Making a global impact: Self-healing concrete

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Cement-based Materials in Infrastructure
Where is concrete used?
Components of concrete

Concrete is a mixture of two components: aggregate and paste. The paste is made up of portland cement and water, which then binds with sand, gravel or crushed stone (aggregate).

- Up to 8% of air
- 7%-15% of cement
- 14%-21% of water
- 60%-75% of aggregates (Coarse & Fine)

https://www.cement.org/civilization
Impressive facts about concrete

**Concrete**

The most-used material in the world
Not the same thing as cement

**Ancient Rome**

The Ancient Romans perfected concrete – and it still stands today.
Concrete from the Latin word ‘concretus’

**Fun facts**

1st concrete road build in 1909
The British Army used concrete to detect enemy aircraft
The world’s largest concrete structure is in China

**Super material**

Incredibly high compression strength
Fire and water resistant
Continues to strengthen for decades

https://www.stratatiles.co.uk
https://www.flickr.com
https://en.wikipedia.org/wiki/Acoustic_mirror
https://www.khaleejtimes.com
Global perspective

4 Billion tonnes
Quantity of cement produced annually

500 Million tonnes
Expected rise in annual cement production ~ 10 years

$355.6 Billion
Value of global cement market
10% Industrial water used for cement production

10% CO₂ Global carbon emissions arising from cement production
Ageing Infrastructure
The effects of time

Mechanical
- Creep
- Fatigue
- Freeze/thaw
- Wetting/Drying
- Thermal
- Shrinkage

Chemical
- Build-up of Corrosion Products
- Further Corrosion: Surface Cracks, Stains
- Eventual Spalling, Corroded Bar Exposed
- Carbonation
- pH<10
  - Lost of passivation of steel

Before damage

Souza, 2019
Concrete management

01 Protect

02 Repair

03 Replace
The problem

Improving the state of our current and future infrastructure has become a priority

- Huge challenges in future construction & management
- Huge global investment needed in infrastructure
  - In the UK, 50% of all construction spending is on repair and maintenance
  - In the US, $18 - $21 billion/year on repair, protection and strengthening
- Repairs ineffective – EU: 20% fail in 5yrs, 55% in 10yrs, most in 25yrs
Biomimetic design
“It is not the strongest of the species that survives, nor the most intelligent but the one most responsive to change”
- Charles Darwin, 1809
Biomimetic materials

- Paradigm change in way we approach design and performance of infrastructure
  Can we proactively manage damage?

- Inspiration from natural/biological systems

  Ability to adapt and respond to their environment
  Ability to sense and repair

Materials and structures that continually monitor, regulate, adapt and repair themselves
Vision for Biomimetic Infrastructure Materials

Sustainable and resilient infrastructure containing truly biomimetic materials and structures that continually:

- Self-monitor and regulate
- Adapt and evolve
- Self-repair without external intervention

Transformation in self-healing of construction materials through:

- Self-control own sensing/diagnosis, immunisation and healing
- Self-healing of diverse and complex damage scenarios

![Diagram of self-diagnosis and self-healing processes]
Self-healing in cement

Autogenic < 150μm
Improving the immunity of cementitious systems

**Intrinsic**
- Fibres
- SAP
- Minerals

**Capsule**
- Minerals, bacteria, and polymers

**Vascular**
- Minerals, bacteria, and polymers
- Shape memory polymers

Autonomic > 150µm

Source: Souza, 2017

[Image of biomimetic product design]

https://www.breslergroup.com/blog/biomimetic-product-design
Improving the immunity of cementitious systems

Souza, 2017
Intrinsic healing

How it works?

Stimulate self-healing by controlling crack opening, offering more water for chemical healing, or including more minerals that can react and seal the cracks.

Z. Tan University of Cambridge

Fibres for crack control

Expansive water retaining polymers

Healing agents

Cyanoacrylates / resins / polymers ...

