

Application of Engineered Cementitious Composites (ECC) in Precast Ultrathin White-Topping (PUWT)

– A Field Demonstration on Jurong Island, Singapore

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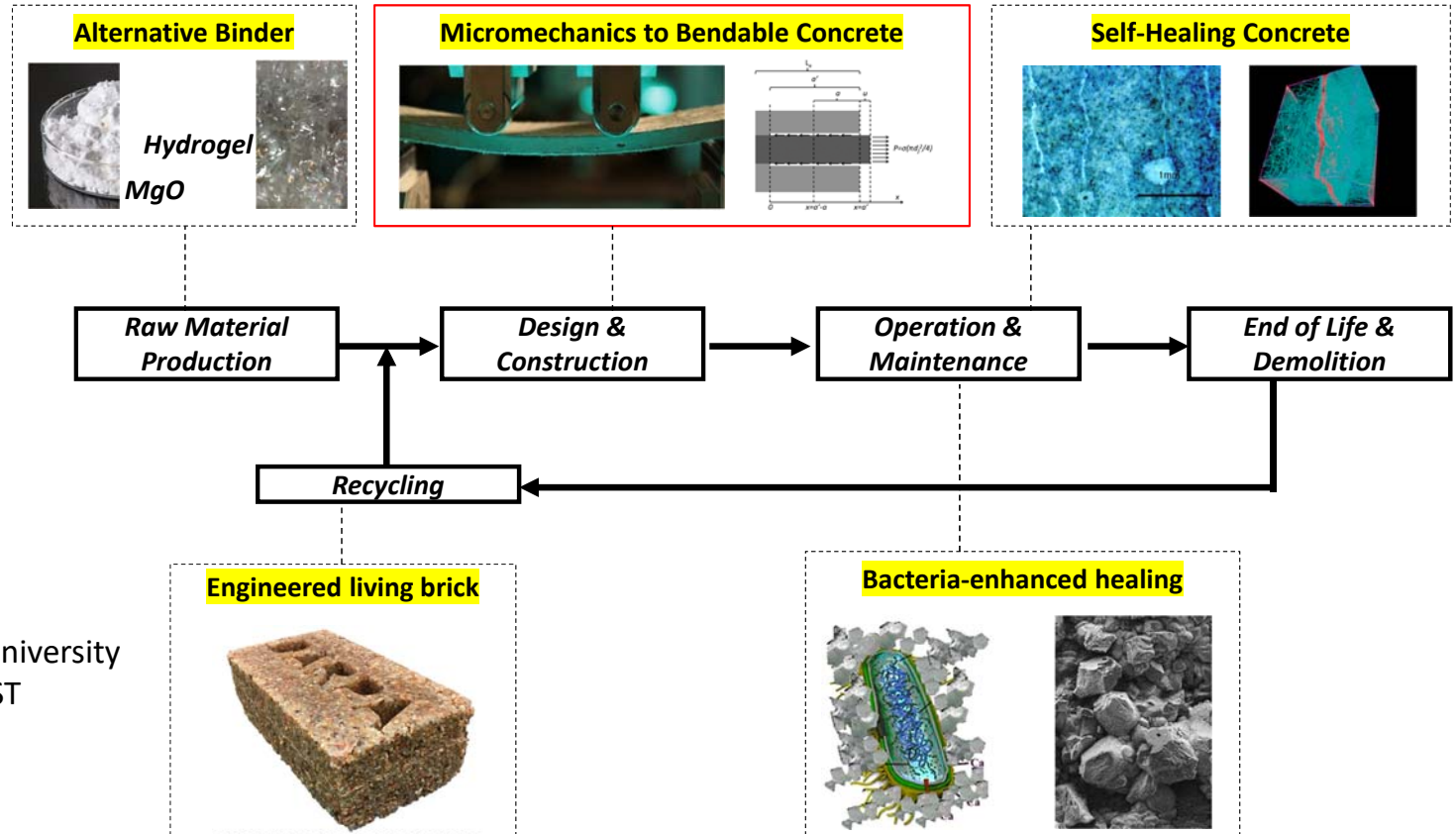
My Research: New Construction Materials

Today's topic



Jishen Qiu, PhD.

2016 PhD. Nanyang Technological University
2019-Now Assistant Professor HKUST



Project Roadmap (2-3 years)



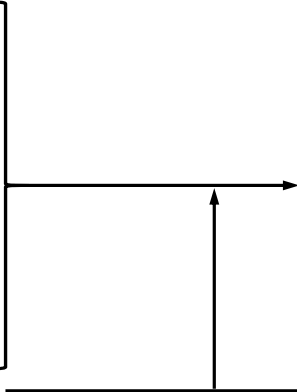
State-owned for-profit company
Largest industrial manager in Singapore



Public University

1. A real-world challenge:
road surface maintenance

2. A maturing material/technology:
fatigue-resistant ECC + ultrathin
white-topping



4. Field demonstration

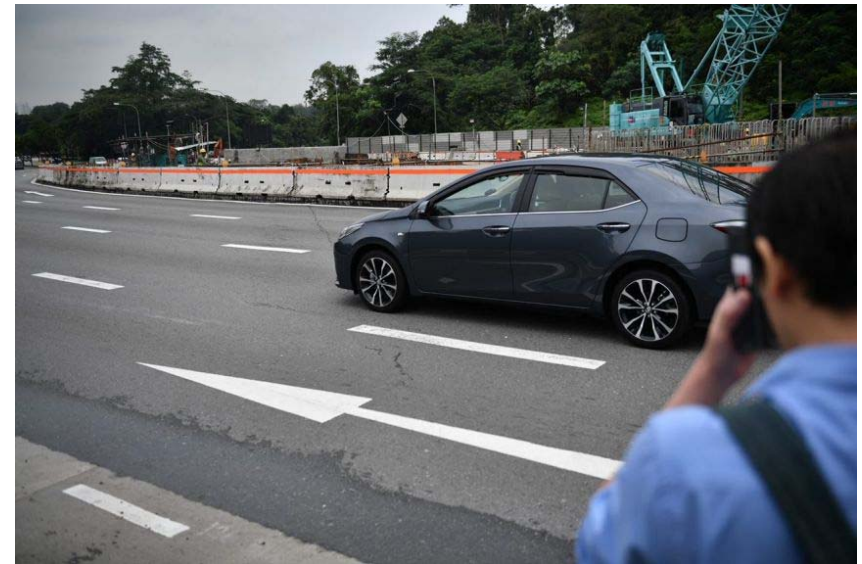
3. Upscaling production



Motivation: Road Surface Damage

Road surface in Singapore

- Year-round hot and humid climate
- Mostly asphalt, susceptible to surface rutting and cracking
- Frequent maintenance and repair



Asphalt road surface cracking and rutting

Junction of Semi Rd. and Adam Rd., Singapore

Credit: Strait Times

Problem Identification

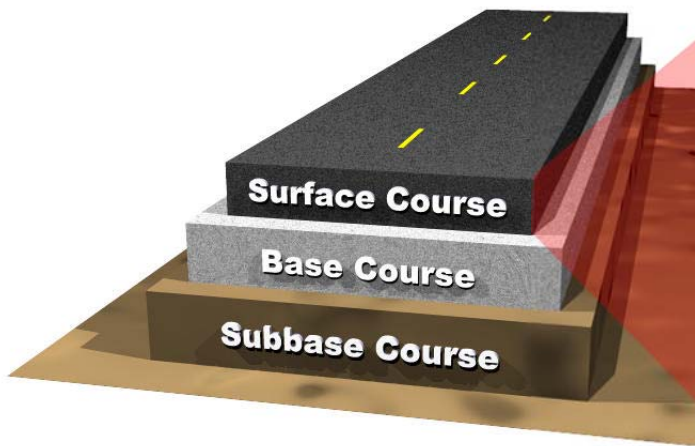
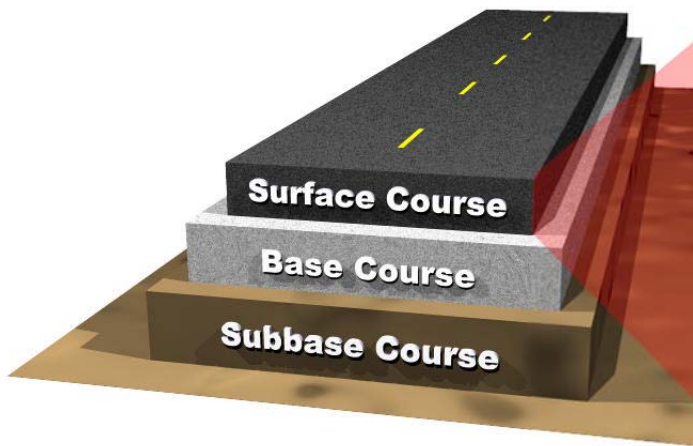


Illustration of Flexible Pavement
Credit: Pavement Interactive

- Asphalt surface of 150-200 mm thick
- Sensitive to heavy vehicles (bus and lorries)
- Distresses only in the top inches
- Base and subbase remain mechanically sound

