香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Development of Ultra-Ductile Cementitious Waterproofing Rendering with Recycled Plastics

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2 Matrix Design for Rendering

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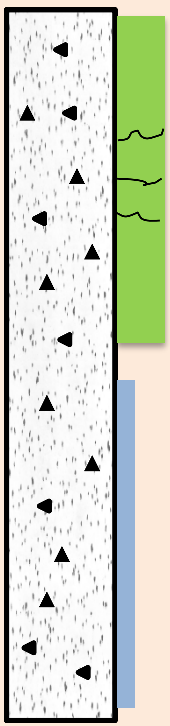
4 Mechanical Properties of Hybrid Fiber ECC

5 Concluding Remarks

1. Introduction and Objectives

A Review of Waterproofing Approach

Conventional Waterproofing Approaches



Cementitious waterproof rendering

Pros: Easy to apply

Cons: Brittle and can crack easily

Polyurethane based waterproof coating

Pros: Excellent tensile strength and ductility

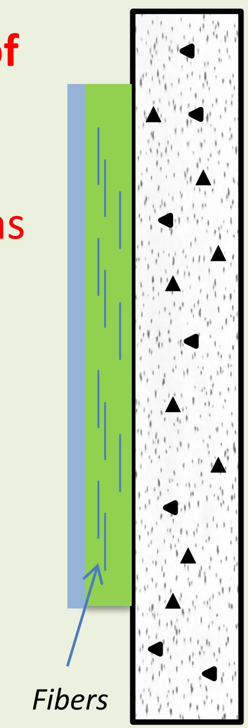
Cons: Cannot be applied on **wet** surface, concrete cracks may penetrate into coating

Proposed Approach

PVA/rPET ECC rendering + Polyurethane waterproof coating

ECC can control cracks to small openings and serve as a buffering layer between concrete and coating

Under low water pressure, polymeric coating may not be necessary



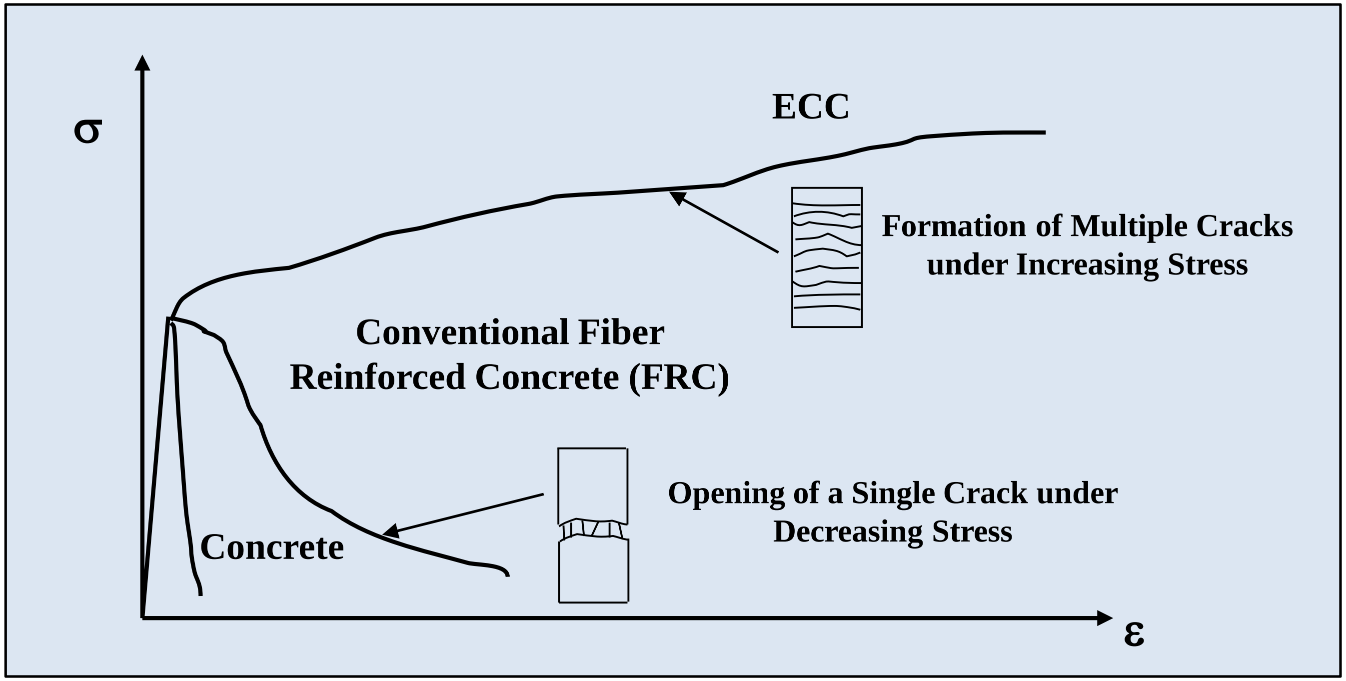
Note:

PVA - Polyvinyl Alchohol

rPET – Recycled Polyethylene Terephthalate

1. Introduction and Objectives
What is ECC?

- Engineered Cementitious Composites (ECC) are composites designed according to micromechanics to achieve
  - High tensile strain (several %) before final failure
  - Excellent crack control ability, with crack opening limited to around 100 micron or below at serviceability state

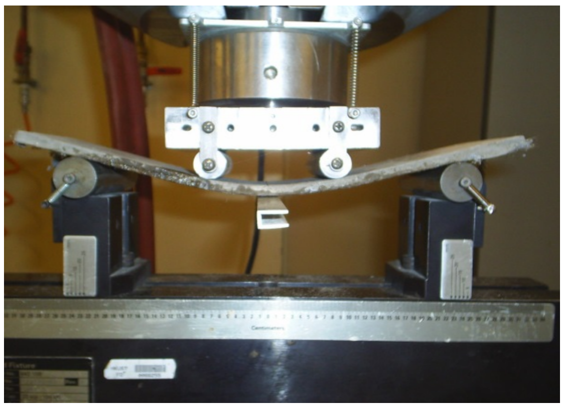


Tensile σ–ε Behavior of Cementitious Materials

1. Introduction and Objectives

Behavior of ECC members

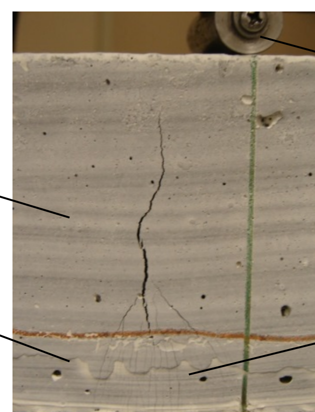
- In practical applications, this translates into high ductility, high energy absorption, excellent resistance to crack propagation, and improved durability (by resisting water/chemical penetration)