Minerals and crystalline admixtures

But also...
Calcite-precipitating bacteria

How it works?
Bacteria germinate and metabolic actions precipitate CaCO$_3$

Strains of Ca-precipitating bacteria, survivability of spores, metabolic paths and encapsulation approaches
Calcite-precipitating bacteria

Microscopic images of spores

SEM image calcite

A healed crack
Encapsulation

How it works?

Microcapsules

Triggering

Healed crack

Credit: Rami Alghamri

Microcapsules
Microcapsules production

Pan coating

Membrane emulsification
Microcapsules production

Microfluidics
Vascular networks

How it works?

Connected capillary tubes for large and repeated delivery of cargo
Vascular networks

Full scale application of active network

Network embedded in concrete

Activated network releasing agent

Shape memory polymers

How it works?
Crack restriction through tendon activation

Shape memory polymers

Polyethylene terephthalate (PET)

Materials
Self-control
Self-immunity
Self-diagnosis
Smart
Sensing

- **Smart**: Self-healing, self-sensing, self-diagnosing
- **Controlling**: Self-diagnosing
- **Reasoning**: Self-sensing concrete
- **Sensing**: Conventional monitoring

Adapted from: Han et al (2015) DOI: 10.1177/1045389X15586452
Sensing

Self-sensing using conductive nanomaterials

Corrosion detection

External novel strain sensors

H. Taha, University of Bath

J Zhang, University of Bath
Reality or fiction?

http://www.basiliskconcrete.com/dig-it/?lang=en

White et al., 2001
Field applications

Full-scale application of combined systems for multi-scale healing in RC panels

A465 Heads of the Valleys
Section 2: Gilwern to Brynmawr
http://a465gilwern2brynmawr.co.uk

## Field applications

<table>
<thead>
<tr>
<th>Panel</th>
<th>Description</th>
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<tbody>
<tr>
<td>Panel A</td>
<td>MC</td>
</tr>
<tr>
<td>Panel B</td>
<td>SMP+FN</td>
</tr>
<tr>
<td>Panel C</td>
<td>BAC+FN</td>
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<tr>
<td>Panel D</td>
<td>CTRL</td>
</tr>
<tr>
<td>Panel E</td>
<td>FN</td>
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(H) 1.85m x (W) 1.00m x (T) 0.15m C40/50 concrete

Field applications | Testing and outcomes

Testing & Measurements

Outcomes

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Panel</th>
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<tbody>
<tr>
<td>SMP &amp; Flow networks</td>
<td>Microcapsules</td>
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<tr>
<td>Crack healing (load regain)</td>
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<tr>
<td>Crack closure / sealing</td>
<td>✔</td>
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Logistics and construction challenges
Feasibility
Future research and development

RM4L Commercial application

New Civil Engineering Building in West Cambridge
UK Collaboratorium for Research in Infrastructure & Cities (UKCRIC)
The National Research Facility for Infrastructure Sensing
- Projected budget of £36m
RM4L Commercial application
Global commercial success signs

- Netherlands/TUDelft: water basin of Port of Rotterdam with bacteria-based SH
- Netherlands/TUDelft: biogROUT for repair
- Netherlands/TUDelft: self-healing asphalt, 1st motorway in 2010, now 4 others, could save €90M/yr
- Schlumberger: self-healing oilwell cement
- Commercial self-healing coatings for polymer composites (Autonomic Materials/Illinois)
Main challenges

- Extensive validation and long-term performance
- Design procedures and compliance with standards
- Development for limited range of damage
- Appropriate cost for commercial viability
Conclusions

**Biomimetic materials are the future of infrastructure**

- Self-healing systems have been developed
- Next generation smart materials are the next step

**Commercialisation**
- Industry driven
- Public traction

**The Challenge**
- We only have 3 years to go

**The Opportunity**
- We still have 3 years to go
THANK YOU
FURTHER INFORMATION:
HTTP://RM4L.COM/ABOUT/