Traditional Solutions & Their Drawbacks



1 Mill off full depth & repave with asphalt

- Overnight construction
- Same problem occurs quickly

2 Mill off the distressed inches & white-topping (concrete)

- Enhanced mechanical strength
- Multiple days of road closure

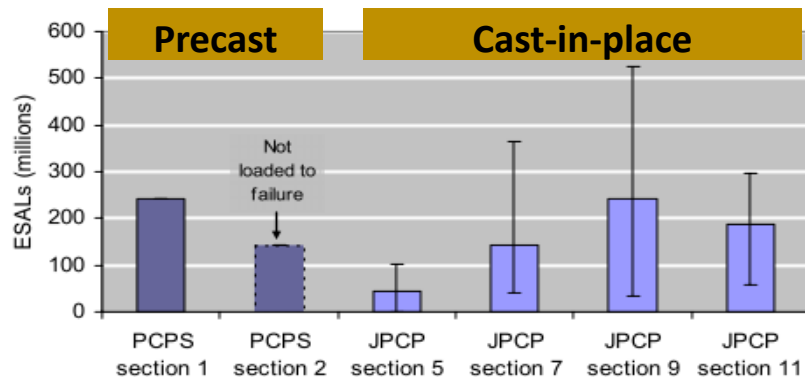
3 Mill off & precast concrete slab (maturing technology)

- Fast construction & enhanced strength
- Full-depth R/C slab: complicated manufacturing
- Full-depth milling-off
- Slab-base and inter-slab joint design

Review: Prefabricated Concrete Pavement

- Reinforcement is mandatory
- Complicated joint design and manufacture
- Prefabrication on site (not plausible in Singapore)

Limit by the brittle nature of concrete



Durability of precast vs. cast-in-place concrete under wheel-pressure test

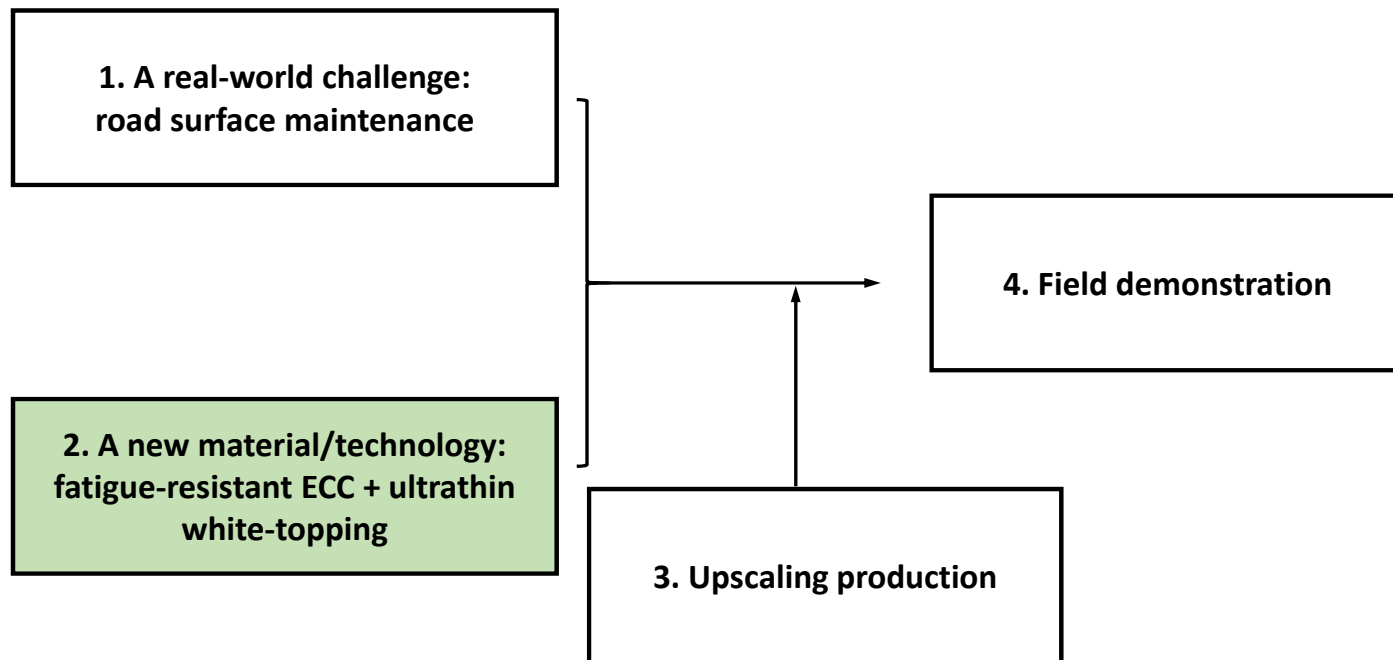
Kohler et al. 2008



Complicate Joint Design: dowel bar + dent grouting (left); pre-stressing the joint (right)

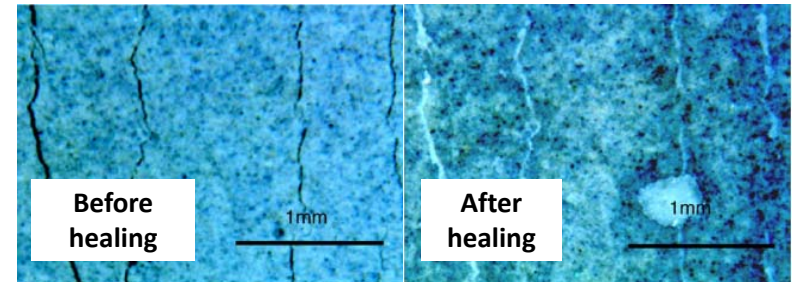
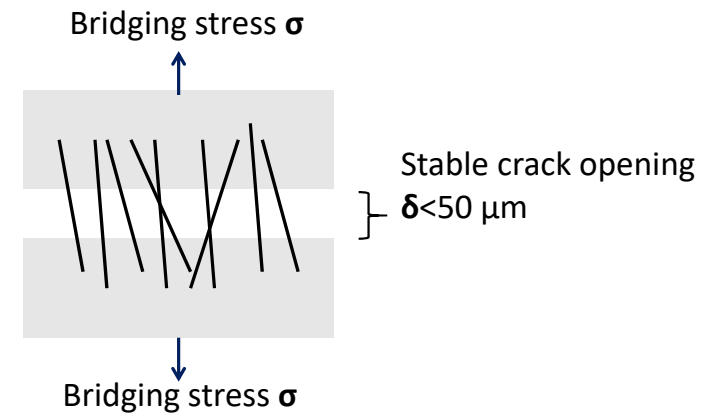
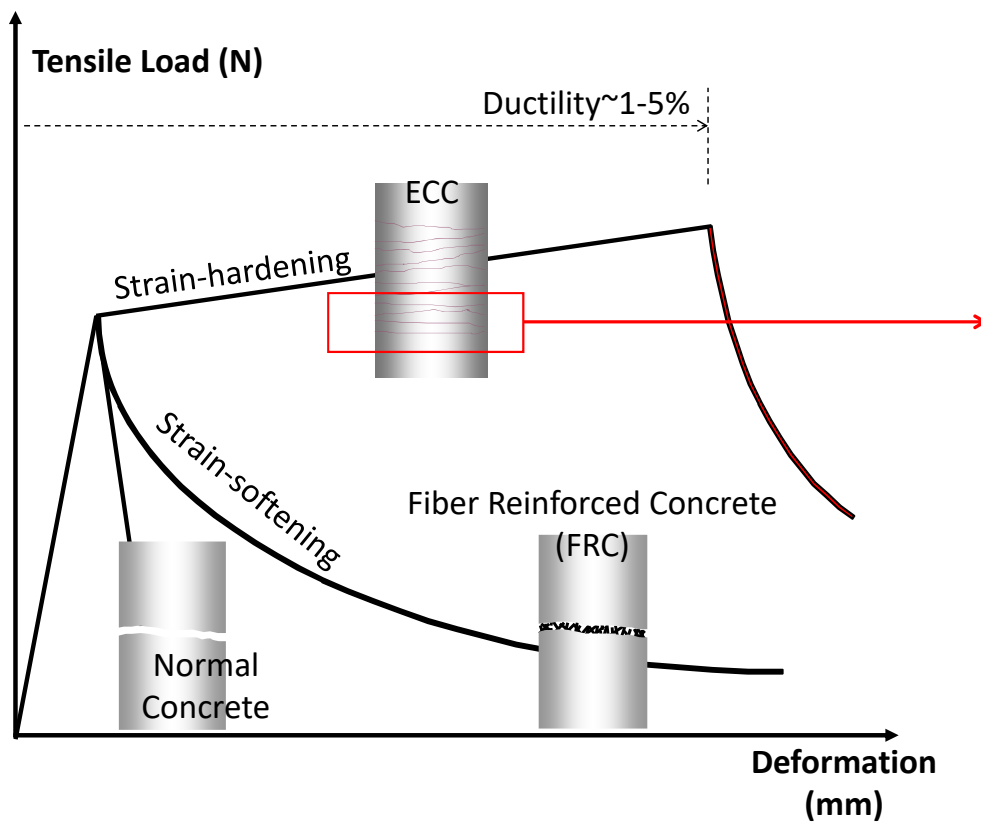
Credit Fort Miller Inc. (left) & Chang et al. 2004 (right)

Project Roadmap



ECC and Its Basic Properties

Common ingredient of ECC: cement, fly ash, ultrafine silica sand, polymer fiber (no aggregates)