High deformability of ECC member

Multiple Cracks with Small Spacing and Opening in ECC

Crack Resistance of ECC Layer



Concrete

ECC

Loading applied through Rollers to introduce cracking in beam

Multiple Fine Cracks Formed in ECC under Major Concrete Crack

1. Introduction and Objectives

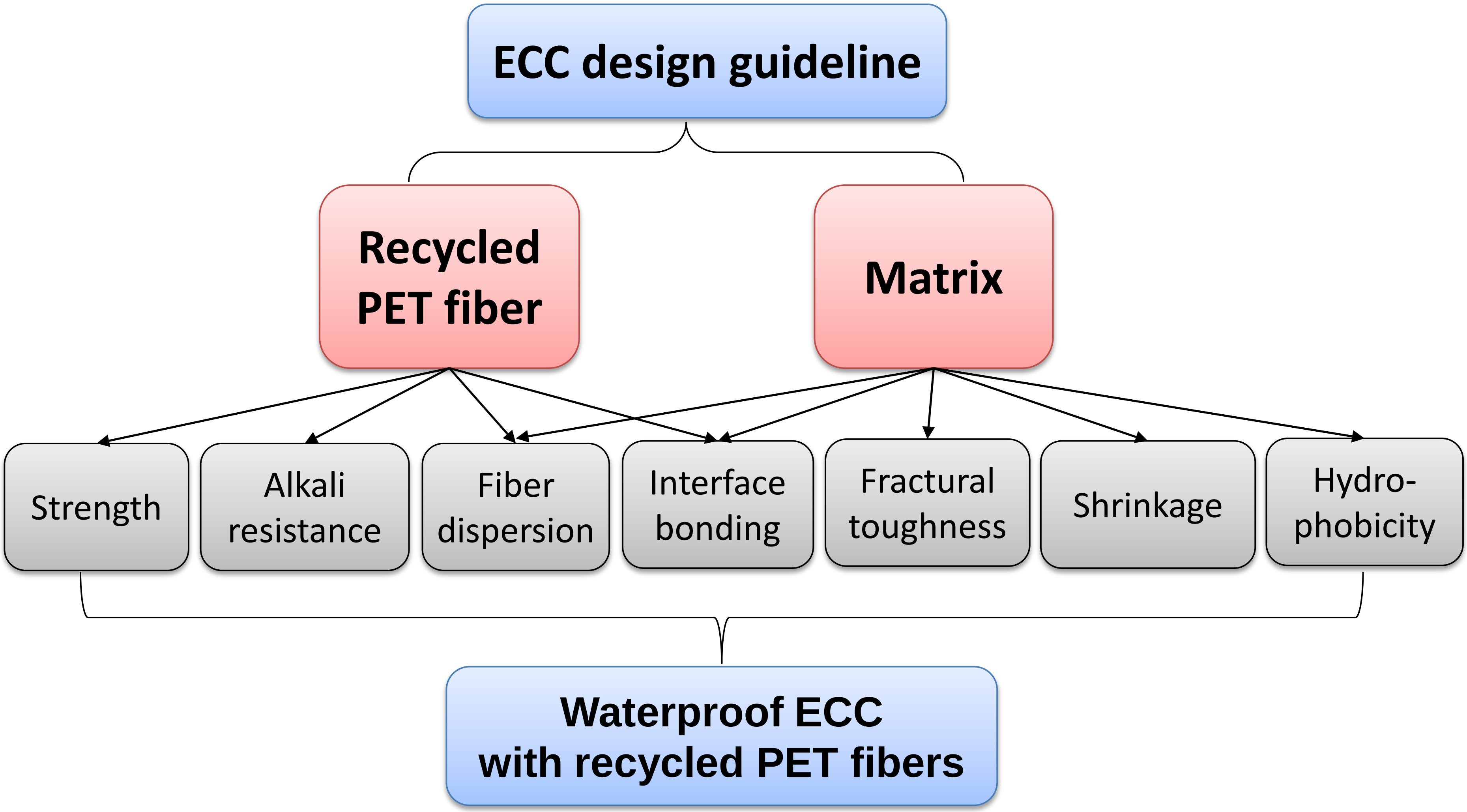
Motivation for the Current Research

- Polyethylene (PE) and Polyvinyl alcohol (PVA) fibers are most widely used in ECC, but the cost of PE/PVA is very high.
- **Solution: cheaper alternative to PE/PVA fiber**
  - HMPE: ~200,000 USD/m^3 (Li et al, 2002: About 8 times that of PVA on an equal volume basis)
  - PVA: ~25,000 USD/m^3
  - PET: ~2,600 USD/m^3
  - PP: ~2,300 USD/m^3
- About 206 tons of plastic bottles are dumped to landfills every day in Hong Kong in 2014.
- **Solution: creating a local demand for recycled plastic bottles**

- **Combined Solution: developing ECC waterproofing rendering with recycled PET fibers**

1. Introduction and Objectives

Technical Roadmap



1. Introduction and Objectives

Objectives

- To develop a suitable matrix for waterproofing rendering. The targets include achieving water contact angle larger than 90°, reducing drying shrinkage and enhancing resistance to water permeation
- To characterize and test the mechanical properties of various fibers, including recycled PET from different suppliers and PVA fibers, and to investigate the durability of recycled PET in alkaline environment
- To propose a suitable surface treatment of recycled PET fibers that can enhance the fiber/matrix bonding and improve the alkali resistance
- To conduct single fiber pull-out test of treated recycled PET and PVA fiber to examine the bonding between fiber and cementitious matrix
- To evaluate the mechanical behavior of hybrid PVA/PET fiber ECC with total fiber content of 2%, including direct tensile behavior and crack opening vs tensile strain, for members under normal and accelerated curing

2. Matrix Design

An UHVFA Matrix (CRM/Binder = 80%)

- The basic mix was based on a sustainable mix of ECC with ultra-high volumes of fly ash (UHVFA) developed at HKUST. The utilization of HVFA can slightly lower the pH value inside the matrix , which would also be beneficial to the durability of PET fibers.

- Silane based waterproofing agent (WPA): Silane hydrolyzes in alkaline environment, and form a hydrophobic layer on the capillary pores to prevent water penetration

- Shrinkage reducing agent (SRA): The SRA operates by interfering with the surface chemistry of the air/water interface within the capillary pores, reducing surface tension effects.

- Calcium sulfoaluminate cement (SAC): Formation of a reasonable (but not excessive) amount of ettringite after setting results in expansion which compensates for the shrinkage

2. Matrix Design

Mix Proportion

Mix ID	Binder (B)				S	W	SRA/ (B+S) [%]	WPA/ (B+S) [%]	SP/B [%]	Fiber (vol. %)	
	OPC	SAC	FA	LSP						PVA	PET
M1	0.2	0	0.72	0.08	0.2	0.3	0	0	0.22	0	0
M2	0.2	0	0.72	0.08	0.2	0.3	0	0.15	0.22	0	0
M3	0.2	0	0.72	0.08	0.2	0.3	0	0.30	0.22	0	0
M4	0.2	0	0.72	0.08	0.2	0.3	0	0.45	0.22	0	0
M5	0.2	0	0.72	0.08	0.2	0.3	0.5	0.30	0.22	0	0
M6	0.2	0	0.72	0.08	0.2	0.3	1.0	0.30	0.22	0	0
M7	0.2	0	0.72	0.08	0.2	0.3	2.0	0.30	0.22	0	0
M8	0.196	0.004	0.72	0.08	0.2	0.3	0	0.30	0.22	0	0
M9	0.188	0.012	0.72	0.08	0.2	0.3	0	0.30	0.33	0	0
M10	0.184	0.016	0.72	0.08	0.2	0.3	0	0.30	0.44	0	0
M11	0.180	0.020	0.72	0.08	0.2	0.3	0	0.30	0.55	0	0
M12	0.196	0.004	0.72	0.08	0.2	0.3	0.0	0.30	0.37	2.0	0
M13	0.196	0.004	0.72	0.08	0.2	0.3	0.5	0.30	0.37	2.0	0
M14	0.196	0.004	0.72	0.08	0.2	0.3	1.0	0.30	0.37	2.0	0
M15	0.196	0.004	0.72	0.08	0.2	0.3	2.0	0.30	0.37	2.0	0

2. Matrix Design

Mix Proportion (cont.)

Mix ID	Binder (B)				S	W	SRA/ (B+S) [%]	WPA/ (B+S) [%]	SP/B [%]	Fiber (vol. %)	
	OPC	SAC	FA	LSP						PVA	PET
M16	0.196	0.004	0.72	0.08	0.4	0.3	1.0	0.30	0.37	2.0	0
M17	0.196	0.004	0.72	0.08	0.8	0.3	1.0	0.30	0.37	2.0	0
M18	0.188	0.012	0.72	0.08	0.2	0.3	1.0	0.30	0.48	2.0	0
M19	0.184	0.016	0.72	0.08	0.2	0.3	1.0	0.30	0.59	2.0	0
M20	0.180	0.020	0.72	0.08	0.2	0.3	1.0	0.30	0.70	2.0	0
M21	0.196	0.004	0.72	0.08	0.2	0.3	1.0	0	0.37	1.0	1.0
M22	0.196	0.004	0.72	0.08	0.2	0.3	1.0	0.15	0.37	1.0	1.0
M23	0.196	0.004	0.72	0.08	0.2	0.3	1.0	0.30	0.37	1.0	1.0
M24	0.196	0.004	0.72	0.08	0.2	0.3	1.0	0.45	0.37	1.0	1.0

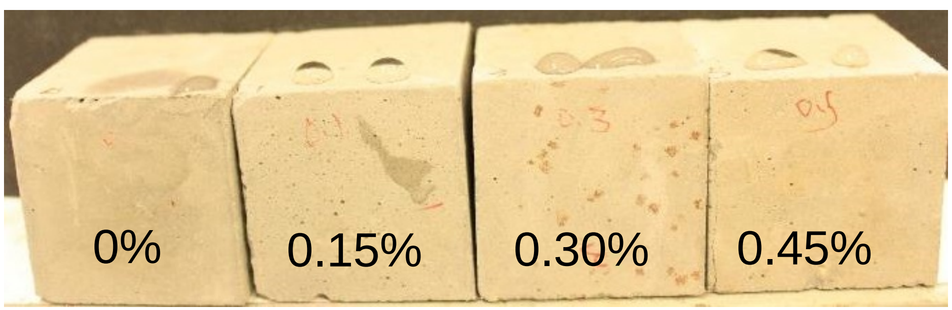
OPC - Ordinary Portland cement CEM I 52.5N;
SAC - Calcium sulfoaluminate cement;
FA - Fly ash (Class F);
LSP - Limestone powder with the nominal diameter of 58 μm;
S - Silica sand with the nominal diameter from 120 μm to 212 μm;
W - Water;
SRA - MUNZING Metolat P872 shrinkage-reducing agent;
WPA - WACKER Powder D silane-based waterproofing agent;
SP - GRACE AVDA 105 superplasticizer;
PVA - KURARAY K-II REC15 polyvinyl alcohol fibers;
PET - Recycled polyethylene terephthalate fibers.

2. Matrix Design

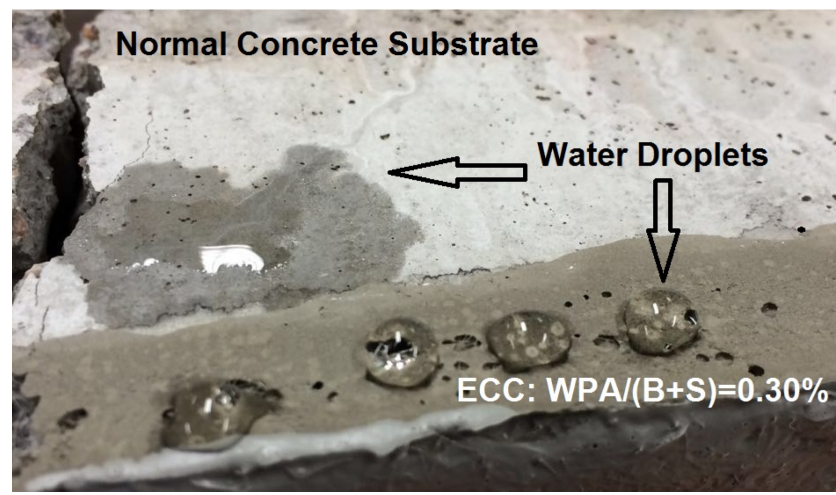
Water Contact Angle: Effect of WPA

WPA was used to enhance the hydrophobility	Water contact angle	28-day compressive strength
WPA/(B+S) = 0%	63°	37.85 MPa
WPA/(B+S) = 0.15%	116°	36.37 MPa
WPA/(B+S) = 0.30%	118°	38.06 MPa
WPA/(B+S) = 0.45%	121°	36.85 MPa

- WPA can significantly increase the water contact angle.
- WPA has no significant influence on the mechanical property.

