings per year [€]
50 (reference)	-	36.5 10^9	-
51	2	35.8 10^9	0.7 10^9
52.5	5	34.8 10^9	1.7 10^9
55	10	33.2 10^9	3.3 10^9
60	20	30.4 10^9	6.1 10^9
75	50	24.3 10^9	12.3 10^9
100	100	18.3 10^9	18.2 10^9

How can savings be accomplished?

- **Target: 10% extension of service life of fixed capital goods**
- Savings: € 3,300 10^6 /year
- Required investment: 20% of the savings: € 660 10^6 /year
- Assume 50% has to be invested in research: € 330 10^6 /year
- Assume 10% for fundamental ageing research: € 33 10^6 /year

Recommendation for the future:

1% of potential savings for fundamental ageing research!

Misapor house - Switzerland

Single family house in Chur, Switzerland | 2003 | Architecture: Schlegel, Malix

Two-component self-healing agent:

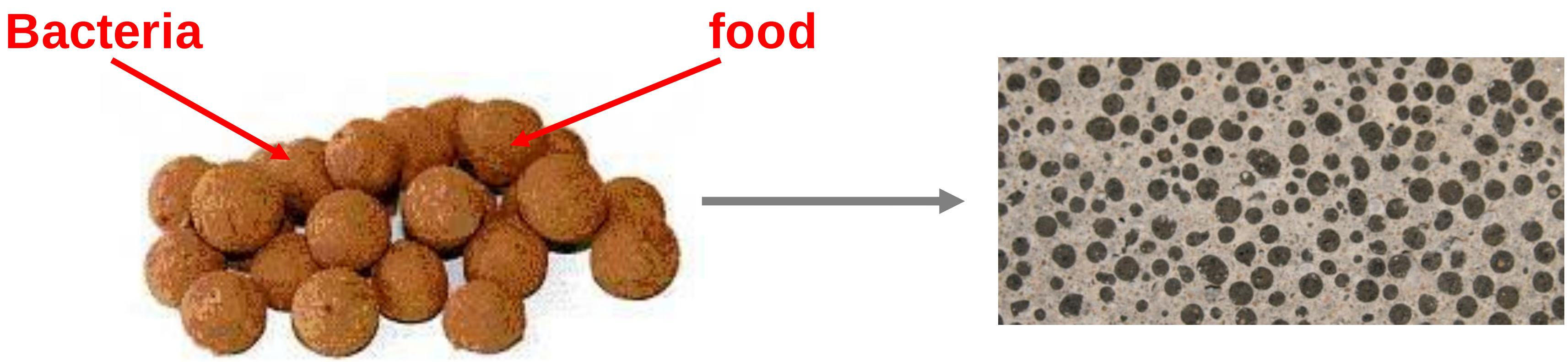
1. Bacteria (catalyst)

2. Mineral precursor compound (chemical / 'food')

TU Delft Patent:

→ **Packing of agents in porous aggregates**

Reservoir for healing agents (bacteria + chemicals)