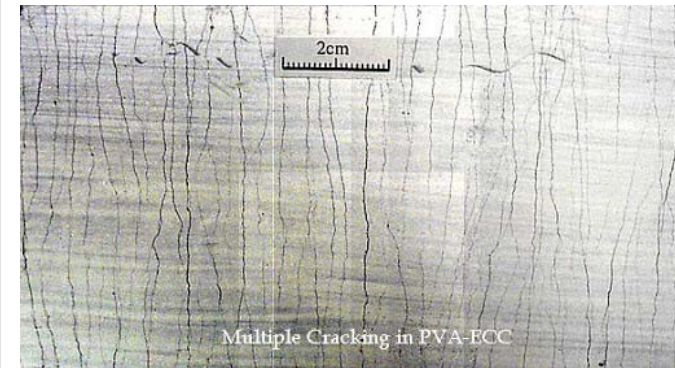
Self-healing of ECC cracks

Yang et al. 2009

ECC – “Bendable Concrete”



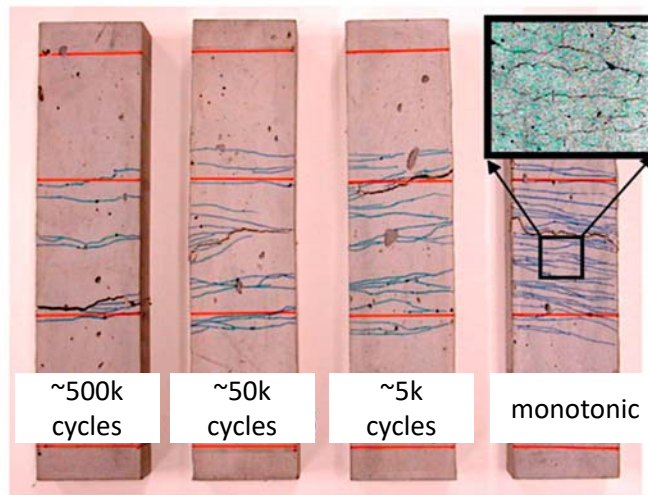
Video Clip



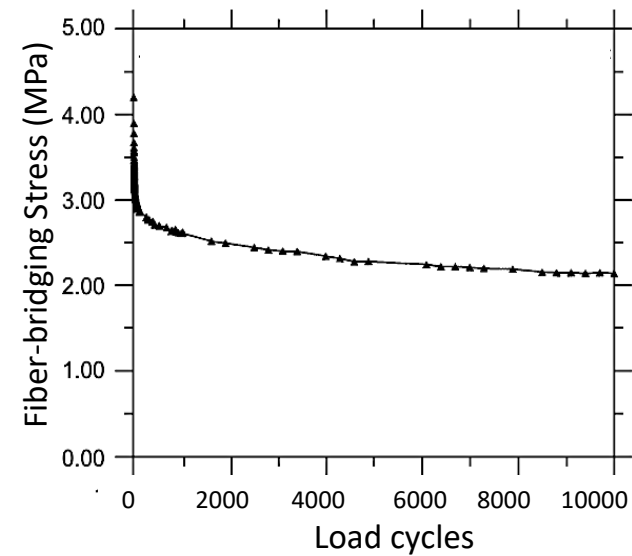
Multiple cracking of ECC
Credit: ACE-MRL Lab at University of Michigan

Fatigue-induced Damage in ECC

- Premature failure – losing the signature multiple cracking and ductility
- Attributed to the fiber-bridging deterioration under cyclic loads

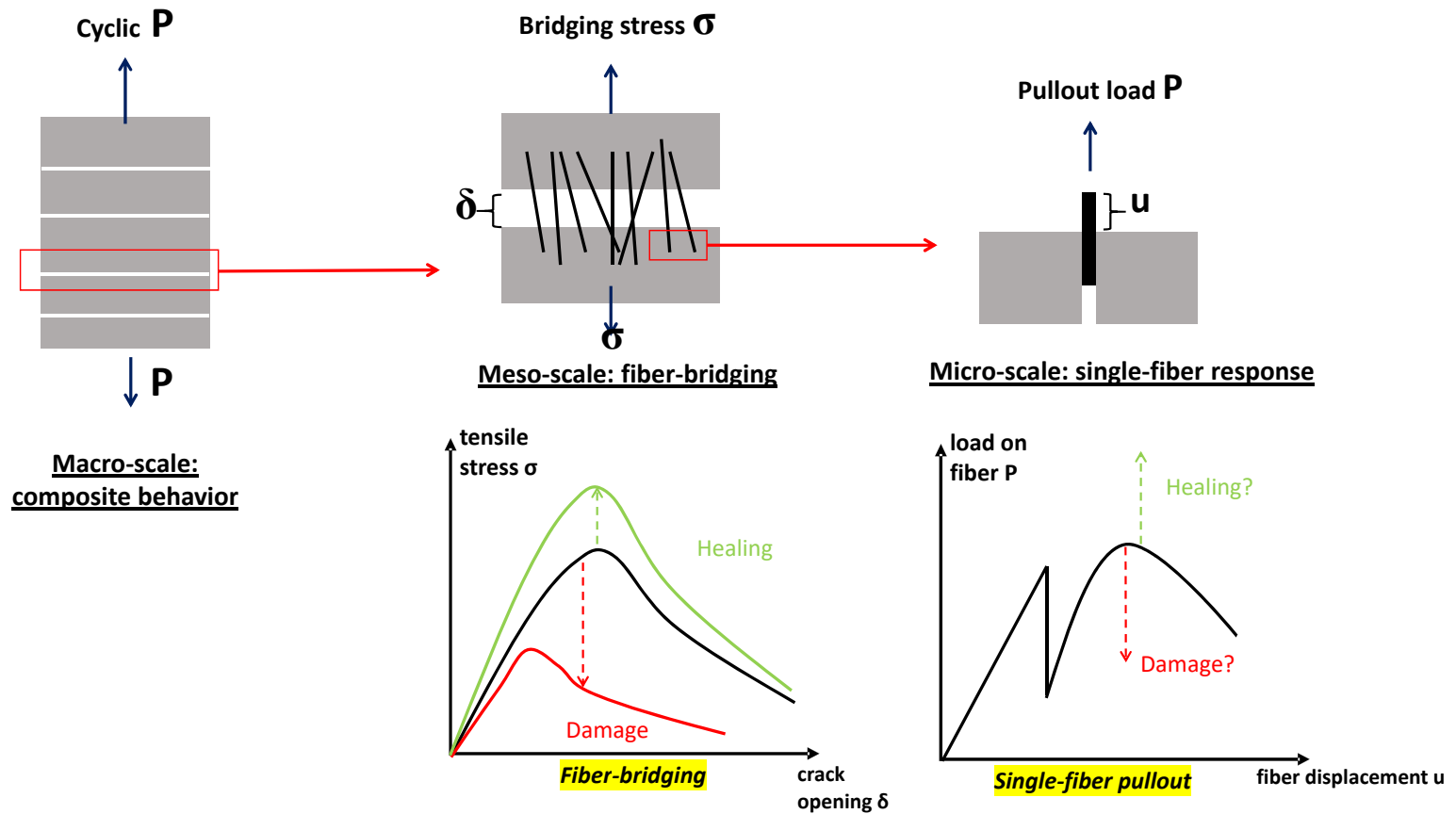


ECC under different cyclic loading
Qian et al. 2012



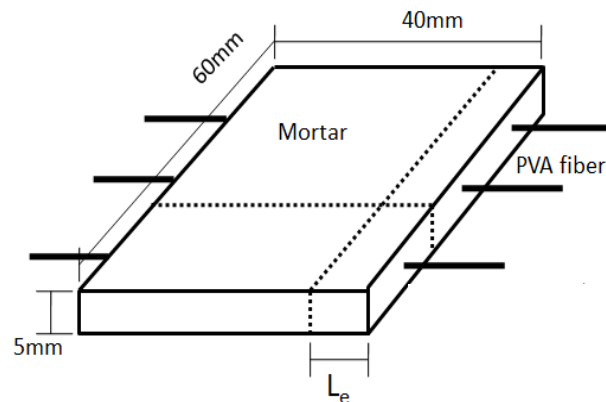
Fiber-bridging stress vs load cycles
Zhang et al. 2000

Micromechanics for ECC Fatigue

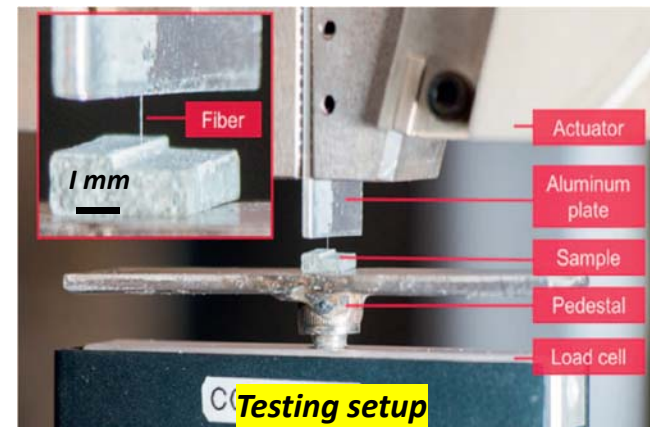


Single Micro-fiber Pullout Test

- First to conduct this test (a micro fiber cyclically pulled out from cement matrix)
- Cyclically loaded vs. Pristine (as control)
- Effect of loading magnitude, number of load cycles, and embedment angles are studied