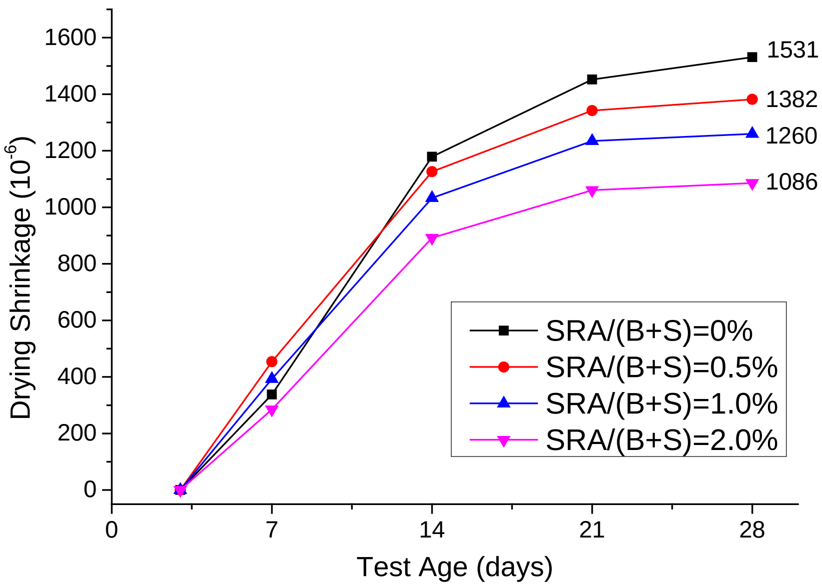


Water repelling effect of different matrices

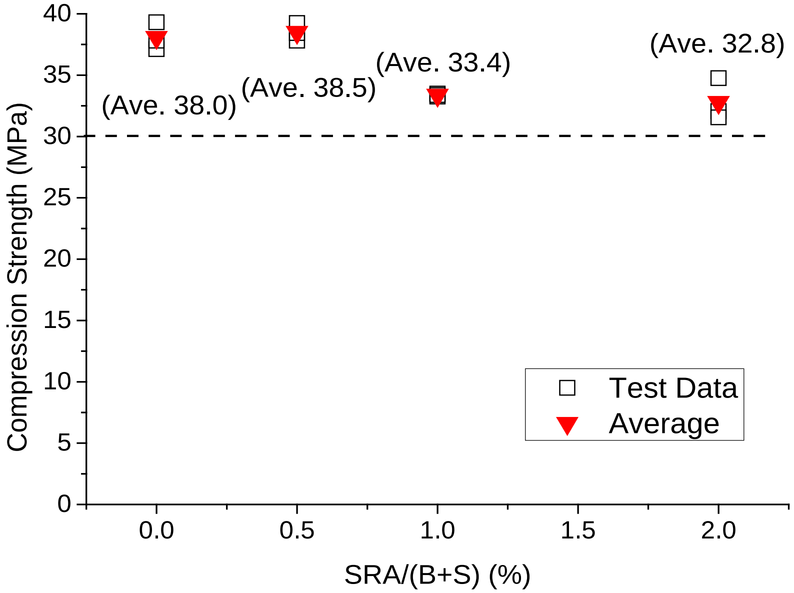


2. Matrix Design

Drying Shrinkage: Effect of SRA



<u>Effects of SRA content on drying shrinkage</u>

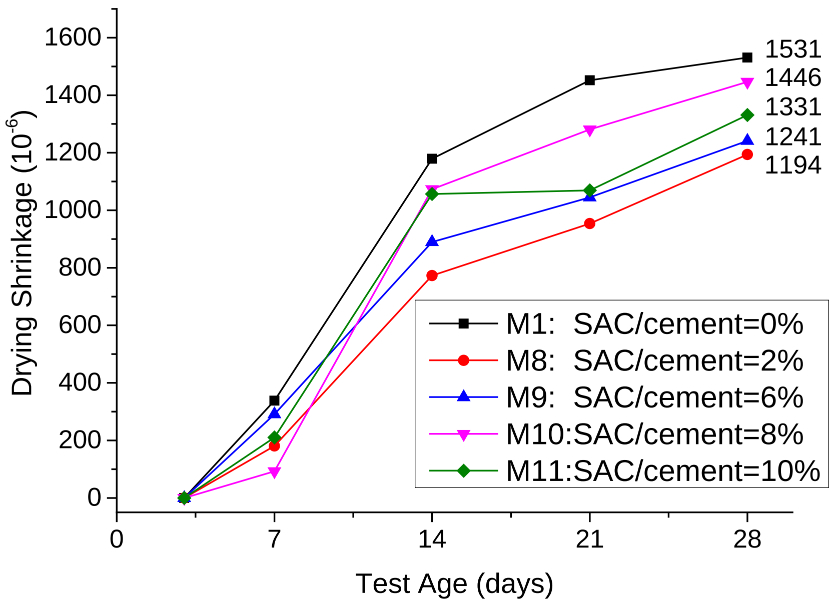


<u>Effects of SRA content on 28-day compressive strength</u>

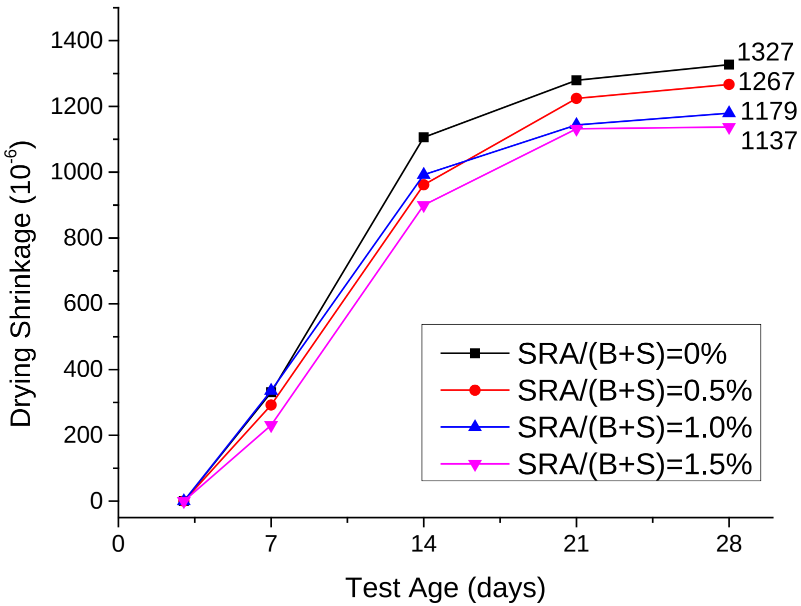
- The addition of SRA can significantly reduce the shrinkage value, and has no obvious effect on the compressive strength