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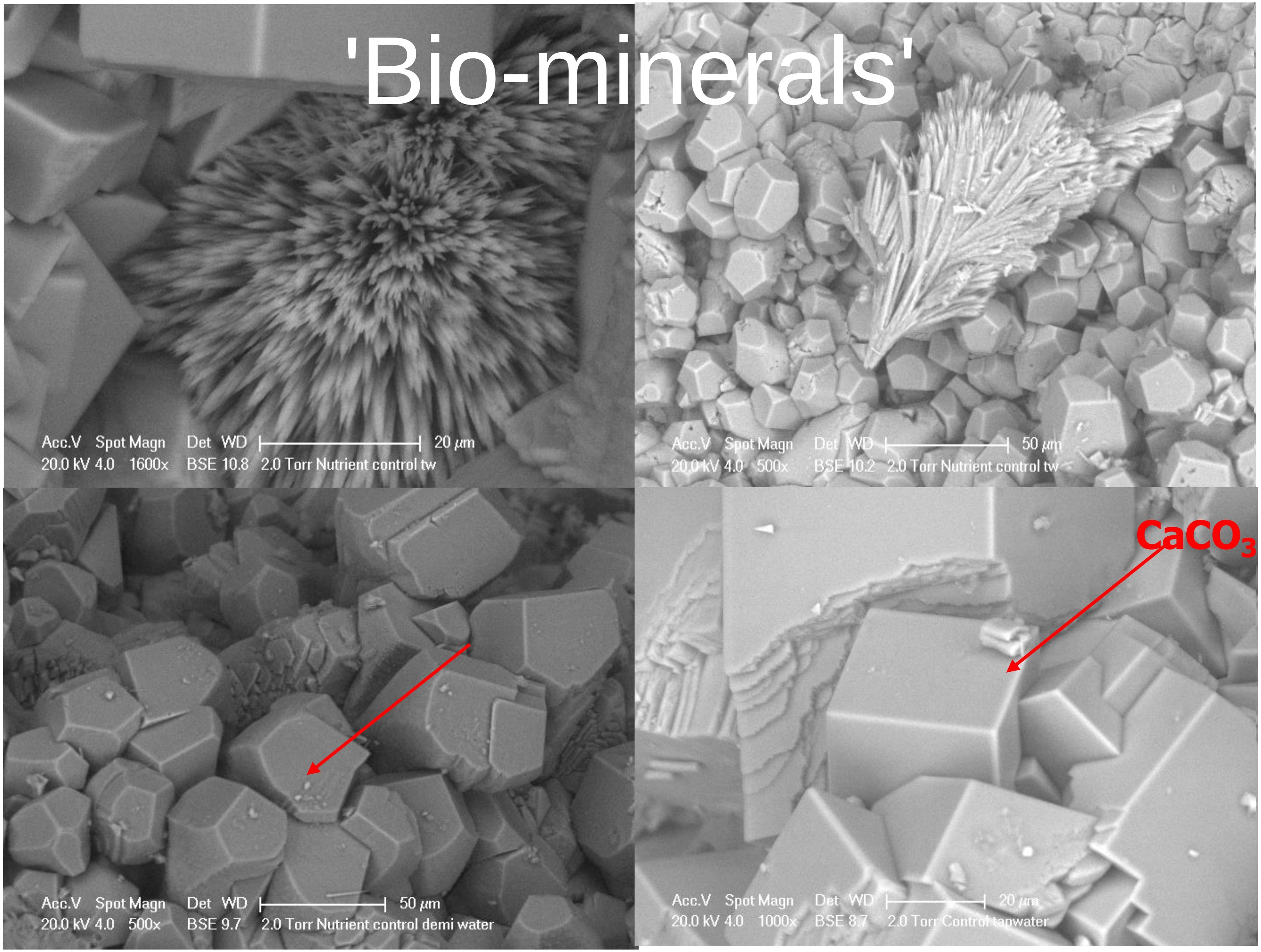
'Bio-minerals'



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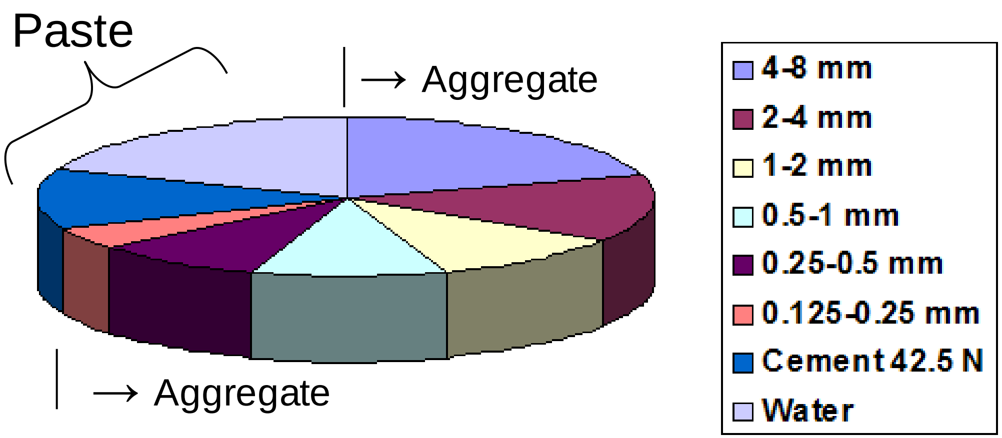
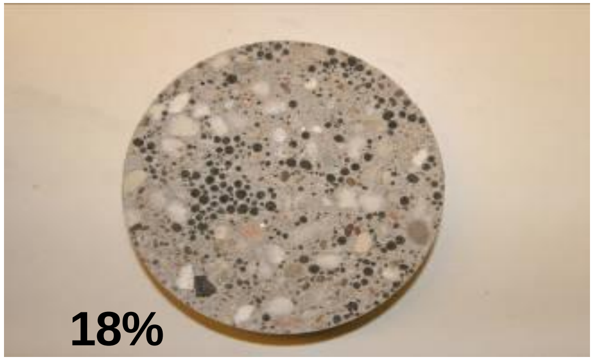
Concrete composition