Single-fiber Pullout Specimen, PVA fiber $\phi=40\mu\text{m}$

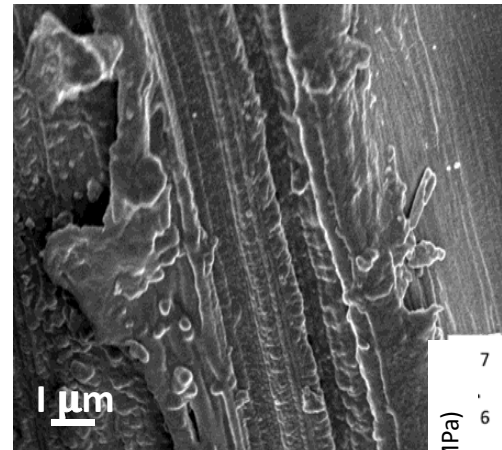


Qiu et al. 2016, Fatigue-induced deterioration of the interface between micro-polyvinyl alcohol (PVA) fiber and cement matrix. *Cement and Concrete Research*
Qiu et al. 2017, Fatigue-induced in-situ strength deterioration of micro-polyvinyl alcohol (PVA) fiber in cement matrix. *Cement and Concrete Composites*

Findings from Our Lab Study

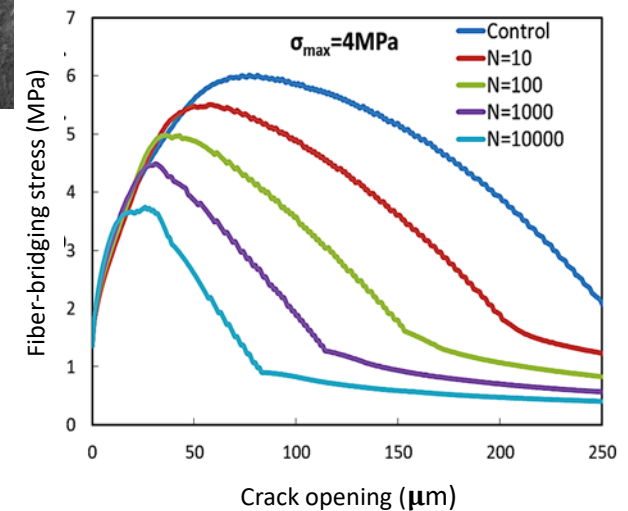
Monotonic Loading → Cyclic Loading

- Polymer fiber debonds from cement matrix at a significantly lower load level
- The loose fiber abraded by the reciprocate movement and gets weaker
- The fatigue-induced fiber-bridging loss can be quantified



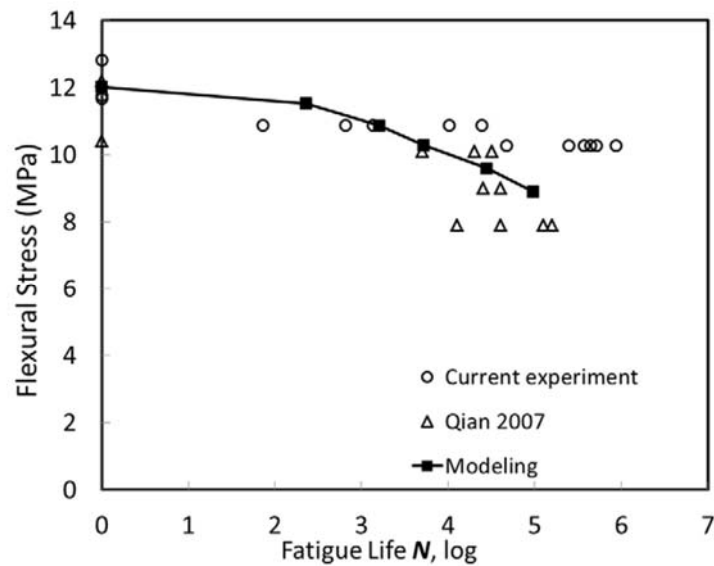
Footprint of the fatigue-debonding

Predicted fiber-bridging loss vs load cycles

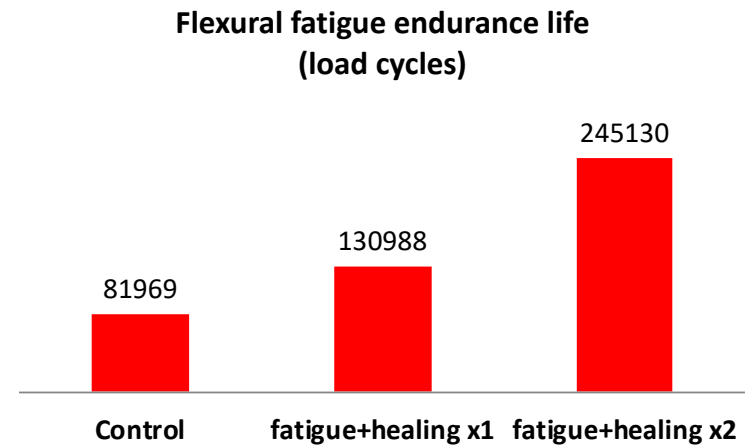


Design Fatigue-resistance ECC

Our Approach: Self-healing of ECC → Mechanical Recovery → Longer Fatigue Life

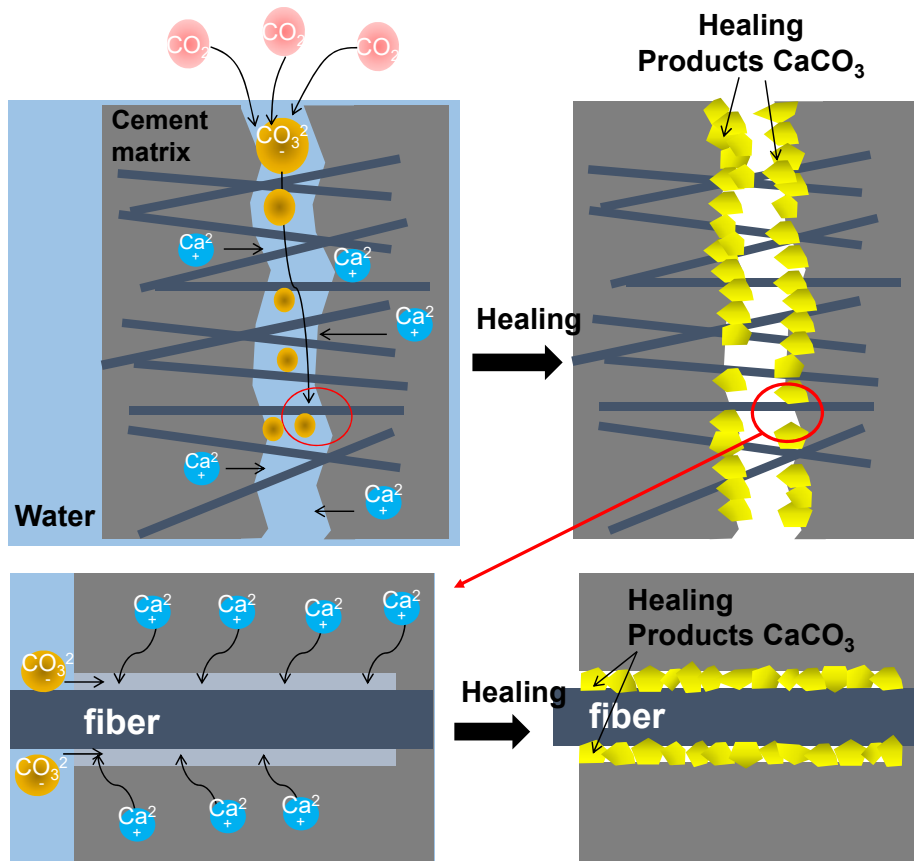


ECC S-N (fatigue life-load) curve: experimental data vs our modeling

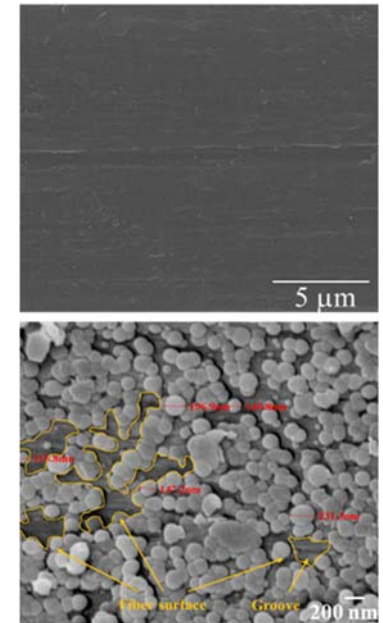


Effect of healing on ECC fatigue life

Enhance the Healing-induced Recovery



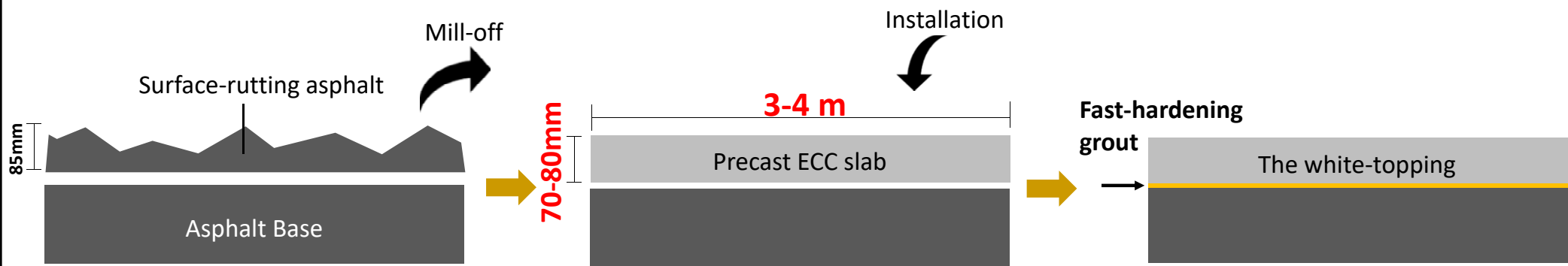
- The mechanical recovery is from the fiber-cement interfacial healing
- Fiber surface coating enhances this interfacial healing (**on-going research**)



