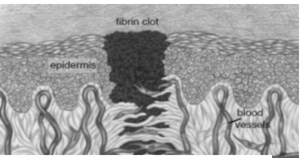
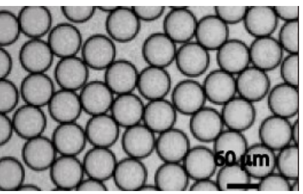
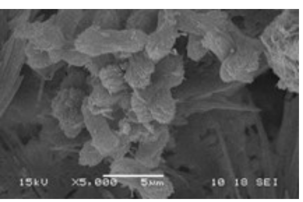
INGENIA

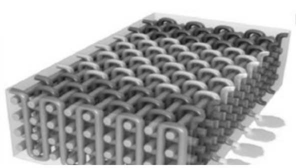
www. nottinghillgate.co.uk



www.surgical-blog.com







www.otm.illinois.edu

EPSRC Pioneering research and skills

Ground and Structural Engineering Research Challenge

Materials for Life (M4L):

Biomimetic multi-scale damage immunity for construction materials

Prof Bob Lark, Dr Diane Gardner, Dr Michael Harbottle, Prof Tony Jefferson.

Dr Abir Al-Tabbaa, Dr Janet Lees, Dr Michelle Oyen, Prof Chris Abell.

Dr Kevin Paine, Dr Richard Cooper, Dr Andrew Heath.

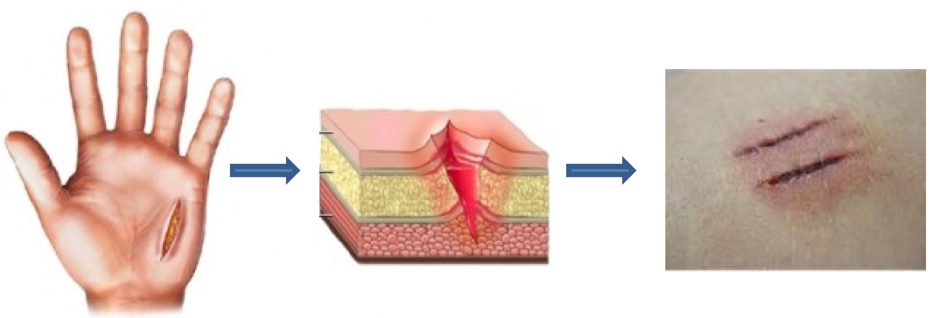
University of Bath

Cardiff University / Prifysgol Caerdydd

University of Cambridge

M4L: Vision

- A **sustainable and resilient** built environment and infrastructure
- **Self healing materials** and structures that continually monitor, regulate, adapt and repair themselves
- Enhanced **durability**, improved **safety**, reduced maintenance costs