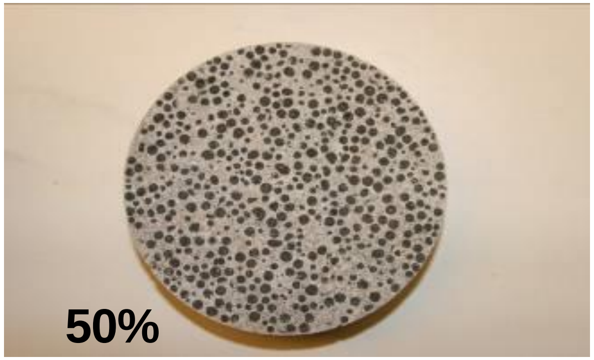
Volumetric



W/C ratio (weight) 0.5

Self-healing concrete:
Replace (fraction of) aggregate material by SH aggregates





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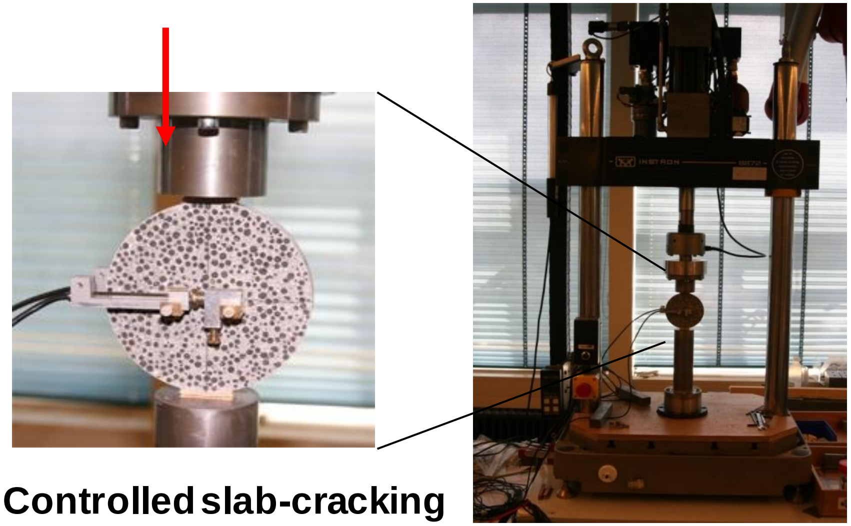
Procedure permeability testing

Expanded clay balls + bacteria + food

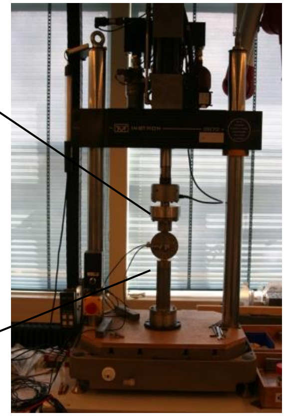
Specimens with varying healing agent proportions