One of the nano-scale coating recently developed at HKUST

Precast Ultrathin White-topping

11 pm to 7 am



Structural Design Considerations

Slab-to-base bond

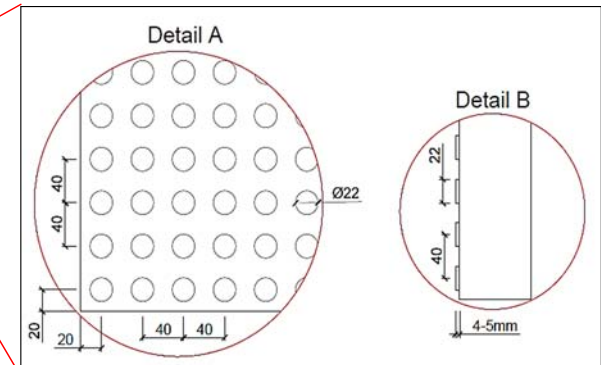
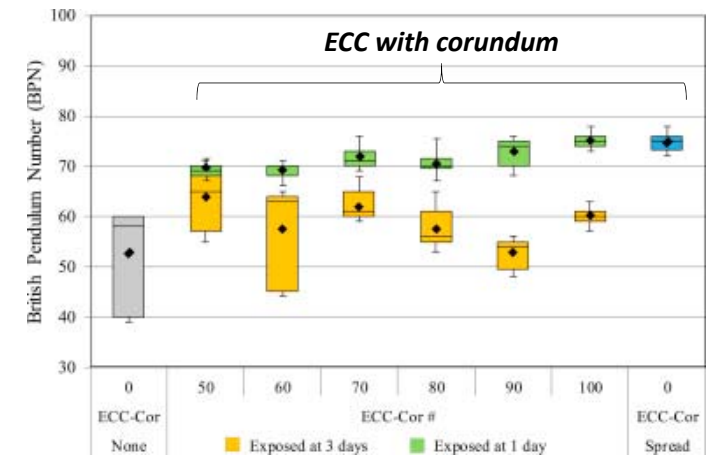
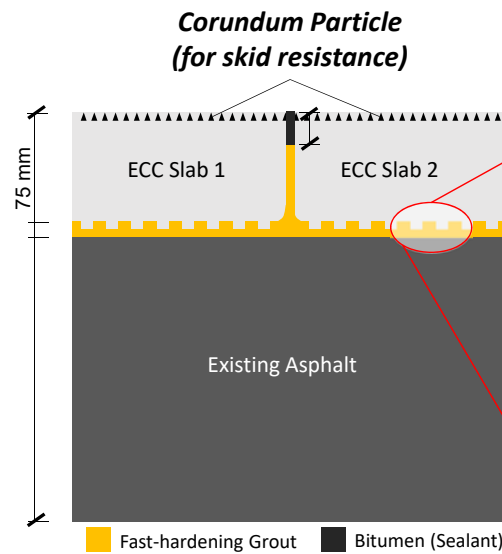
- Shear-key

Inter-slab joint

- The base guarantee the load-transfer

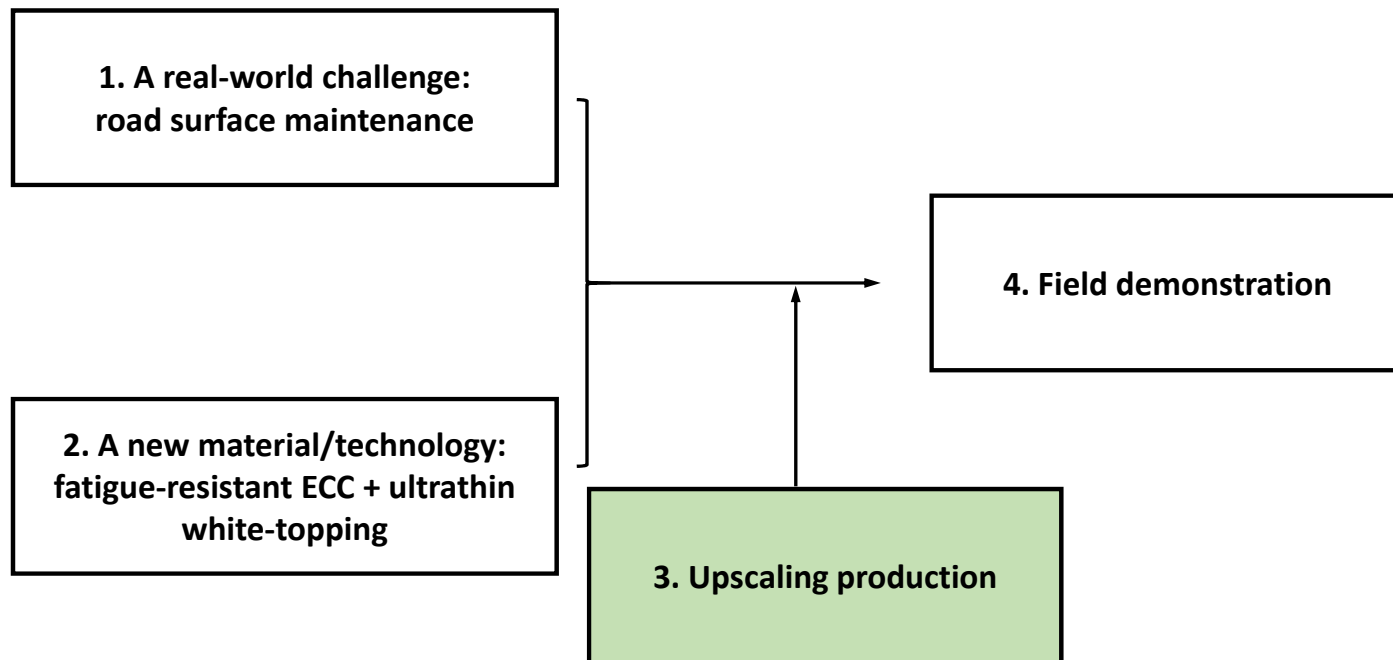
Low skid resistance of ECC (no coarse aggregate)

- Corundum added into ECC mix design
- Expose by steel-wire brushing



Shear keys at the bottom of slab

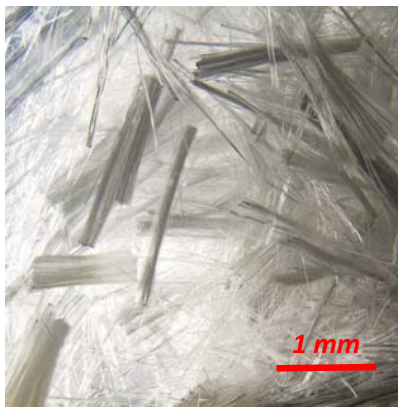
Project Roadmap



Challenges in Large-Scale ECC Mixing

Factors on fiber dispersion

- Rheological the fresh cement
- Mixer type and power



PVA fiber received in bundles, needs to be separate by shear flow of fresh cement

Credit: Nycon



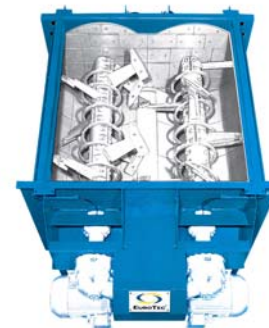
Lab planetary mixer (3-10 L)

Credit: Myers Associates



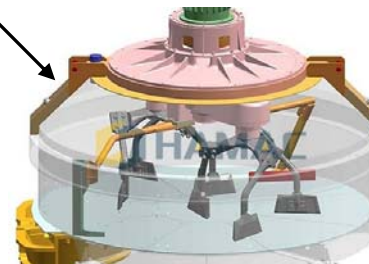
Gravity drum mixer (1000 L)

- No revolution, no rotation
- Unworkable balling



Twin shaft mixer (3000 L)