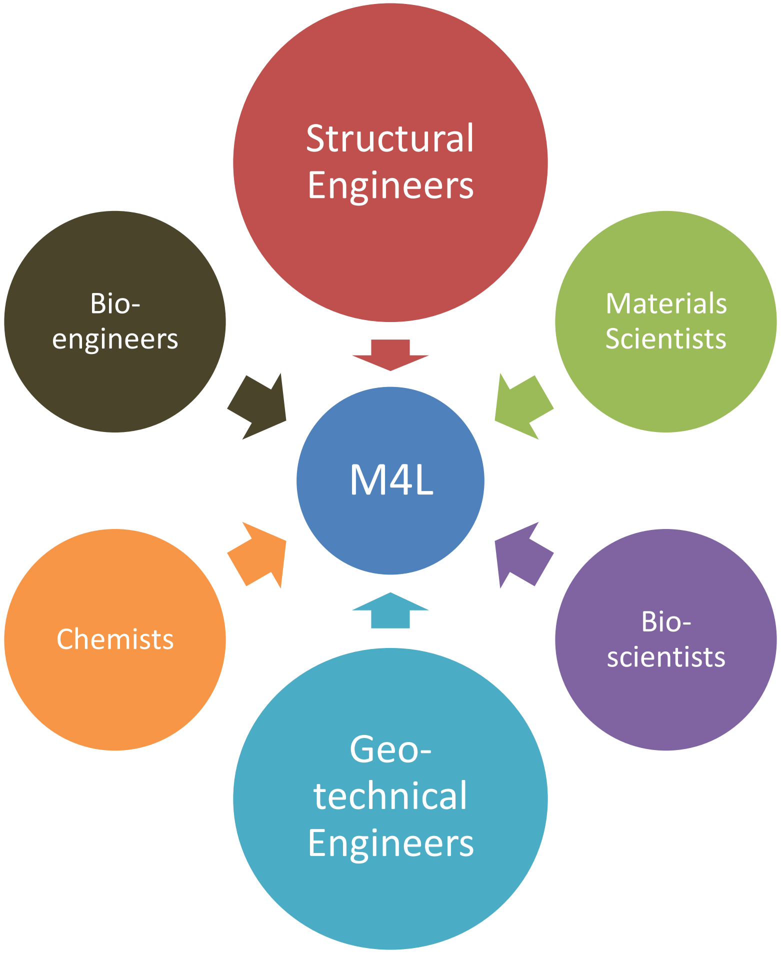


M4L *inspired by nature*

M4L: Scope and Aims

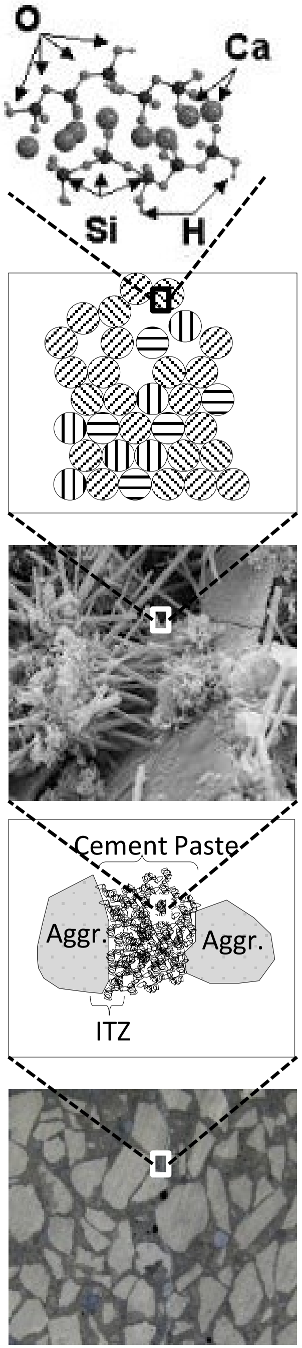
A new generation of unique, versatile & robust self-healing construction materials

- Address structural/geotechnical applications & damage scenarios
- Focus on conglomerate materials (e.g. concrete, grout, grouted soils)
- Interdisciplinary, inspired by nature
- Self-healing over multiple spatial & temporal scales
- Novel and transformative
- Born of both Networks



LimesNet

FIF EPSRC Network Future Infrastructure Forum



Atomic scale
C-S-H
Molecular level
<1nm

Nano scale
C-S-H matrix/gel
5nm – 100nm

Nano/Micro scale
Cement paste
0.1µm – 100µm

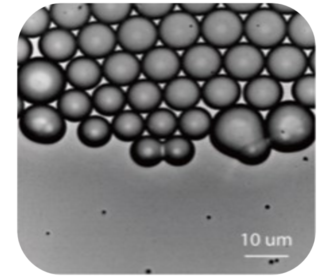
Micro/Meso scale
Cement paste + sand
0.05mm – 5mm

Macro scale
Mortar, Concrete
>5mm

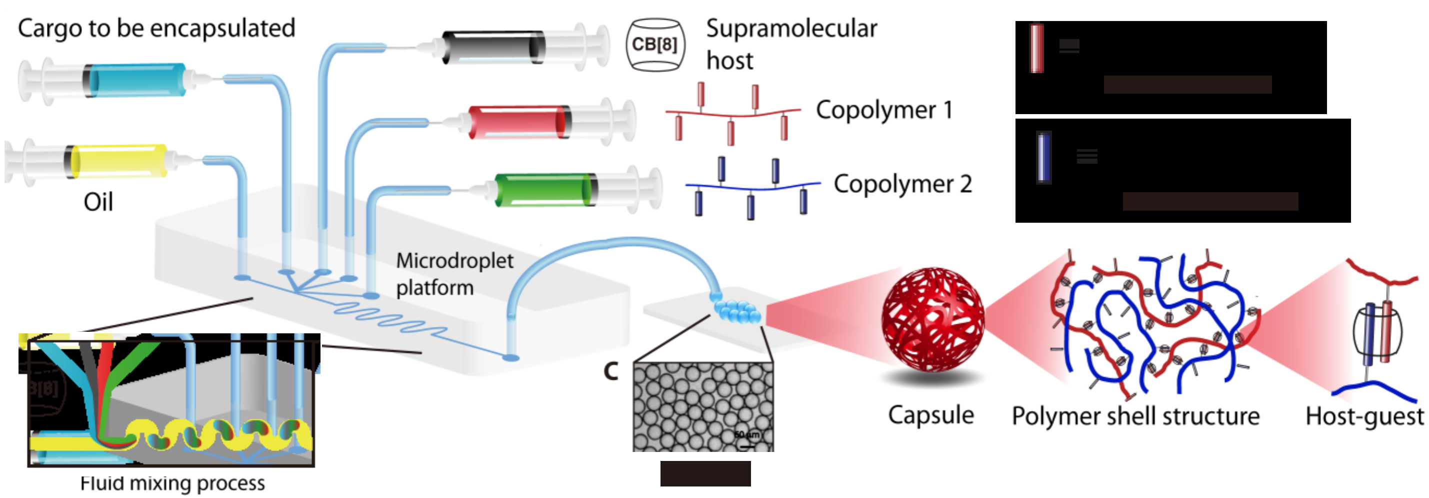
Multi-scale Damage

Size of crack /dislocation	Scale of phase	Description of damage/dislocation
<1nm	5nm (nano)	Defects in the structure (e.g. vacancies due to dissolution of certain atoms, calcium leaching, interstitial or extra atoms etc.). Structural changes due to chemical reactions such as alkali-silica reaction etc.
5nm – 100nm	100nm (nano)	Dislocations between CSH particles seen as changes to packing of CSH 'globules'
0.1µm - 50µm	0.1µm - 100µm (nano/micro)	Dislocations (or damage) within the CSH matric and $Ca(OH)_2$ crystals.
50µm – 1mm	50µm – 5mm (micro-meso)	Micro cracks coalesce to form networks of meso cracks. Also debonding between aggregate particles and cement matrix in Interface Transition Zones (ITZs).
0.2mm – 10mm	>1mm (macro)	Continuous macro cracks formed when meso cracks in hardened cement paste merge and also link adjacent debonded ITZs.