2. Matrix Design

Drying Shrinkage: Effect of SAC and SRA



<u>Effects of SAC content on drying shrinkage</u>

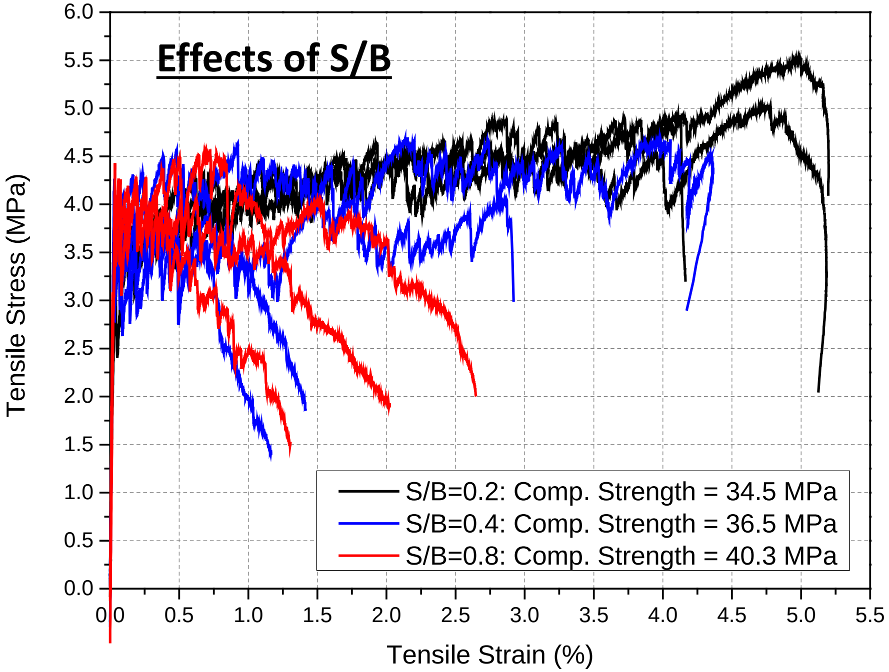


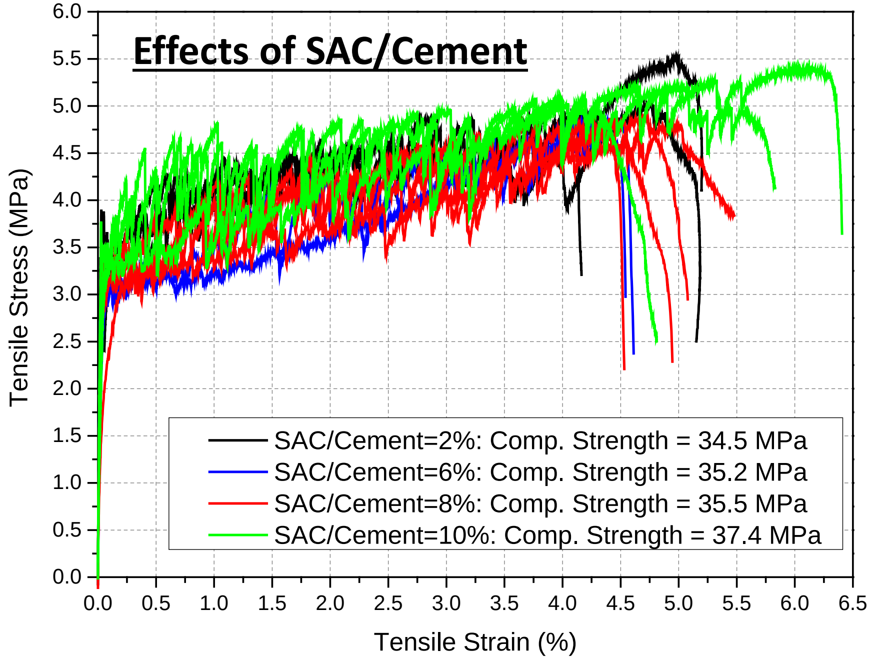
<u>Combined effect of SAC and SRA on drying shrinkage (SAC/Cement=2%, PVA=2.0 vol.%)</u>

- Replacing some OPC with SAC is beneficial as the lowest shrinkage was achieved with the blended ratio of SAC/Cement=2%
- Balancing among compression strength, shrinkage reducing effect and cost, a SRA/(B+S)=1.0% is adopted
- 28-day drying shrinkage about 2/3 the value for normal ECC

2. Matrix Design

Tensile Performance (w/ 2.0 vol% PVA Fibers at 28-day age)



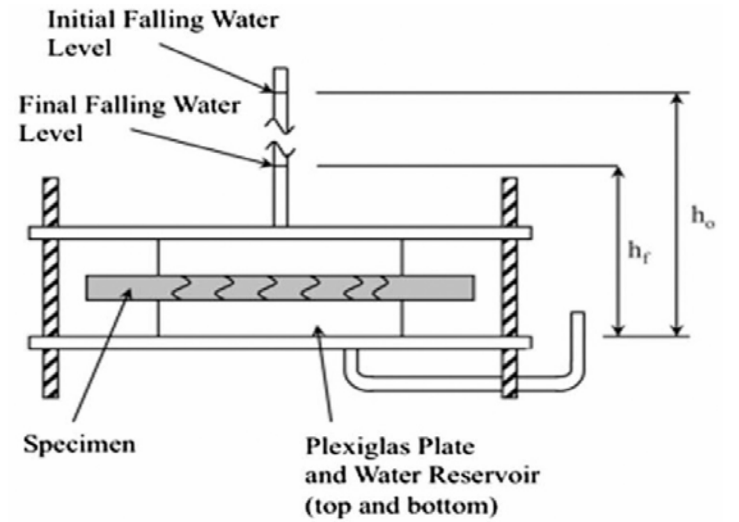


- Tensile strain capacity decreases with increasing S/B, S/B=0.2 is chosen
- More SAC results in a wider crack opening, SAC/Cement =2% is selected

2. Matrix Design

Water Permeability (28d)

$$k_w = \frac{A'}{A} \frac{L}{t} \ln \frac{h_o}{h_1}$$



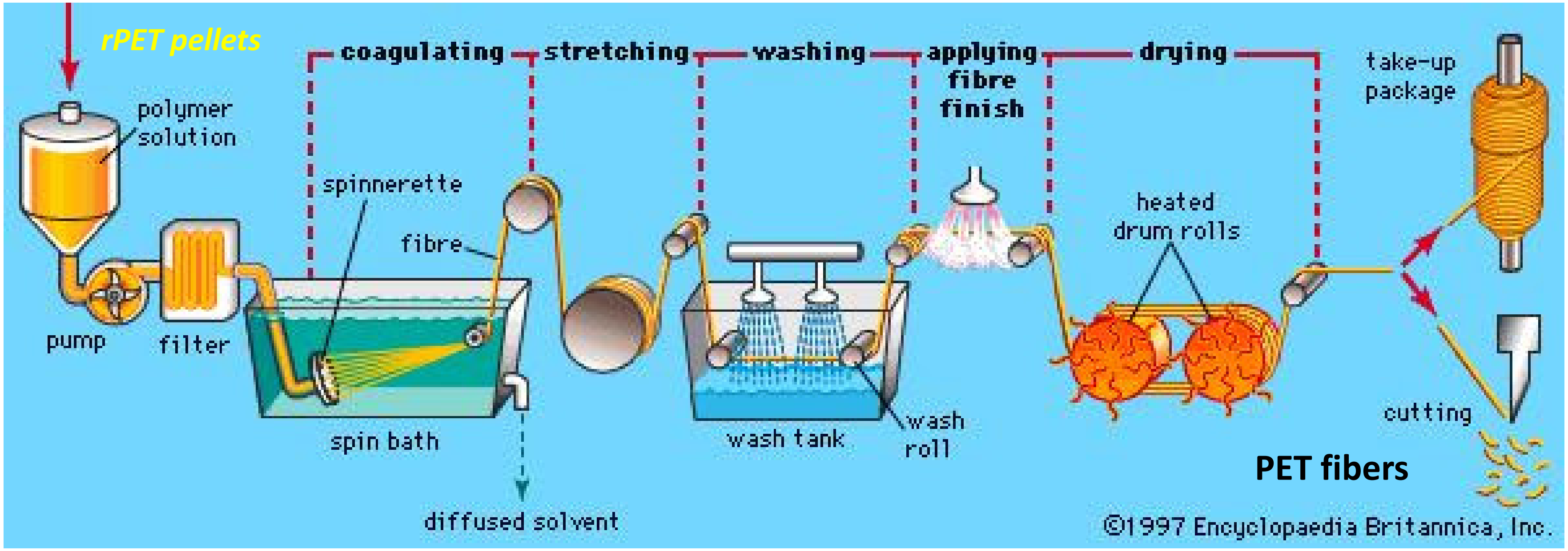
Mix ID	Kw (10^{-10} cm/s)
WPA/(B+S) = 0.00%	16.27
WPA/(B+S) = 0.15%	7.35
WPA/(B+S) = 0.30%	4.46
WPA/(B+S) = 0.45%	3.36
General Mortar with w/b =0.35 (Lepech & Li, 2009)	45.8
Typical ECC with w/b = 0.25 (Lepech & Li, 2009)	8.18
High-Strength ECC with w/b = 0.22 (Zhao, 2012)	1 ~ 4

- Comparing WPA/(B+S)=0% to typical ECC: larger w/b and more fly ash
- WPA can efficiently improve the water permeability resistance
- Low water permeability of P10T10 have been observed

3. Recycled PET Fiber Design

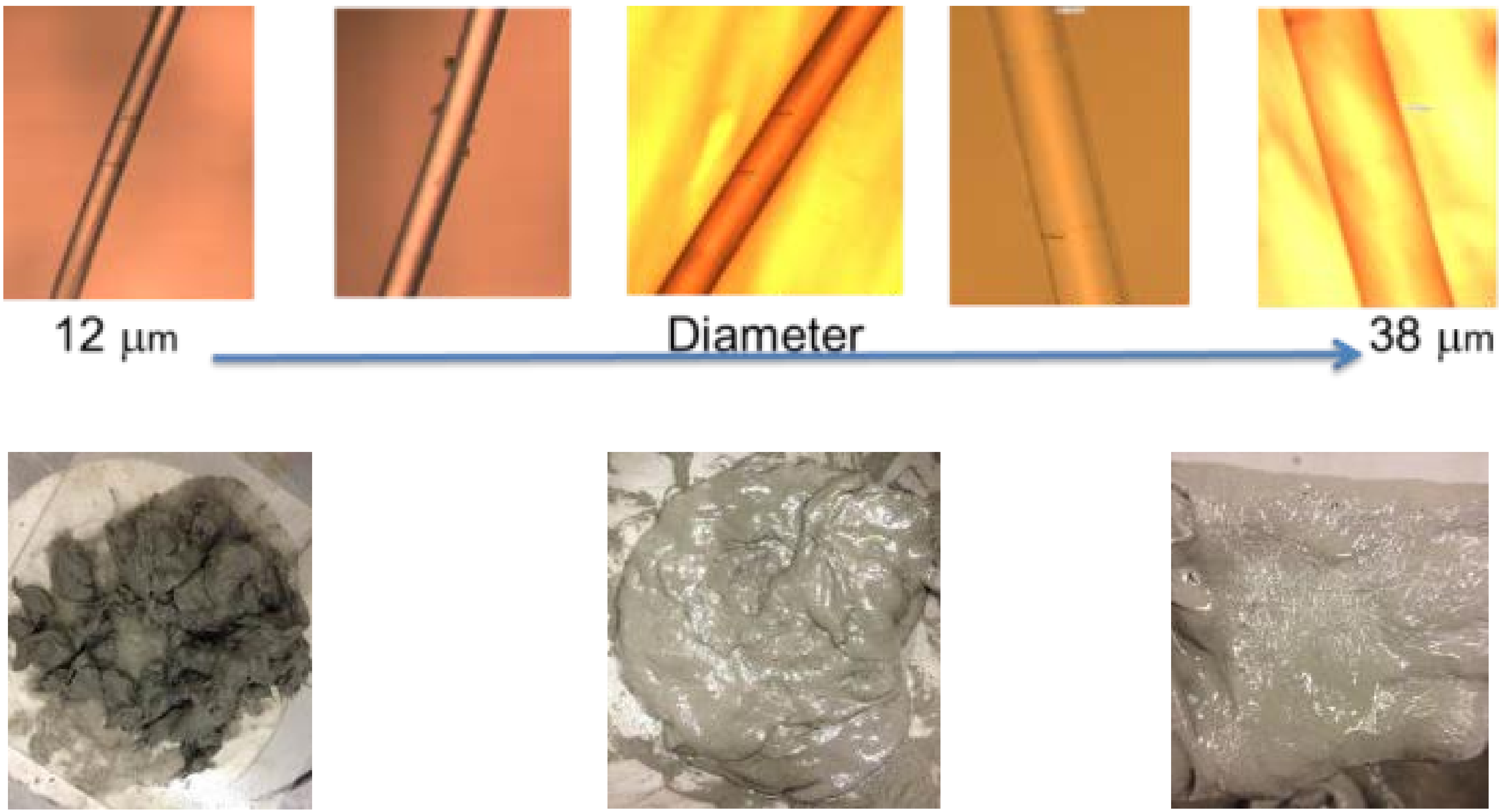
Recycling of PET Bottles into PET Fibers