- Revolution, no rotation
- Unknown fiber dispersion

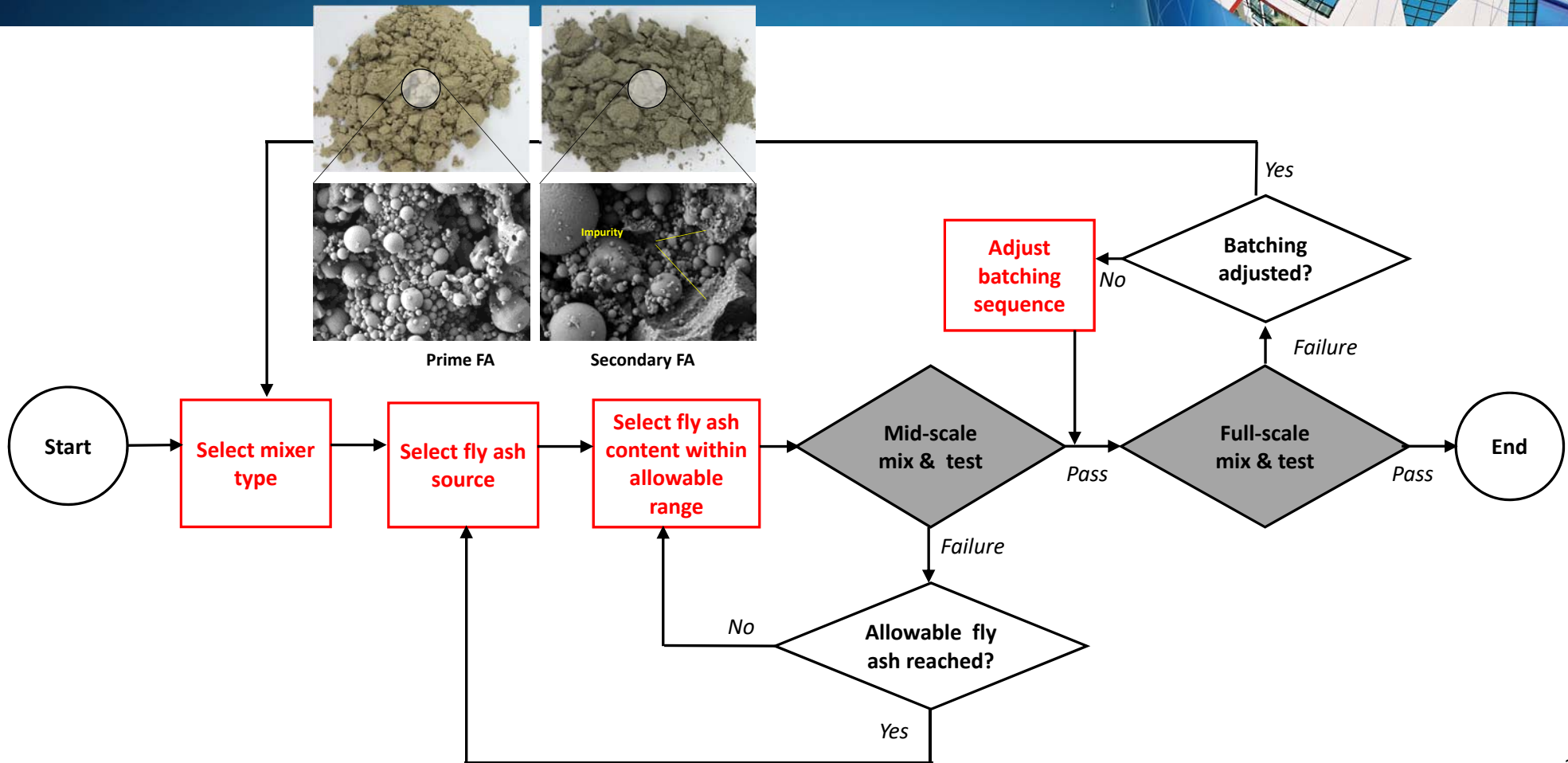


Planetary (500 L-3000 L)

- Revolution & rotation
- Good fiber dispersion

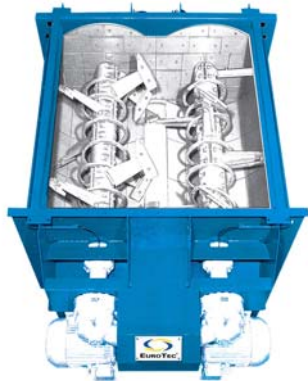


Tuning the Factors of Mixing



Final Design of the Mixing

Select mixer type



Twin shaft mixer

Select fly ash source

Select fly ash content



Primary Fly Ash, 50% cement replacement

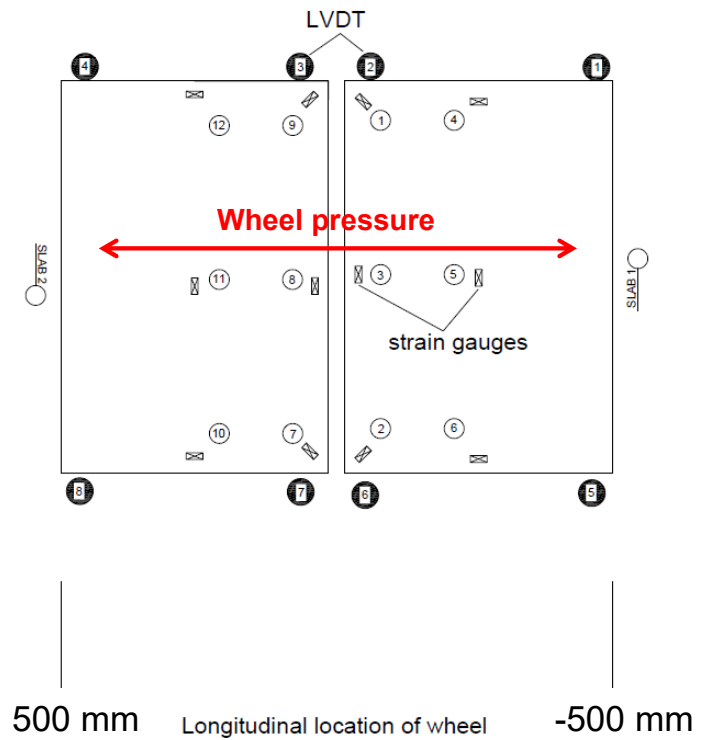
Adjust batching sequence

Step	Original batching	Modified batching
1	<ul style="list-style-type: none"> • FA ash • Silica sand • Type I cement • Expansive cement 	<ul style="list-style-type: none"> • FA ash • Silica sand • Expansive cement
2	<ul style="list-style-type: none"> • Water • Super-plasticizer • Shrinkage-reducing agent 	<ul style="list-style-type: none"> • 50% water • Super-plasticizer • Shrinkage-reducing agent
3	<ul style="list-style-type: none"> • Fiber 	<ul style="list-style-type: none"> • Type I cement
4		<ul style="list-style-type: none"> • 50% water
5		<ul style="list-style-type: none"> • Fiber

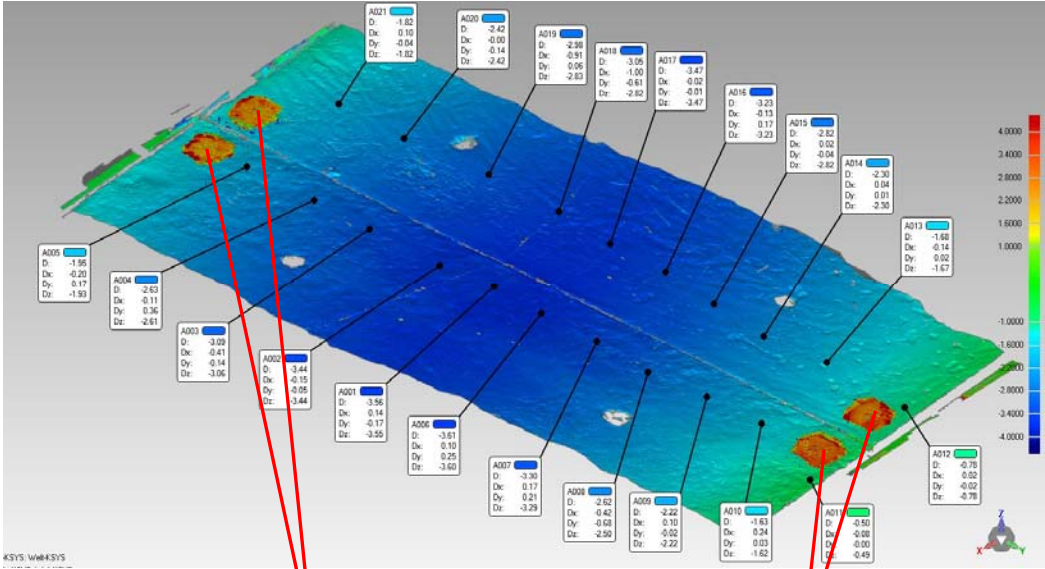
Wheel Test



- Vehicle weight (cyclic) + elevated temperature
- Four sessions:
 - 10 tons, 100000 cycles
 - 10 tons, 40°C 50000 cycles
 - 10 tons + braking force 1000 cycles
 - 10 tons + braking force, 40 °C 500 cycles