Micro-scale Healing

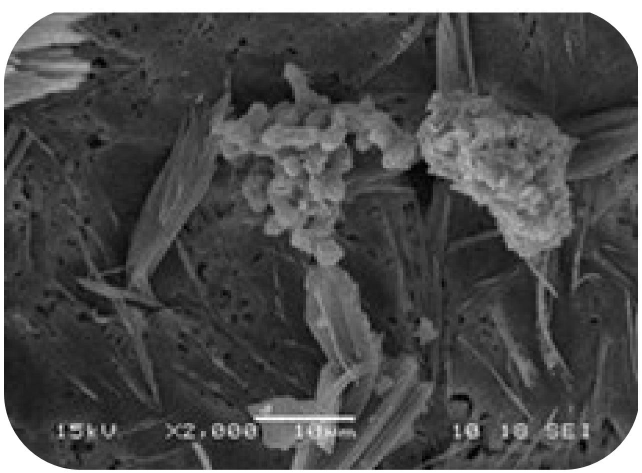


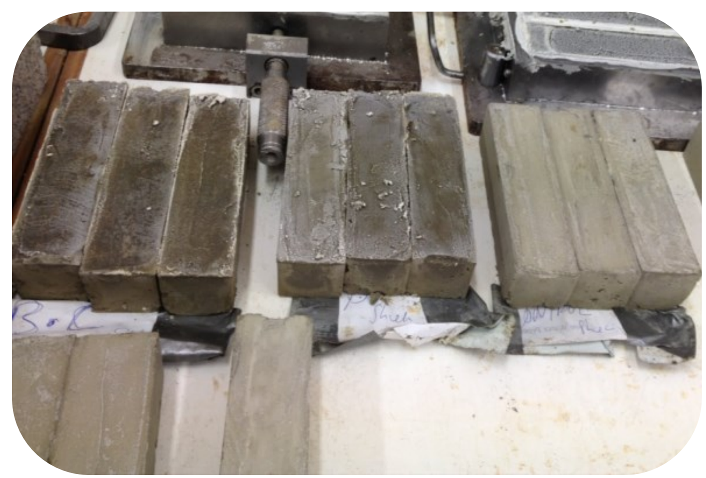
- Microencapsulation
- Range of cargos
- Responsive to different stimuli and trigger mechanisms
- Release and healing efficiency



Meso-scale Healing

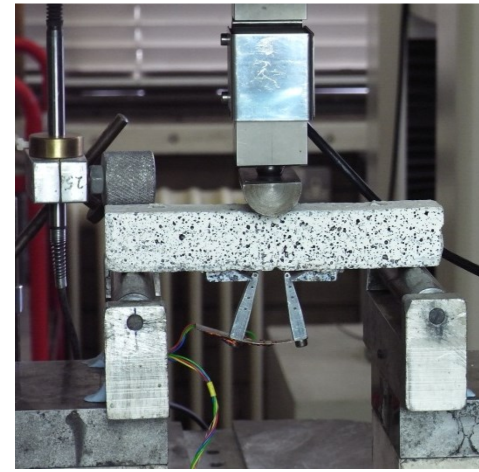
- Bacterial healing
- Calcium Carbonate ($CaCO_3$) / Calcite
- Delivery & survivability in cementitious matrix
- Release & healing efficiency

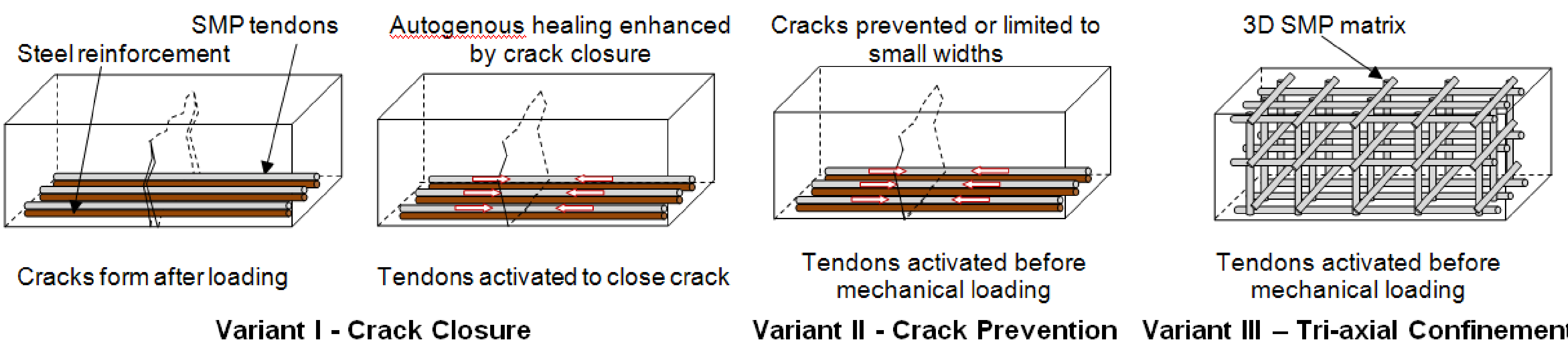


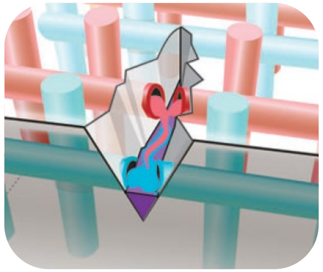


Macro-scale Healing

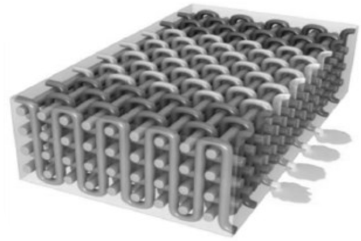
- Autonomic / Autogenic
- Use of SMP tendons and grids
- Use of recycled plastics
- Monitoring & activation systems
- Alternative crack control mechanisms