33 million tons of plastic waste in 2013



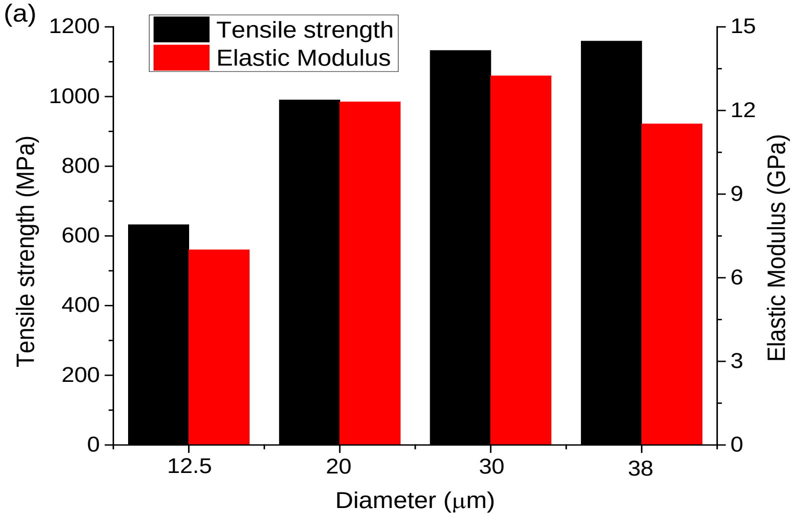
3. Recycled PET Fiber Design

PET Fiber Diameter (L = 12 mm): Fiber Distribution

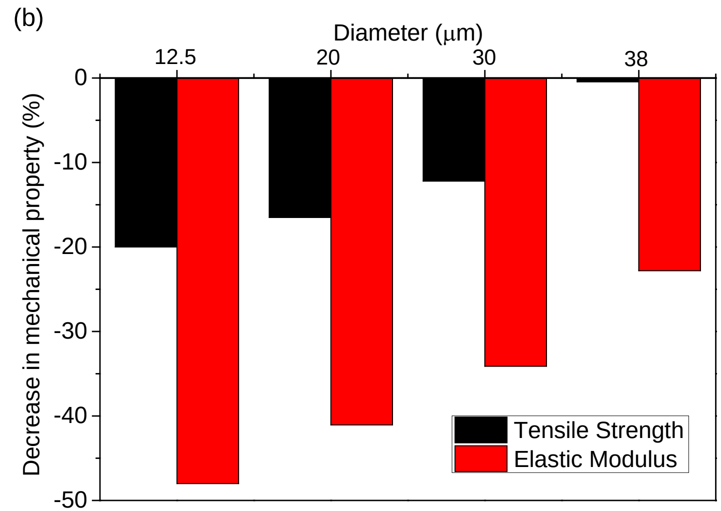


3. Recycled PET Fiber Design

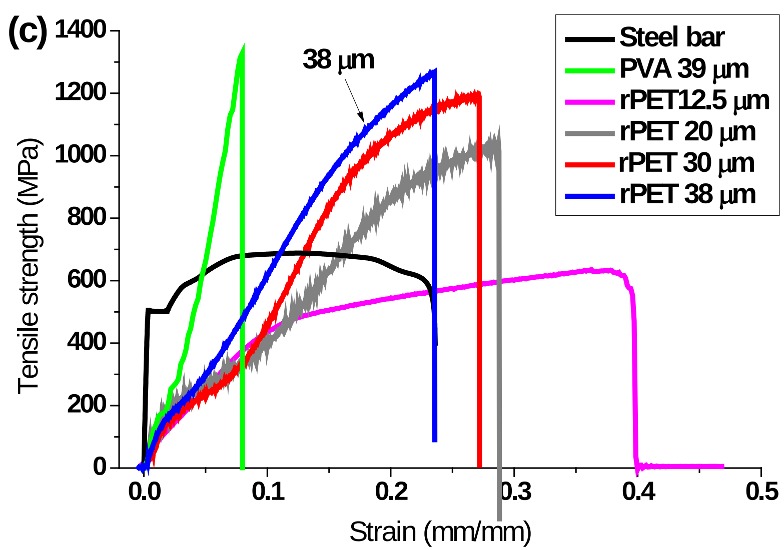
PET Fiber Diameter (L = 12 mm): Mechanical Properties



Tensile strength and elastic modulus of untreated PET fiber



Mechanical property change after alkali resistance test (5 wt% NaOH solution for 6 hours)

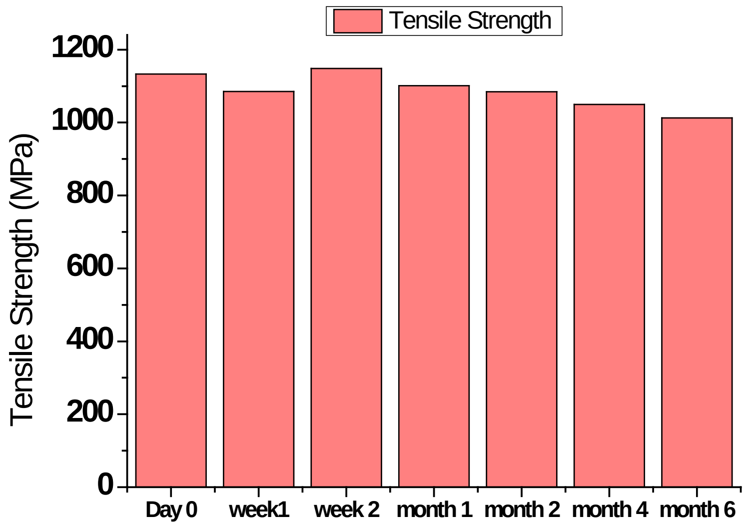


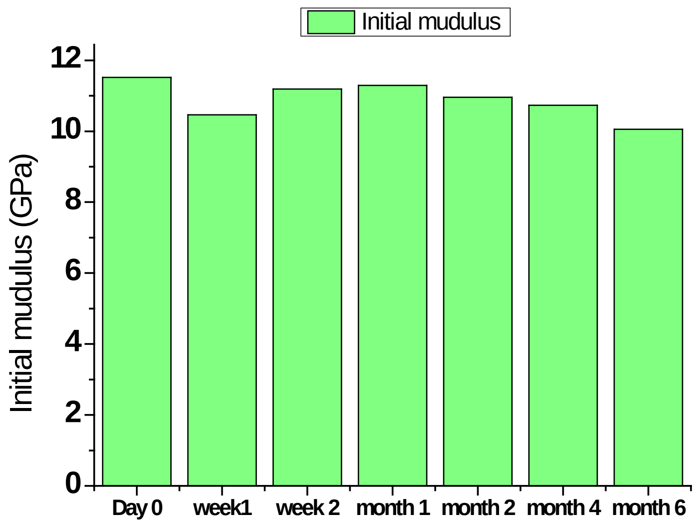
- Property degradation under alkaline environment decreases with fiber size
- Fiber diameter of 38 μm was selected

3. Recycled PET Fiber Design

Alkali Resistance of Fresh 38 µm PET Fiber @ pH=12.6

ASTM D7705: long-term accelerated alkali resistance test
(pH=12.6, and kept in water bath at 60°C)