Verified Structural/Material Design

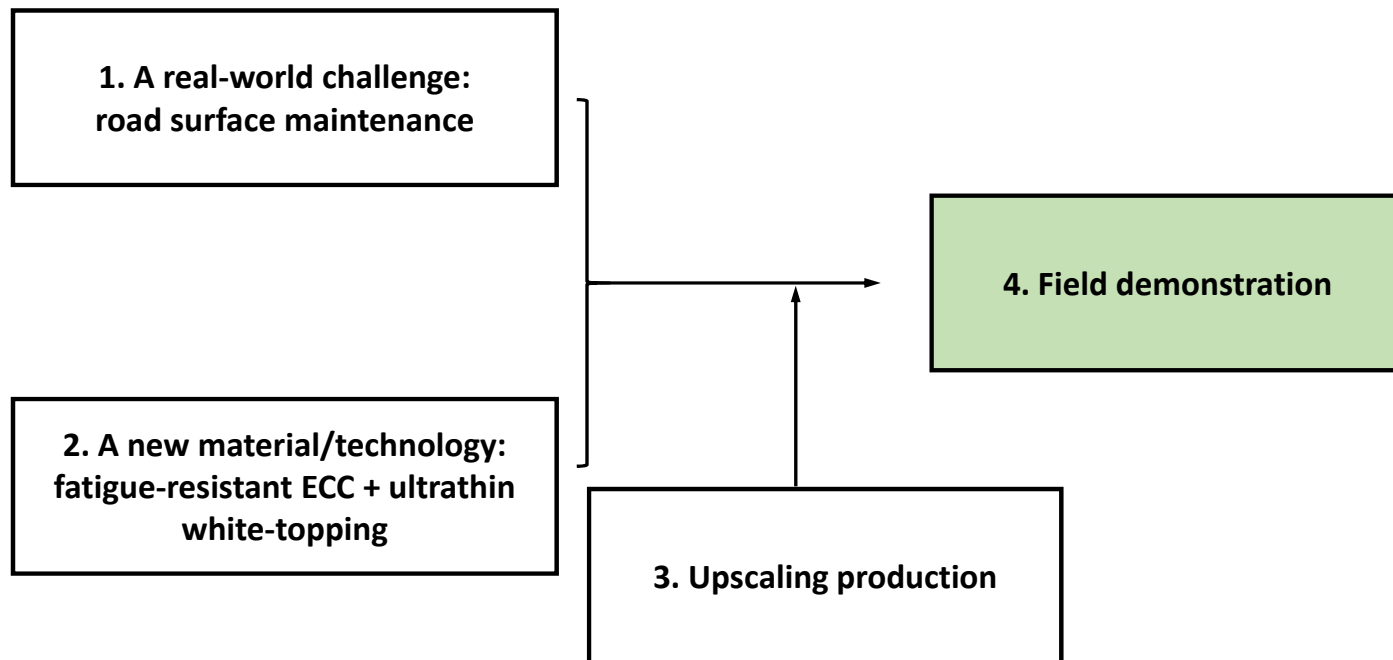


Test result:
Comparable slab corner displacement with structural design



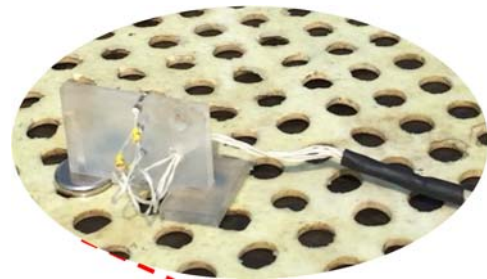
No visible damage at the cored joint

Project Roadmap

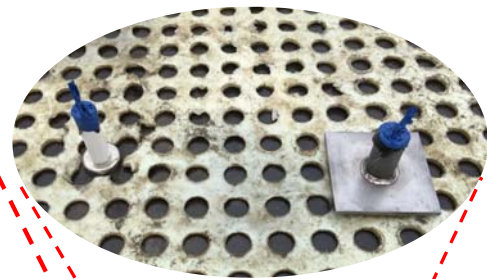


ECC Slab Manufacturing (1)

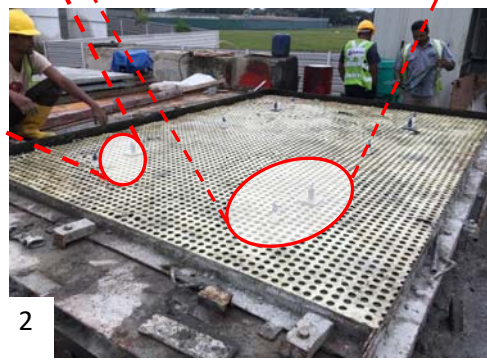
In-slab thermocouple



Grouting & lifting holes



Surface corundum



ECC Slab Manufacturing (2)



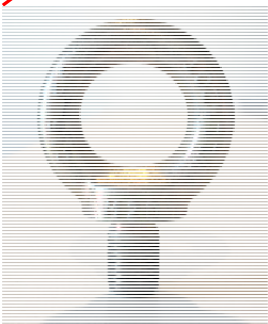
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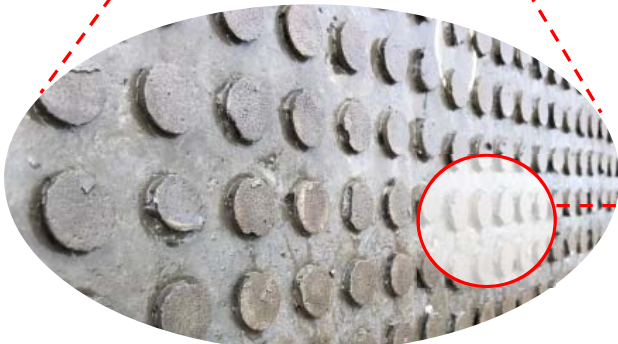
5



6



Lifting ring



Shear keys

Fibers minimizes the spalling during tearing-off



Strain gauges

Video Clips



Casting ECC slab



Flipping ECC Slab

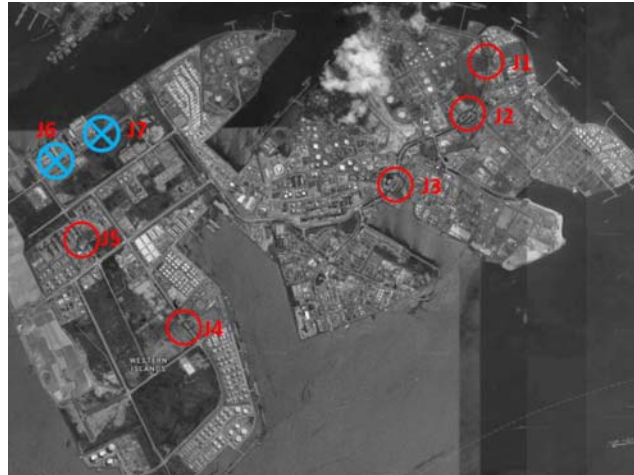
Field Demonstration of ECC-PUTW

Site Selection Criteria

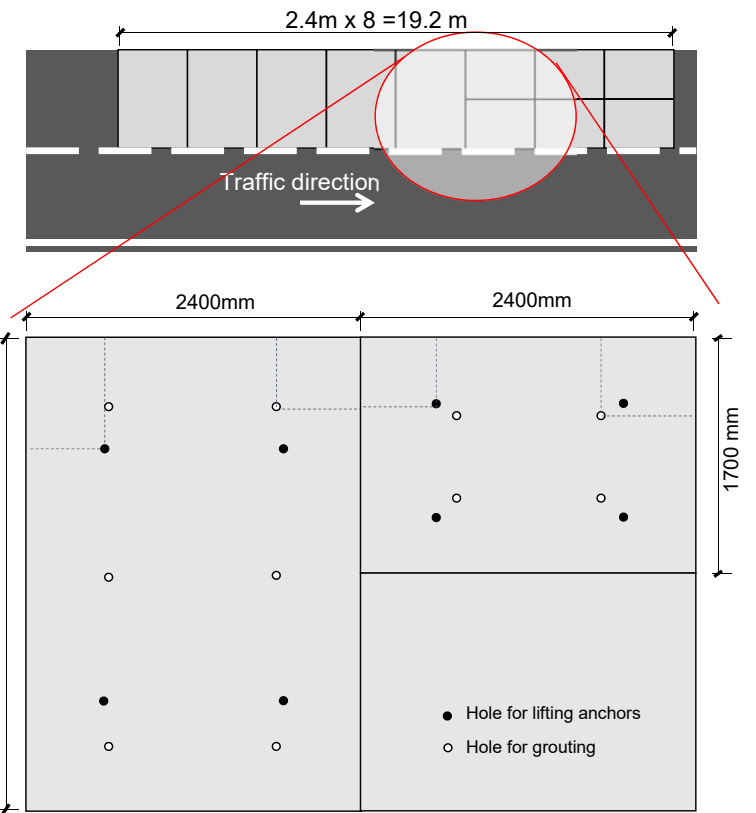
- Regular heavy vehicle
- Braking force
- No shadow

Construction Plan

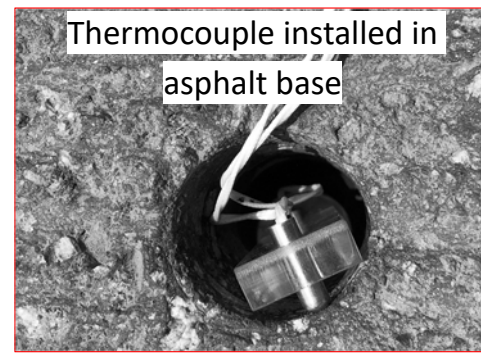
- 5 large slabs (3.4 x 2.4 m)
- 4 small slabs (2.4 x 1.7 m)
- 1 with minor reinforcement



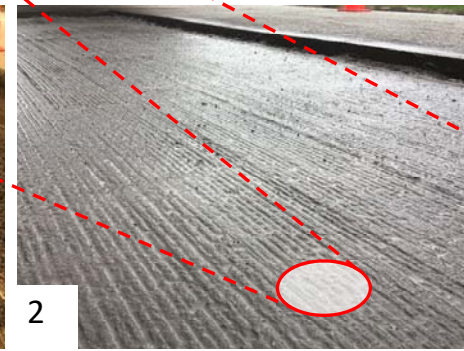
Selected construction site: a bus stop on Jurong Island (J16)