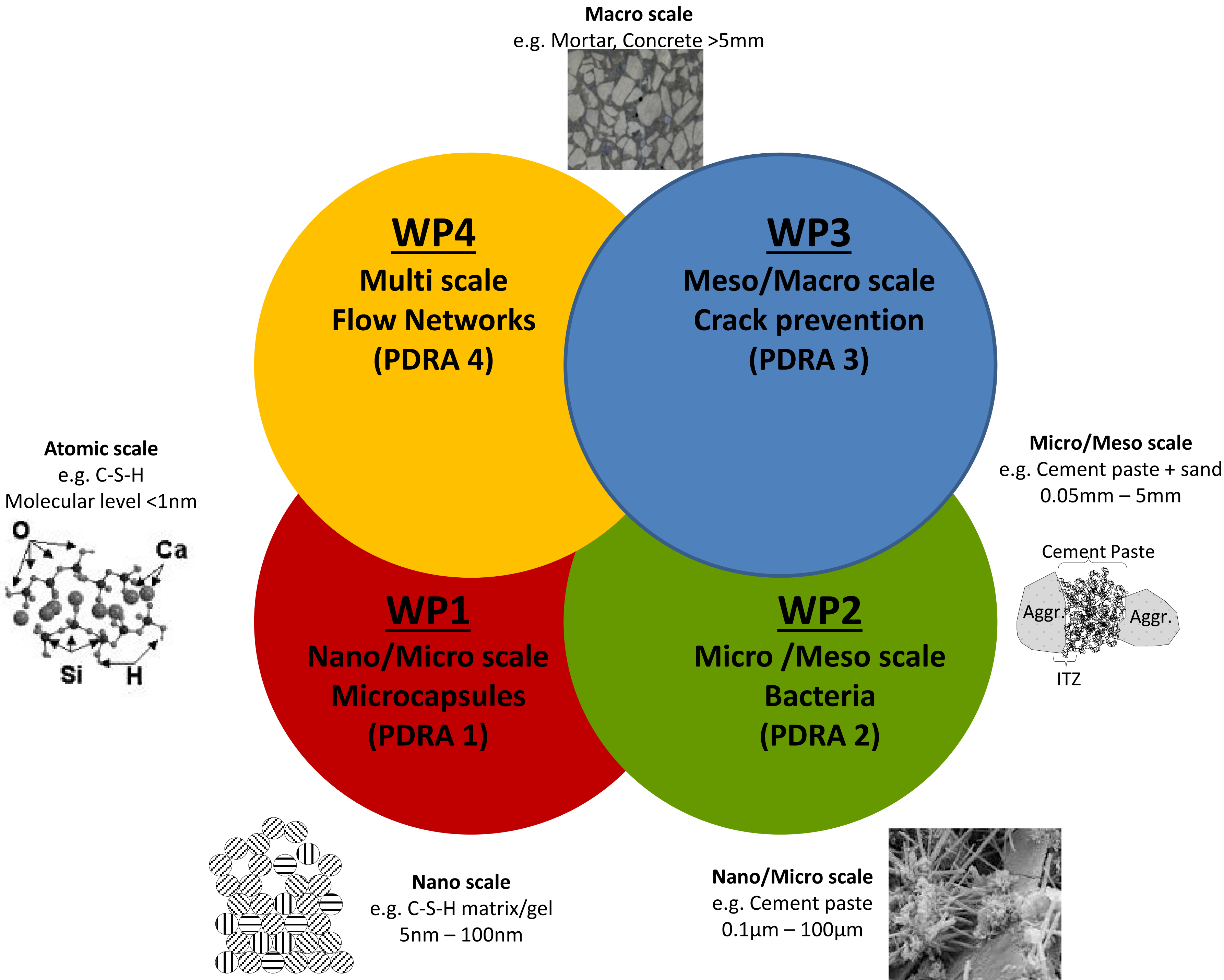


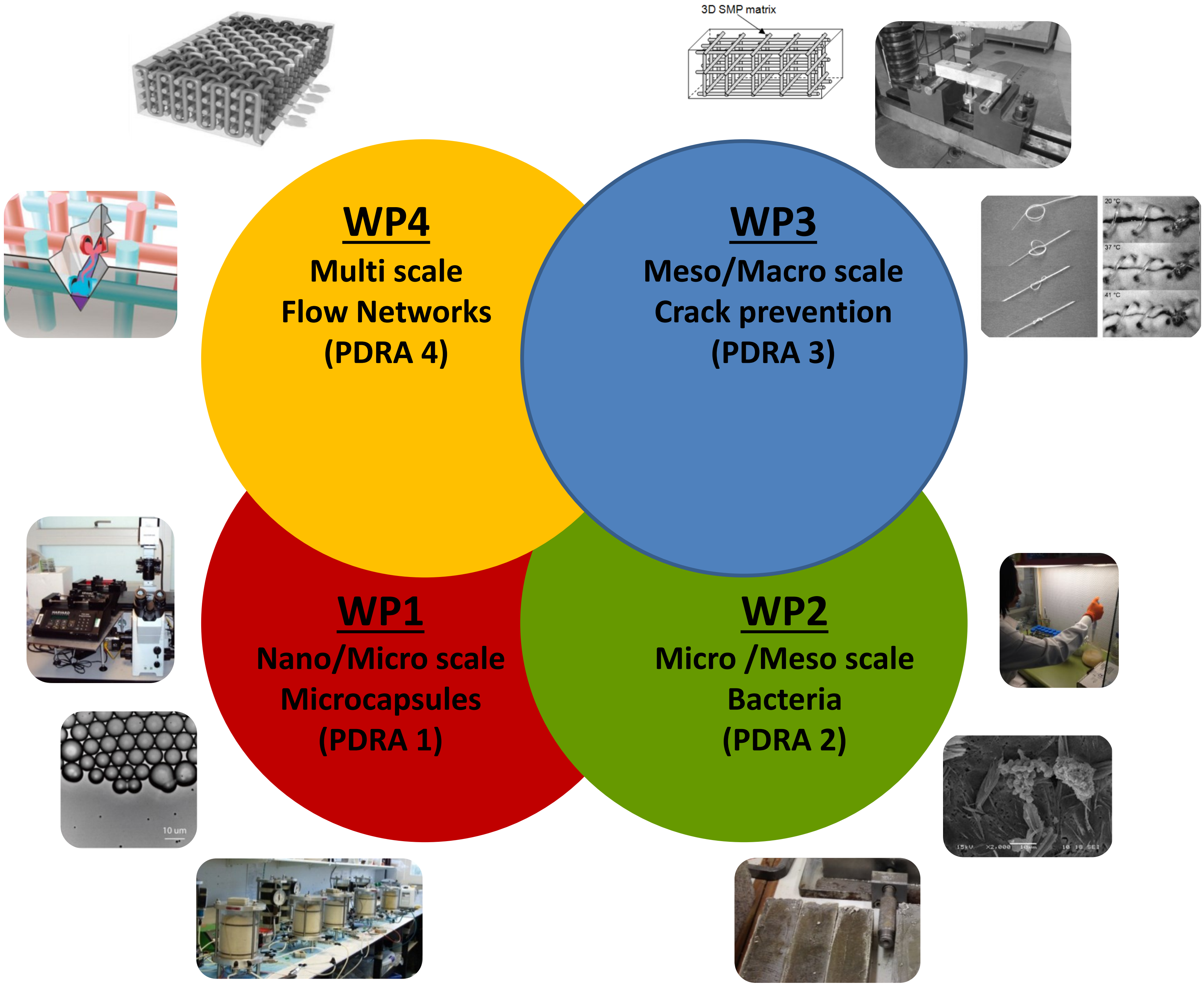


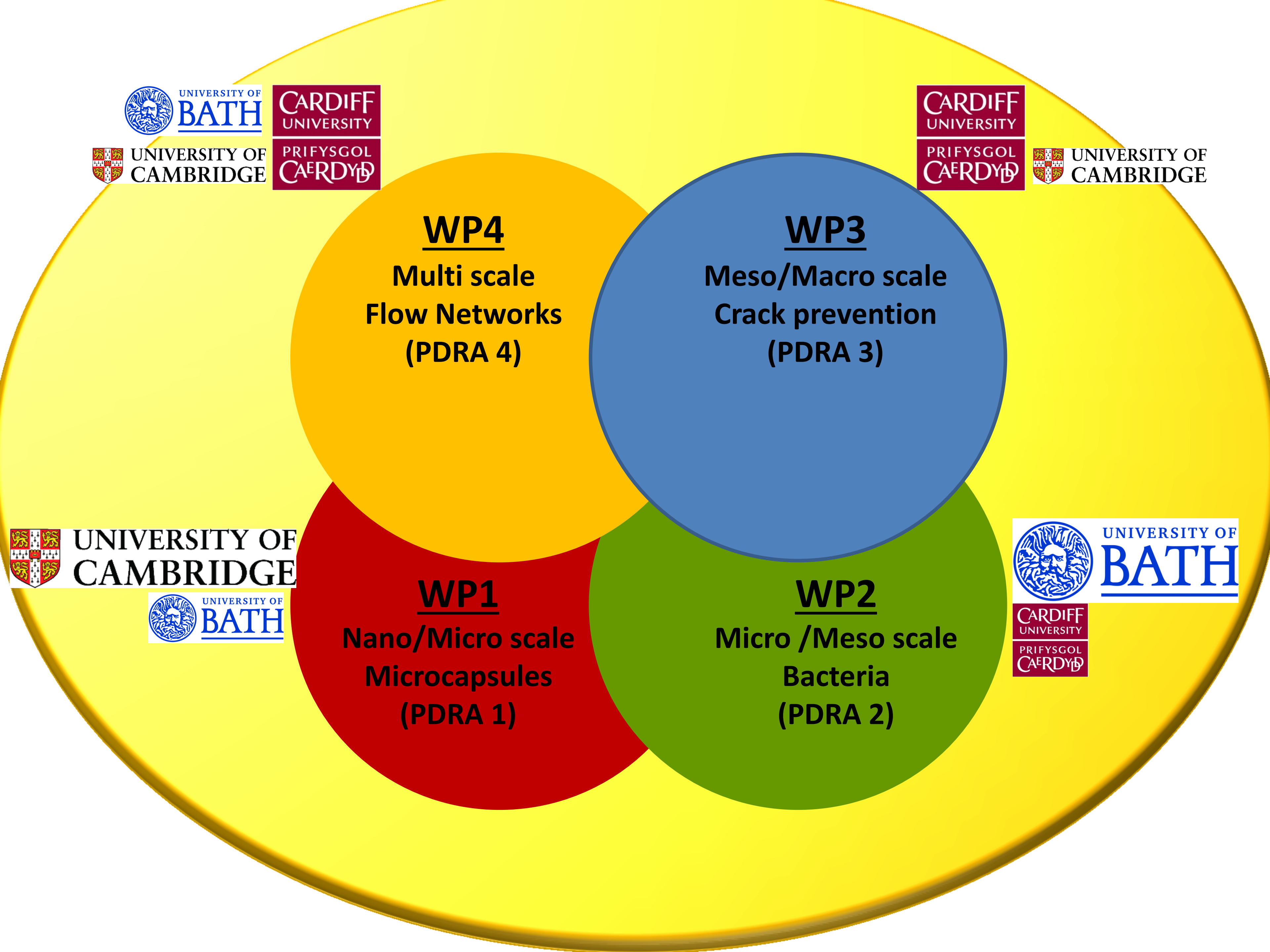
Multi-scale Healing



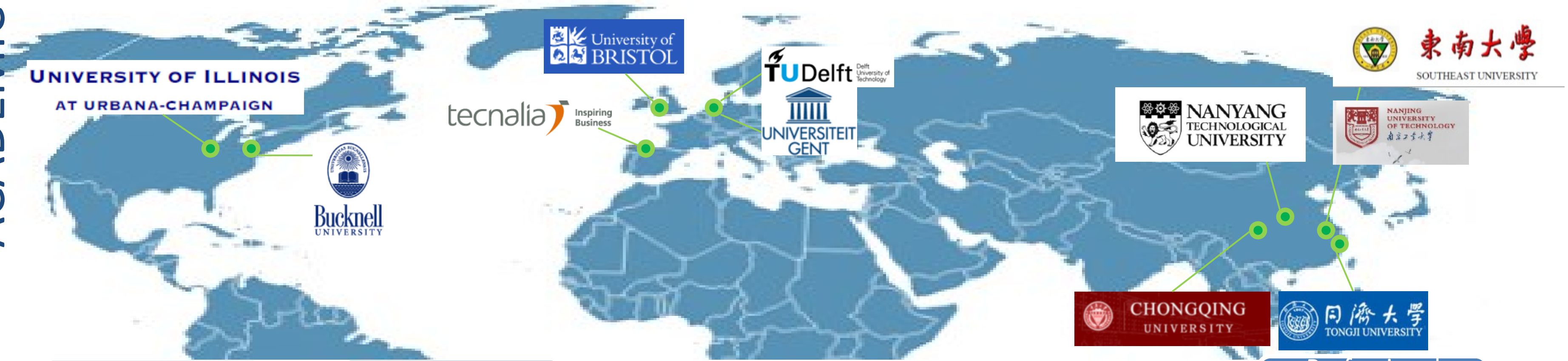
- Vascular flow networks
- Methods for network incorporation in cementitious matrix
- Integration & testing of multi-scale healing systems
- Optimise system behaviour
- Economic study of individual & combined healing systems
- Demonstration projects in field environments


Macro scale
e.g. Mortar, Concrete >5mm
WP4
Multi scale
Flow Networks
(PDRA 4)
WP3
Meso/Macro scale
Crack prevention
(PDRA 3)
Atomic scale
e.g. C-S-H
Molecular level <1nm
O
Ca
Si
H
Micro/Meso scale
e.g. Cement paste + sand
0.05mm – 5mm
Cement Paste
Aggr.
Aggr.
ITZ
WP1
Nano/Micro scale
Microcapsules
(PDRA 1)
WP2
Micro /Meso scale
Bacteria
(PDRA 2)
Nano scale
e.g. C-S-H matrix/gel
5nm – 100nm
Nano/Micro scale
e.g. Cement paste
0.1µm – 100µm


3D SMP matrix
WP4
Multi scale
Flow Networks
(PDRA 4)
WP3
Meso/Macro scale