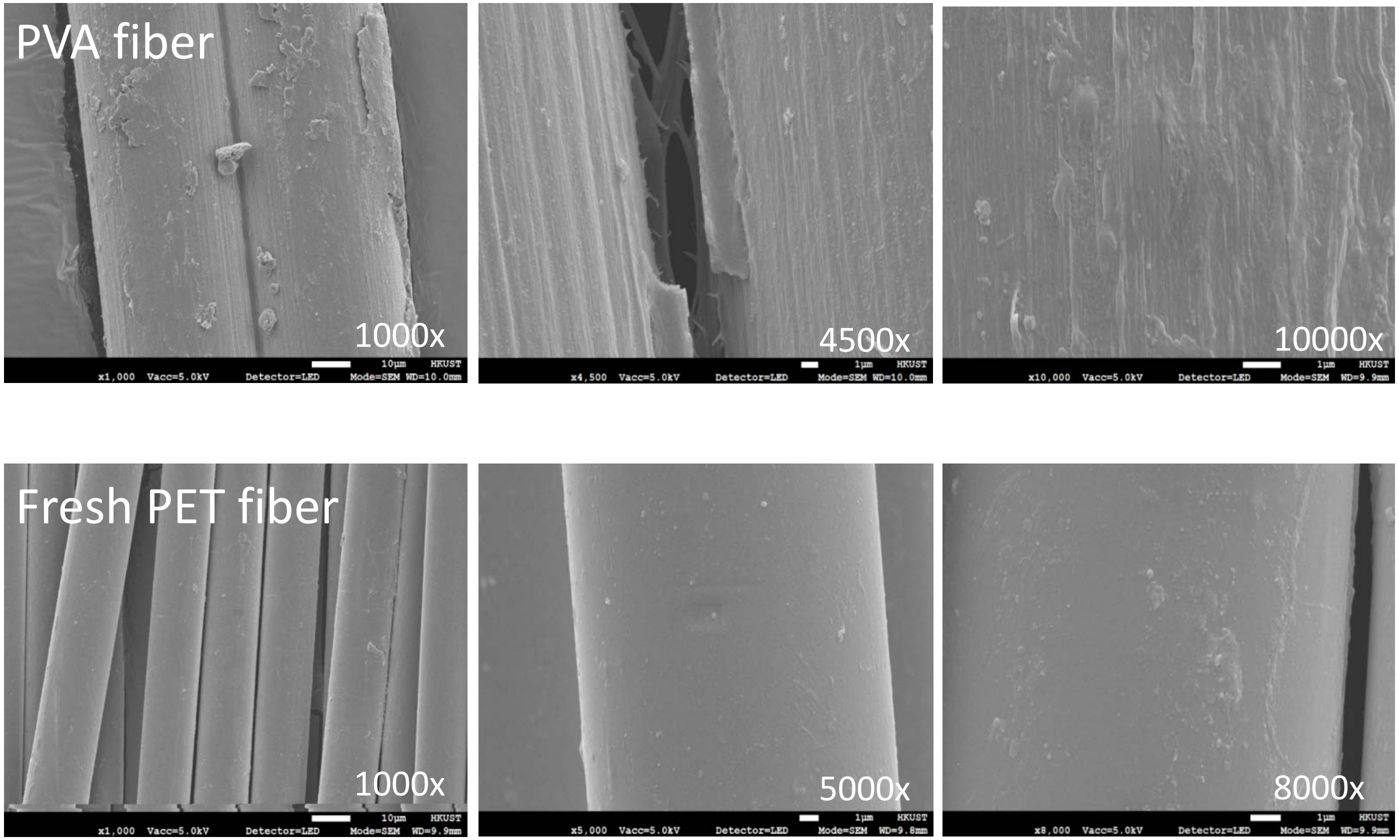


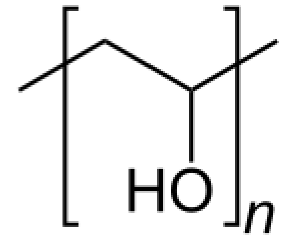


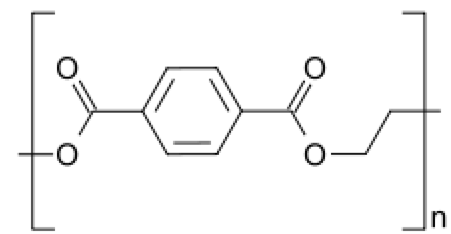
Results indicate Acceptable alkali resistance of fresh PET fibers in cement-based matrix

3. Recycled PET Fiber Design

Surface Morphologies of PVA and PET Fiber



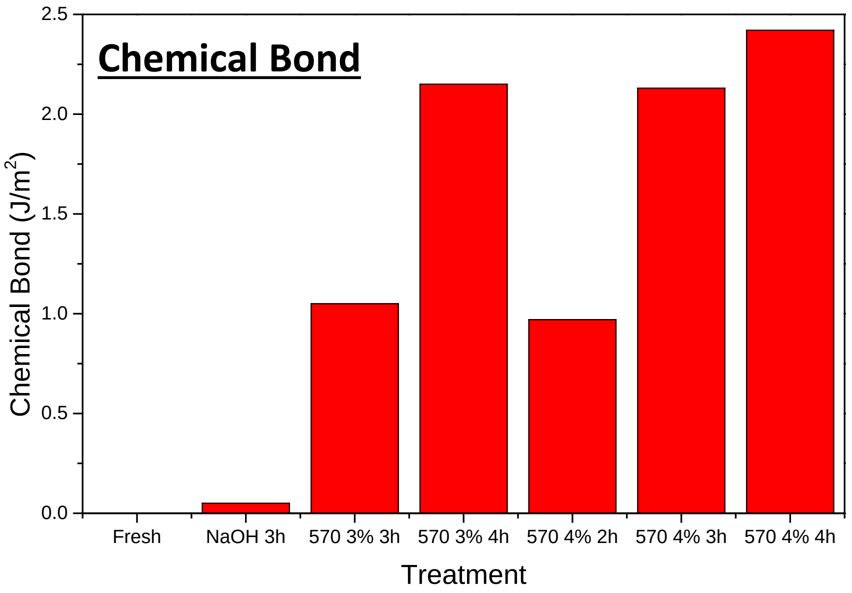


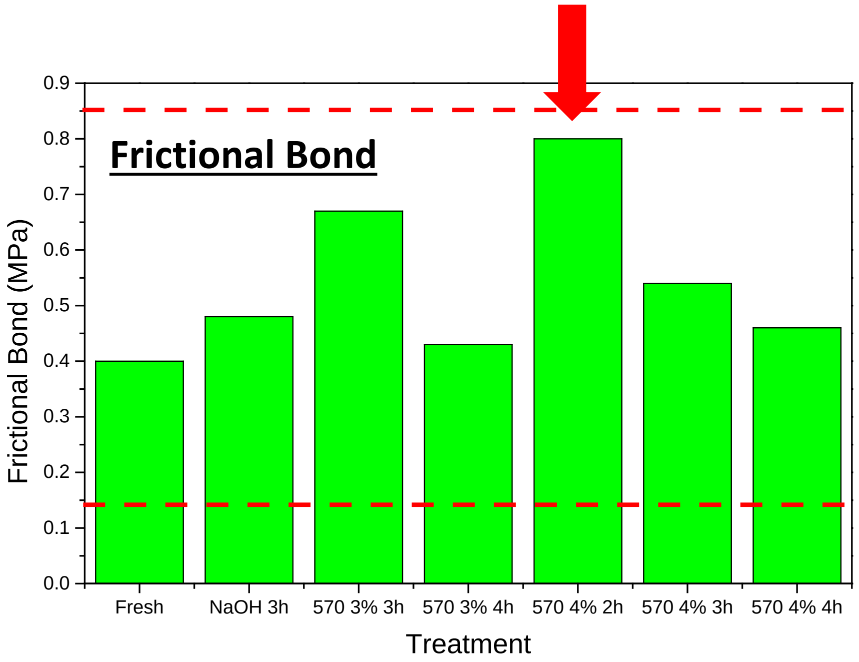


- Fresh PET Fiber: smooth surface and hydrophobic nature (PVA is hydrophilic)
- Surface Modification can be performed to improve PET performance in ECC