ECC Slabs Installation (1)



Mill off top asphalt

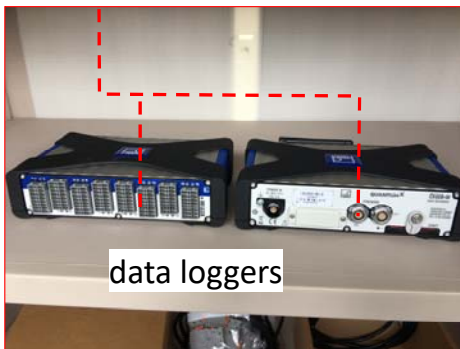
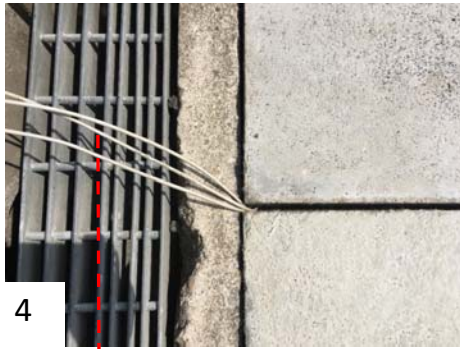


Clean-up by water jetting

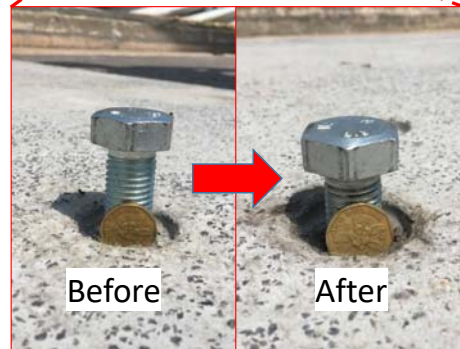


Place the slabs

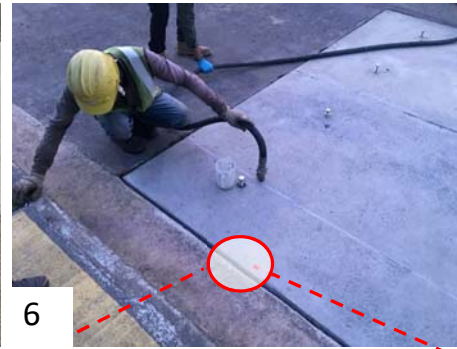
ECC Slabs Installation (2)



Install monitoring devices



Adjustment slab position



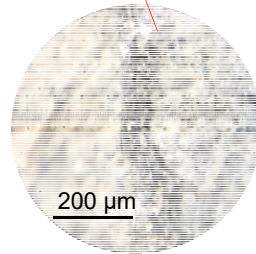
Grouting and sealing

Opening to Traffic & Monitoring

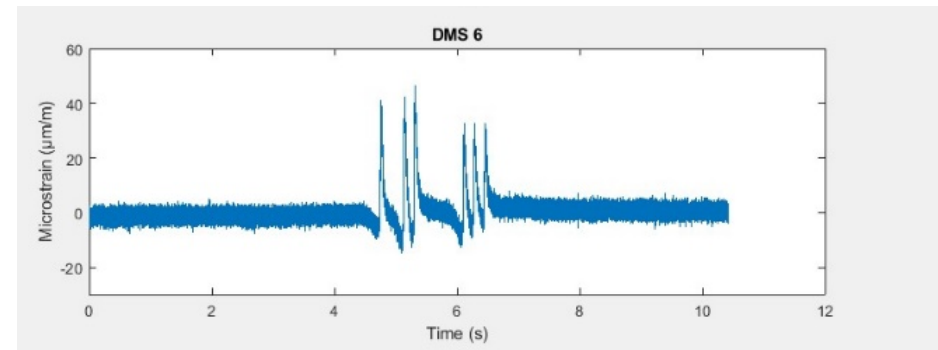
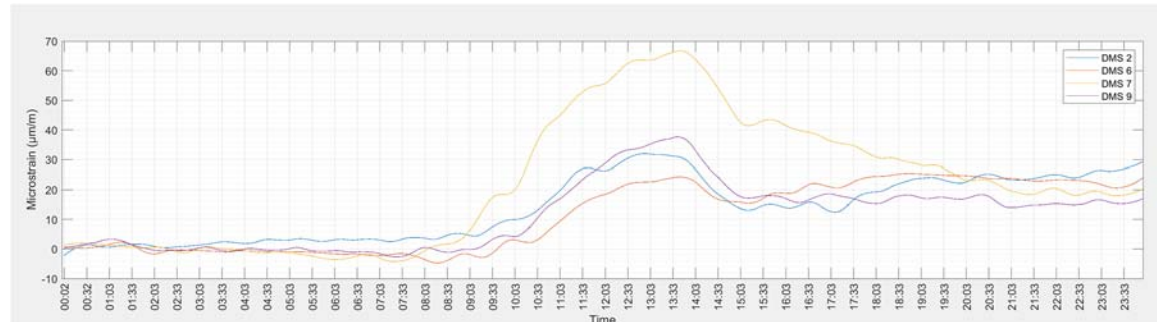
The shelter and cabinet housing data loggers



The new bus stop opened to traffic in July 2018, after a 2-day construction



Healed cracks on-site



Bottom strain at the corner of a large slab (DMS 6)

Temperature-induced strain in 24 hours

20 micron

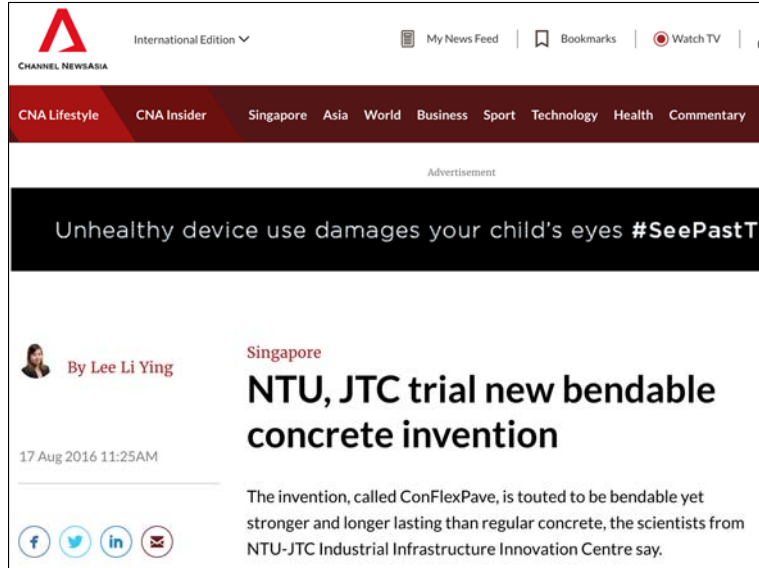
Heavy truck-induced strain

40 micron

The first cracking of ECC

200 micron

Media Coverage



A screenshot of the Channel News Asia website. The page features a red navigation bar with categories like 'CNA Lifestyle', 'CNA Insider', and 'Singapore'. Below the navigation bar is an advertisement banner with the text 'Unhealthy device use damages your child's eyes #SeePastTh'. The main article is titled 'NTU, JTC trial new bendable concrete invention' by Lee Li Ying, dated 17 Aug 2016 11:25AM. The article text states: 'The invention, called ConFlexPave, is touted to be bendable yet stronger and longer lasting than regular concrete, the scientists from NTU-JTC Industrial Infrastructure Innovation Centre say.'

Channel News Asia



A screenshot of the Strait Times website. The page features a blue navigation bar with categories like 'SINGAPORE', 'POLITICS', 'ASIA', 'WORLD', 'VIDEOS', 'LIFESTYLE', 'FOOD', 'FORUM', 'OPINION', and 'BUSINESS'. Below the navigation bar is a sub-navigation bar with categories like 'SINGAPORE', 'Courts & Crime', 'Education', 'Housing', 'Transport', 'Health', 'Manpower', and 'Environment'. The main article is titled 'NTU scientists invent flexible concrete'. Below the title is a photograph of a piece of concrete being tested in a machine. To the right of the photograph is a sidebar with a 'ONEBERRY' advertisement and 'ST VIDEOS' section.

Strait Times

What We Learned



- ECC is suitable for prefabricating thin structural members of large dimensions
- Know-hows on the quality control of large-scale ECC mixing, esp. in twin-shaft mixer
- Construction method matters
- PUTW-ECC is a promising option to repair/upgrade road surface with high traffic



Thanks for your attentions

ECC vs. Fiber-UHPC

	ECC	UHPC
Compressive Strength	50-80 MPa	100-150 MPa
Tensile ductility	1.0%-4.0%	0.5-1.0%
Fiber type and fraction	PVA fiber, 26kg/m ³	Steel fiber, 150-200 kg/m ³
Unit weight	2000 kg/m ³ (4 slabs)	2600 kg/m ³ (3 slabs)
Workability	Medium SP for self-compacting	High SP for self-compacting
Effect on tires	Acceptable skid resistance with corundum	Steel fiber is dangerous to tires (forbidden in Germany)
Raw material cost	\$\$\$\$	\$\$-\$\$\$
Life cycle cost	\$\$	\$\$