Crack prevention
(PDRA 3)
20 °C
37 °C
41 °C
WP1
Nano/Micro scale
Microcapsules
(PDRA 1)
WP2
Micro /Meso scale
Bacteria
(PDRA 2)
10 um


WP4
Multi scale
Flow Networks
(PDRA 4)
WP3
Meso/Macro scale
Crack prevention
(PDRA 3)
WP1
Nano/Micro scale
Microcapsules
(PDRA 1)
WP2
Micro /Meso scale
Bacteria
(PDRA 2)
UNIVERSITY OF BATH
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
UNIVERSITY OF CAMBRIDGE

ACADEMIC



INDUSTRIAL

Contracting Engineers
- Costain
- Griffiths civil engineering and construction
- Laing O'Rourke

Consulting Engineers
- ARUP
- Atkins – The official engineering design services provider for the London 2012 Games
- Mott MacDonald
- Parsons Brinckerhoff
- URS

Client Organisations
- Highways Agency – Safe roads, reliable journeys, informed travellers
- nationalgrid
- Schlumberger
- Shell
- Llywodraeth Cymru Welsh Government

R&D Organisations
- bre
- ciria
- Knowledge Transfer Network – Modern Built Environment
- TRL – Creating the future of transport

Professional Institutions and Trade Organisations
- fib CEB-FIP
- ice – Institution of Civil Engineers
- The Institution of Structural Engineers
- mpa – The Concrete Centre

£1.04M
Contribution in kind

•Field demonstration projects •Steering group participation •Scale-up and commercialisation
• Technology transfer • Host PDRA visits • Dissemination of project findings • Fund PhD students

Scale-Up and Affordability

Scale up

- Learning from our academic collaborators and other sectors
- Potential scale up of individual components being identified
- Industrial collaborators will help address constructability challenges

Affordability

- Promising initiatives in other sectors to minimise production costs of similar materials e.g. microcapsules
- Compatibility with cost of admixtures and additives
- Potential use of recycled materials, e.g. plastics
- Reduction in overall costs, e.g. with less steel reinforcement and cement
- Reduction in whole life costs