3. Recycled PET Fiber Design

Bond Strength of PET fiber

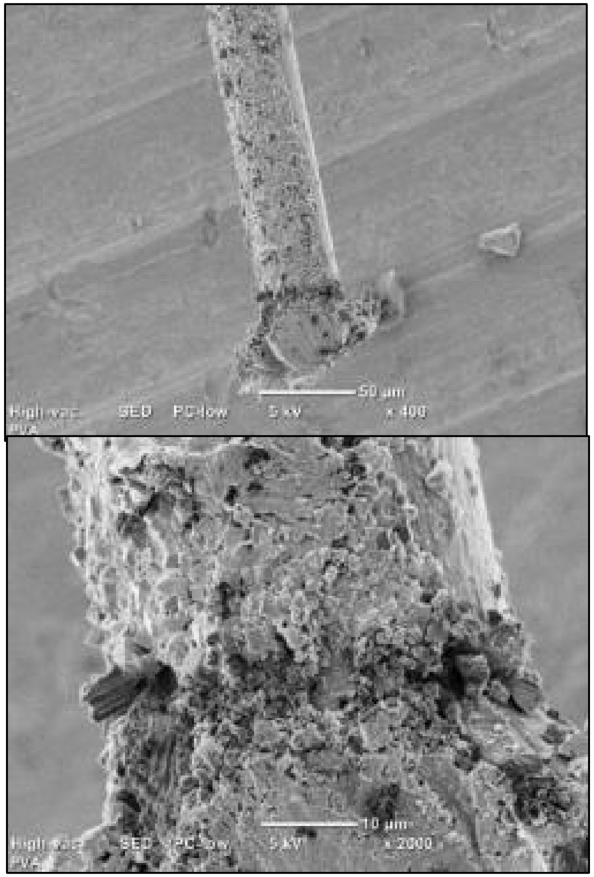




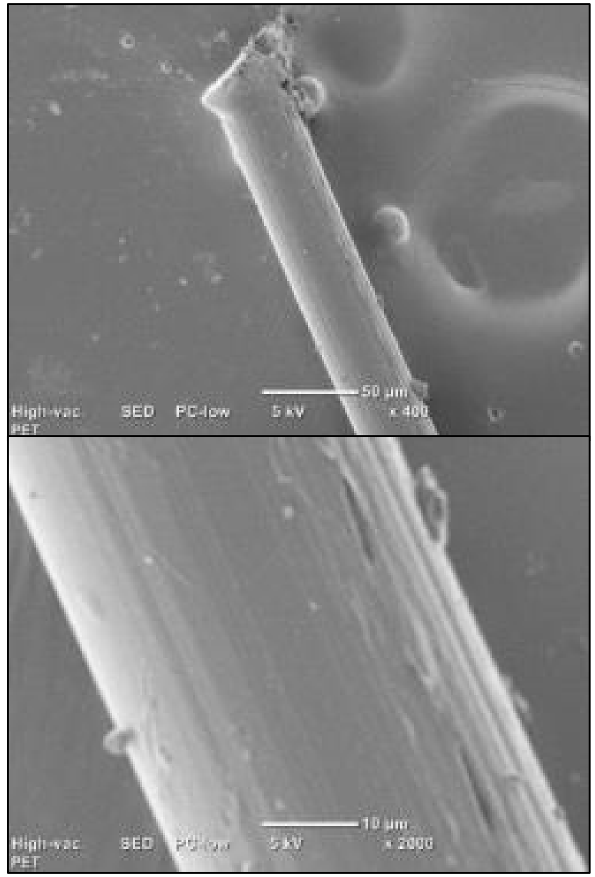
- Bond between fiber and matrix is determined from the pull-out test
- Surface treatment has significant effect on the chemical bond strength.
- From calculation, the target frictional bond is $0.145\ MPa \leq \tau \leq 0.851\ MPa$, with better crack control when the friction is higher
- Treatment with 4% KH570 for 2h is chosen

3. Recycled PET Fiber Design

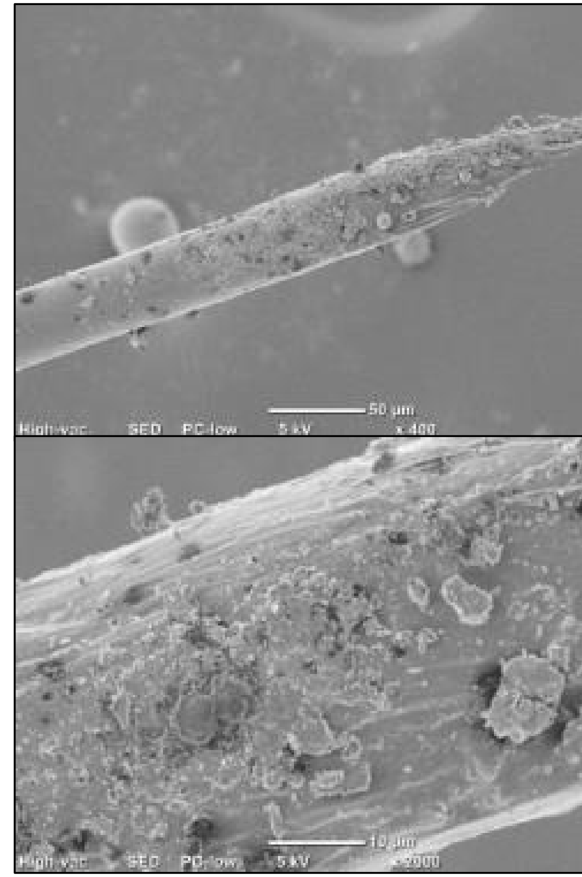
Fibers after Pulling-out from Matrix



PVA



Fresh PET



Treated PET

3. Recycled PET Fiber Design

Comparison of Different Fibers

Fiber	Cost (HKD/kg)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation (%)
PVA (Japan Kuraray)	150	1600 (nominal)	40 (nominal)	7
PVA (Mainland China)	30~40	1300 (nominal)	17 (nominal)	7
Normal PP for construction	13-20	>400	3.5	20~30
PET for construction	14	>500	9	>15
Recycled PET with treatment	**18**	**>1000**	**11**	**20~30**

- **The recycled PET fibers exhibit good performance at low cost.**

4. Mechanical Properties

Mix Proportion

Mix ID	Binder (B)				S	W	SRA/(B+S) [%]	WPA (B+S) [%]	SP/B [%]	Fiber, vol.%		
	OPC	SAC	FA	LSP						PVA	PET-U	PET-T
P20	0.196	0.004	0.72	0.08	0.2	0.3	1	0.3	0.37	2.0	0	0
P15U05										1.5	0.5	0
P15T05										1.5	0	0.5
P10U10										1.0	1.0	0
P10T10										1.0	0	1.0
P05U15										0.5	1.5	0
P05T15										0.5	0	1.5
U20										0	2.0	0
T20										0	0	2.0

- Total fiber volume fraction: 2.0%
- Curing: 28-day standard curing and accelerated aging curing (50°C for an additional 35d)
- Tests:
  - Compression: 50 mm × 50 mm × 50 mm (ASTM C109/C109M)
  - Uniaxial tension: Dumbbell Sample with 30 mm × 13 mm Cross Section (JSCE, 2008)
  - Four-point bending: 300 mm (span) × 50 mm (width) × 15 mm (height)

4. Mechanical Properties

Test Results

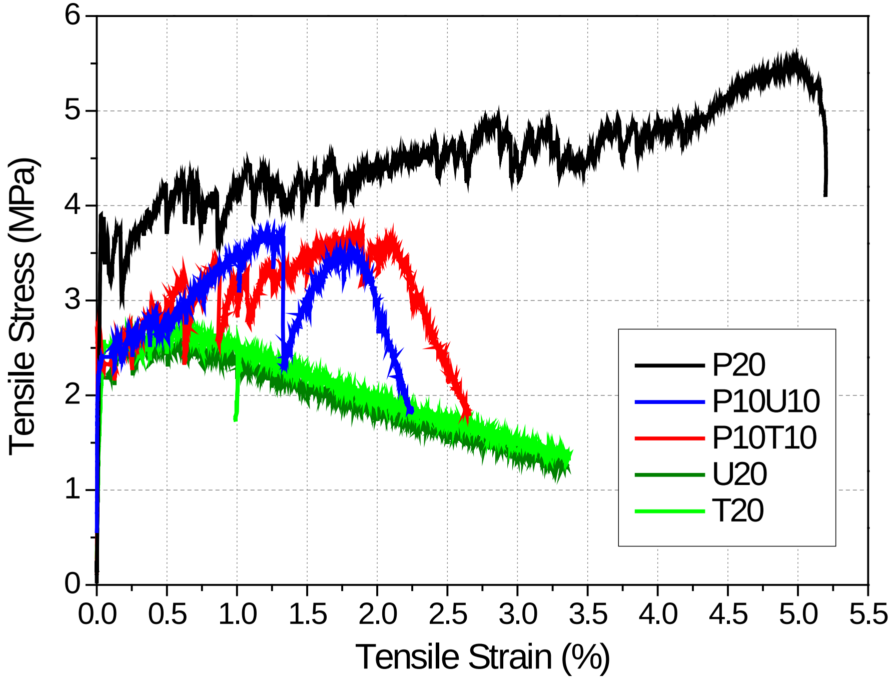
Mix ID	Standard 28-day Curing					Accelerated Aging Curing		
	Comp. Strength [MPa]	Tensile Capacity [%]	Tensile Strength [MPa]	Bending Capacity [1x10^{-3}/cm]	Bending Strength [MPa]	Comp. Strength [MPa]	Tensile Capacity [%]	Tensile Strength [MPa]
P20	36.02	4.63	5.17	3.10	11.40	49.16	3.73	6.15
P15U05	37.50	3.27	4.44	2.86	10.20	63.54	2.62	4.60
P15T05	37.23	3.90	4.35	2.92	10.35	59.14	3.14	4.53
P10U10	34.46	1.83	3.59	2.45	10.19	60.35	1.20	3.76
P10T10	34.37	2.16	3.63	2.53	10.10	54.58	1.35	3.86
P05U15	37.22	0.97	3.20	1.82	7.52	58.29	0.53	3.60
P05T15	35.41	1.05	3.26	1.81	7.80	58.23	0.64	3.41
U20	32.62	0.66	2.82	0.76	6.63	50.06	0.54	2.76
T20	33.31	0.85	2.63	1.29	6.89	48.15	0.99	2.63