Concrete cylinder: cut in slabs



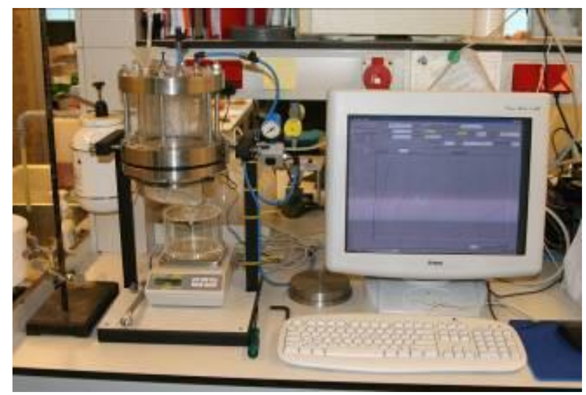
Controlled slab-cracking

Procedure permeability testing



Glue in ring

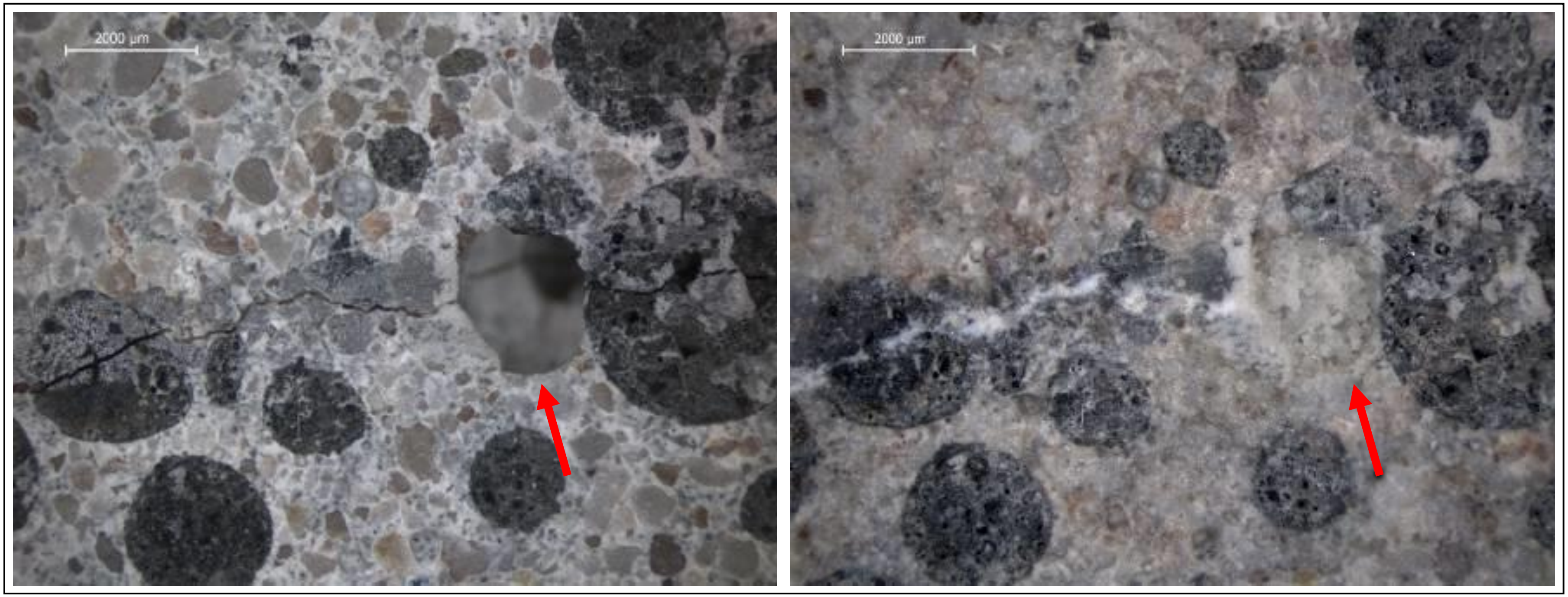
To permeability setup



Automated permeability determination

Results permeability testing

Bacterial concrete (bacteria, food)



0.15 mm crack width

Before **After**

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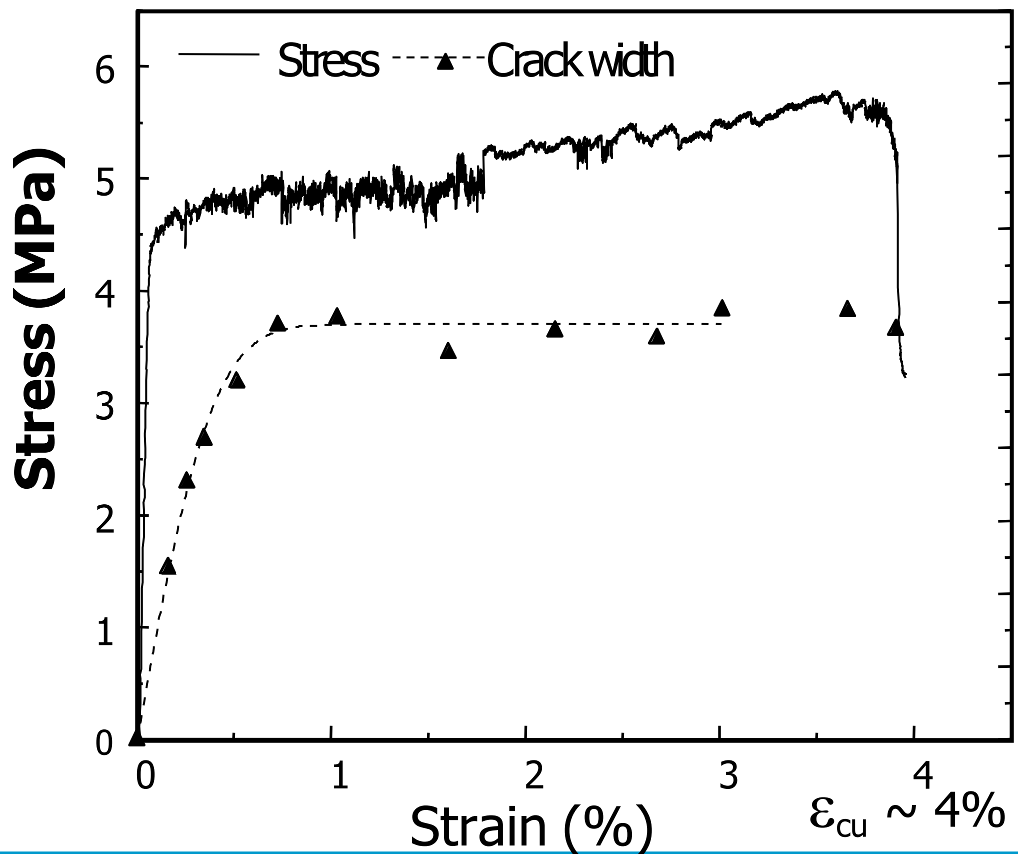
Metal-like Behavior of Engineered Cementitious Compound



Victor Li, Michigan, USA