www.tudelft.nl

Scaling up of healing agent at TU Delft

www.tudelft.nl

Whole Life Costs

Initial indications demonstrate up to 50% saving in life cycle costs

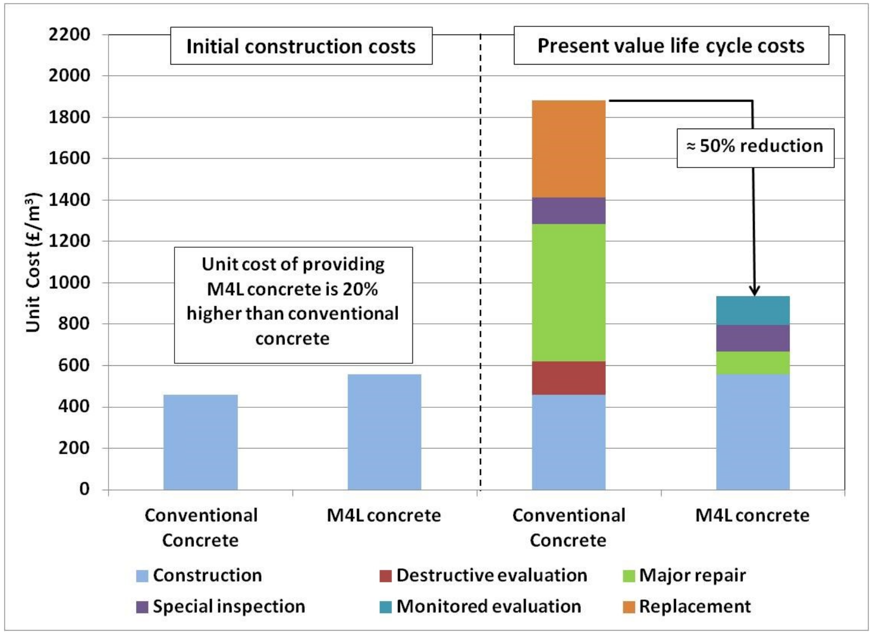
Activity in T4.5 will address the whole life cost in more detail.

Items for steel reinforced concrete	Quantity for 1m³ of concrete (kg)	Unit Cost (£/kg)	Cost for 1m³ of conventional reinforced concrete (£)	Cost for 1m³ of M4L reinforced concrete (£)
Concrete	2400	46	46	46
Reinforcing steel*	413	1	413	413
Microcapsules**	5	2.5		12.5
Bacteria**	5	4		20
Flow Networks	4	6.5		26
PET	6	6.5		39
TOTAL			**470**	**556.5**

*Based on 250kg/m³ concrete

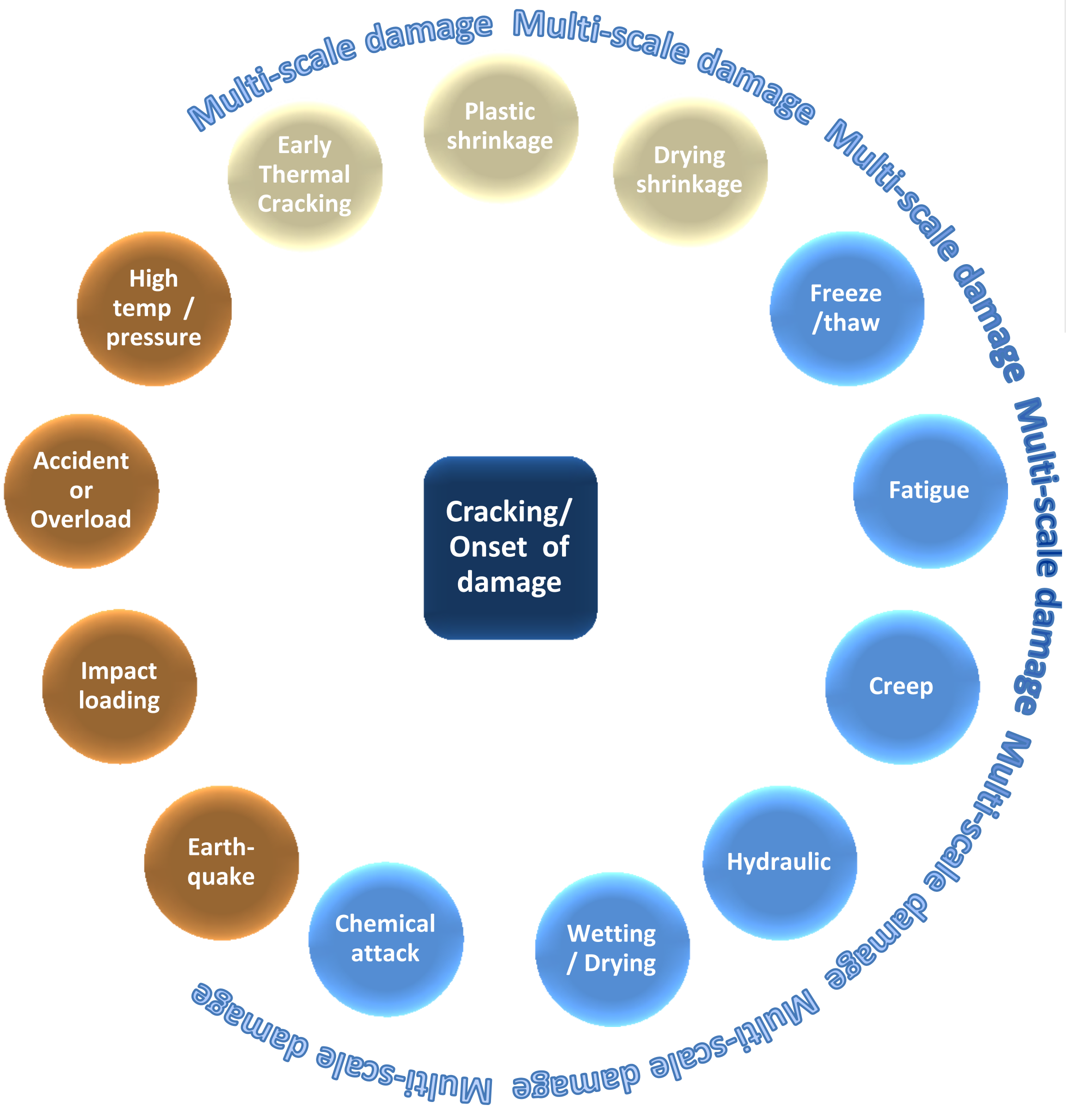
**2% weight with respect to cement

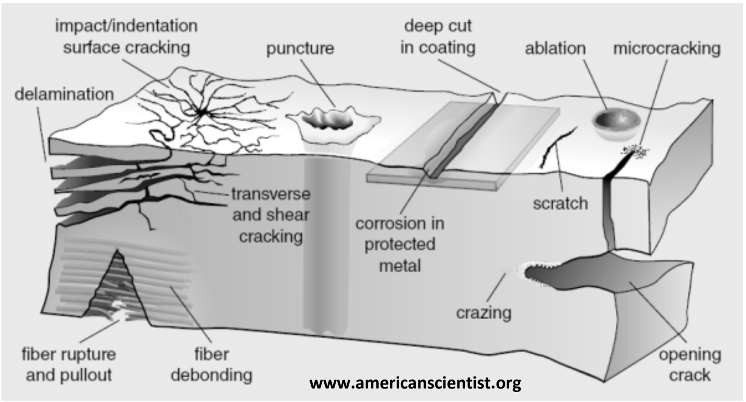
Activity	Unit cost (£/m³)	Frequency
Special Inspection	2.6	Every 5 years
Destructive evaluation	16	Every 10 years for conventional concrete
Monitored evaluation	9.6	Continual process for M4L concrete
Major patch repairs	111	6 every 100 years conventional concrete 1 every 100 years M4L concrete
Replacement	Initial Construction cost	Once every 100 years for conventional concrete only



Cusson D., Lounis, Z., Daigle, L. Cement & Concrete Composites 32 (2010) 339-350

Dunn S. C., Jefferson A. D., Lark R. J., Isaacs B. Journal of Applied Polymer Science 120(5), 2516-2526, 2011.





Properties of healing components:

- Responsive to host material damage
- Resistant to internal and external actions
- Compatible with the host matrix
- Long term efficacy

www.commandalkon-tms.nl

Protection of healing agent in porous aggregates and coated compressed powder tablets

1. A58, The Netherlands, 2010

- First engineered self-healing asphalt road with conductive fibres

2. University of Illinois, USA (field trial), 1994

- Four full scale concrete bridge decks with adhesive filled fibres
- Strength increased and cracks diverted following repeated loading
- Excellent performance over 3 years of monitoring

3. Interstate 94, Michigan, USA, 2009

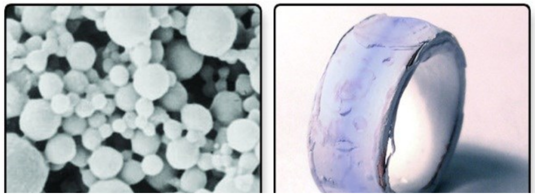
- Bridge deck link slabs: Engineered Cementitious Composite with polypropylene fibres

4. Paviljoen Galder, The Netherlands, 2012

- Concrete crack *repair* with bacterial solution

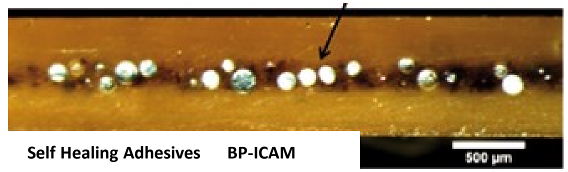
5. Delft University, The Netherlands (field trial), 2009

- Soil Stabilisation using bacterial solution



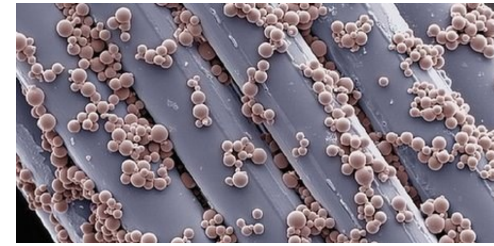
Damage Indicating Paint www.sensorprod.com

Coatings and paints



Self Healing Adhesives BP-ICAM

Sealants and adhesives



Self Healing Polymers www.americanscientist.org

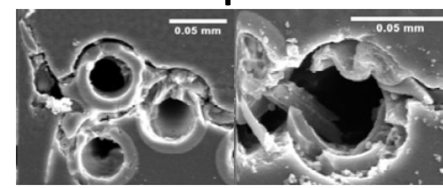
Polymers and Polymer Composites

Scratch Healing Paint www.autoevolution.com

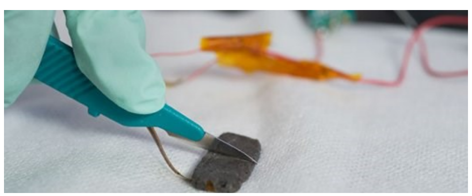
Automotive	Aerospace
Medical	Oil and Gas

Collaboration

PDRAs

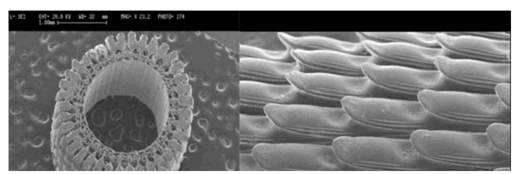


HGF within CFRP www.iccm-central.org/bondip222498p



Artificial Skin www.theengineer.co.uk

Polymer-Metal Skin



Sea Urchin www.asianscientist.com/

Bio-inspired materials

Oil and Gas Sector BP-ICAM

- Self-healing systems • Fundamental properties • Implementation • Routes to commercialisation
- Technology transfer

M4L and Beyond

- Development and demonstration of a **suite of self-healing construction products and technologies** that have been tested in real life situations.
- Establishment of **UK Virtual Centre of Excellence** to act as a **platform** for the further development of **intelligent construction materials** for **structural and geotechnical applications**.
- Bring together the relevant **international community** for the first time to collectively make significant advances for optimum impact.
- Establishment of **site-based demonstration** projects for further exploitation.
- Contribution to the **vision** and **legacy** of Limesnet and FIF communities by working closely with other successful bids to address the wider structural and geotechnical engineering challenges.
- Continuation of the work through **PhD projects** and with others.
- Acquisition of **additional funding** to expand **skills** and further exploit the **momentum** of M4L.