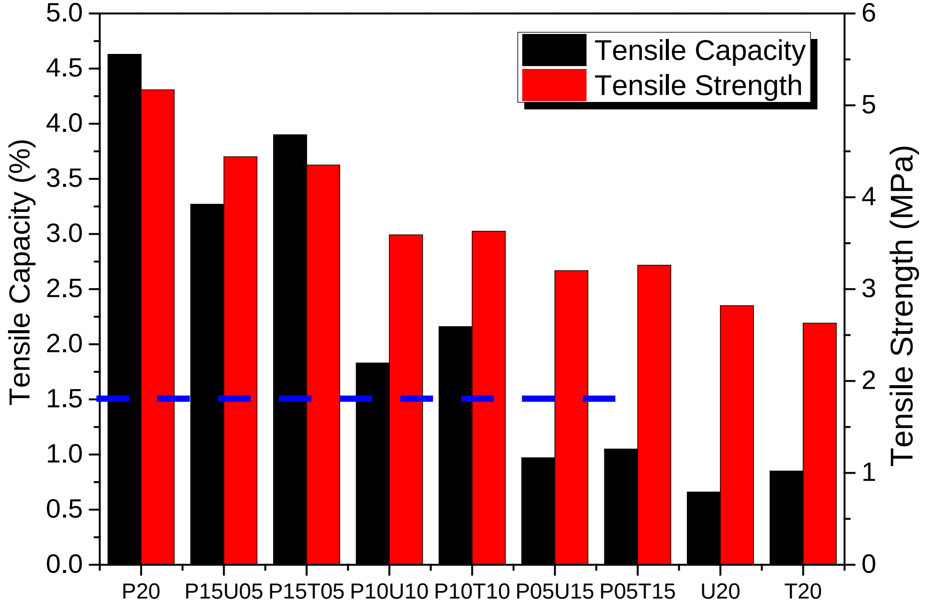
- **Compression:** The compressive strength of all the mixtures achieved higher than 30 MPa at 28-day age, effects of fiber on compressive strength is small

- **Bending:** ECC with pure PVA fibers (P20) shows the best performance, treated PET fibers (T20) perform better than untreated PET fibers (U20)

4. Mechanical Properties

Tensile Test Results: Fiber Combination

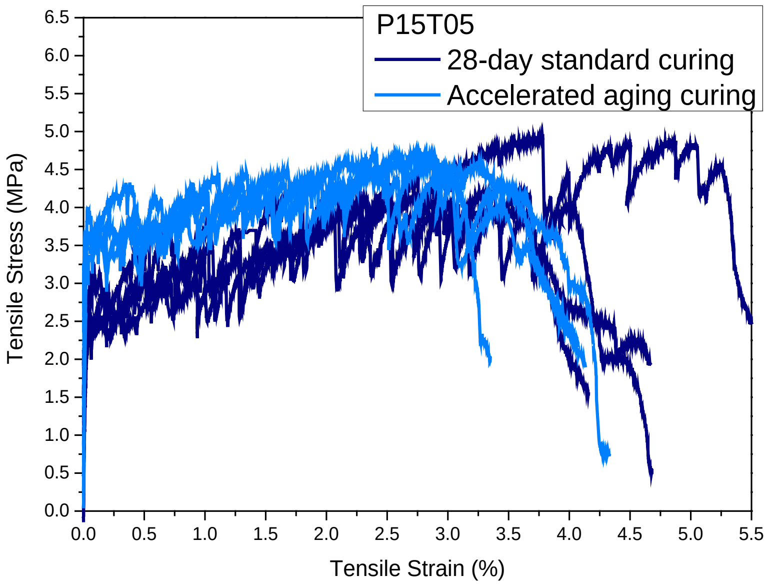


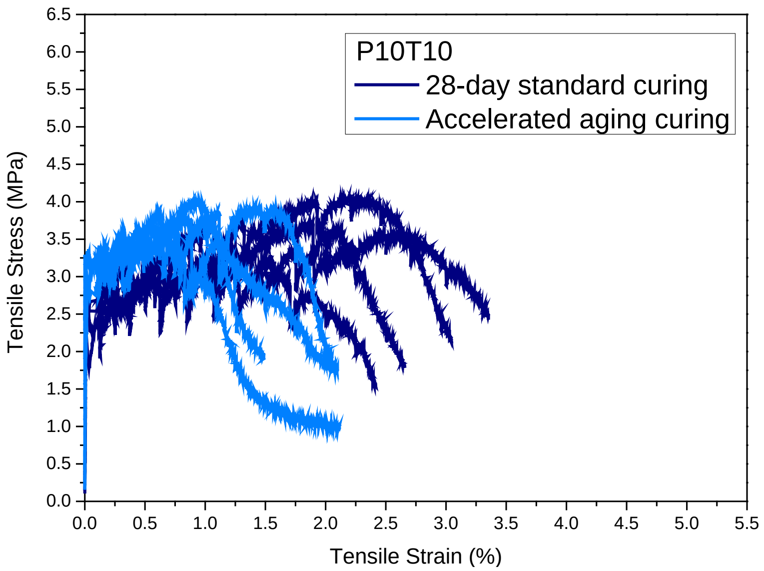


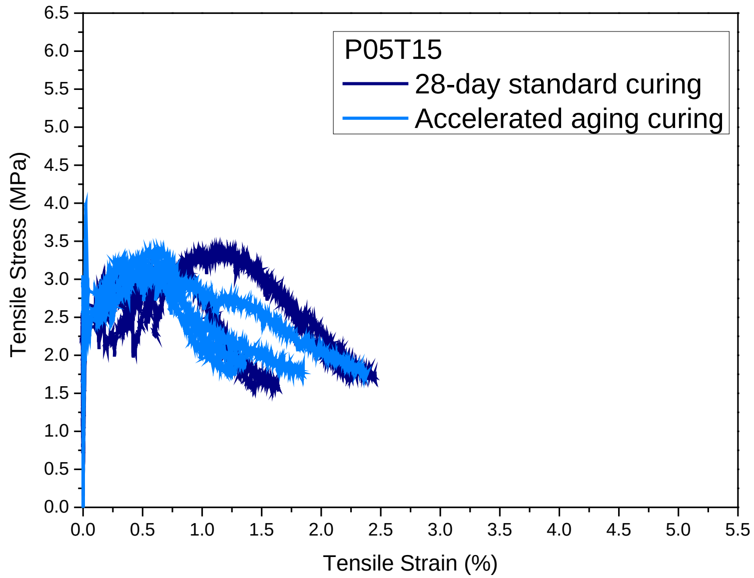
- ECC with pure PVA fibers (P20) shows the best performance
- The ductility for mixes with treated PET fibers is higher than those with untreated PET fibers
- When 50% of PVA fibers are replaced by recycled PET fibers, the performance is still acceptable

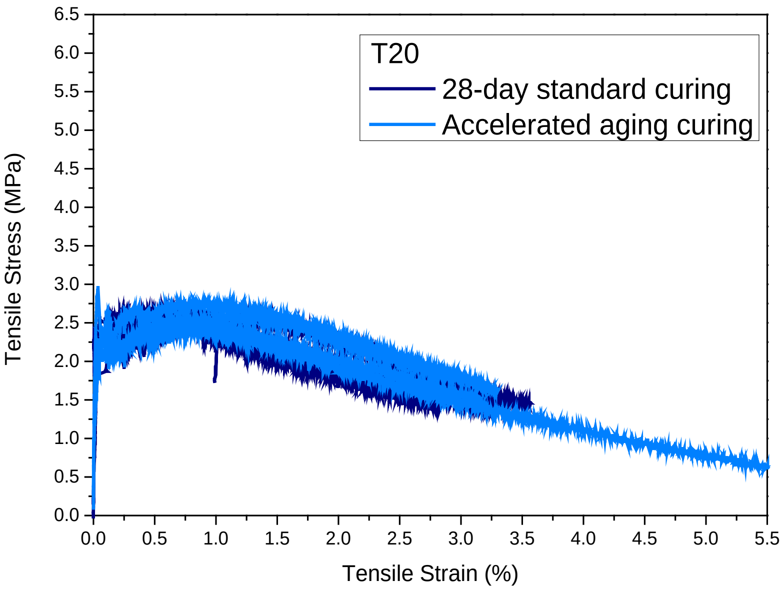
4. Mechanical Properties

Tensile Test Results: Treated-PET Series



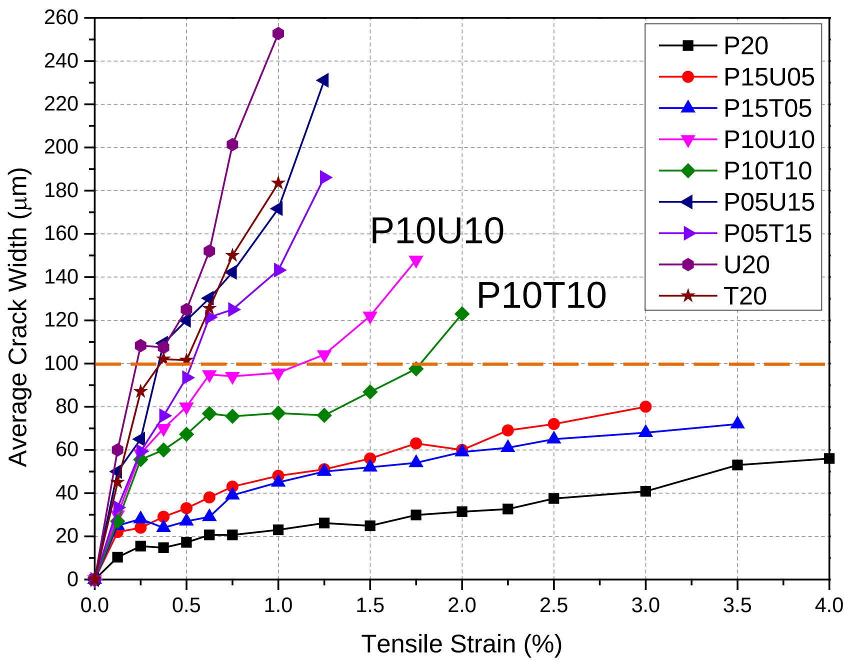


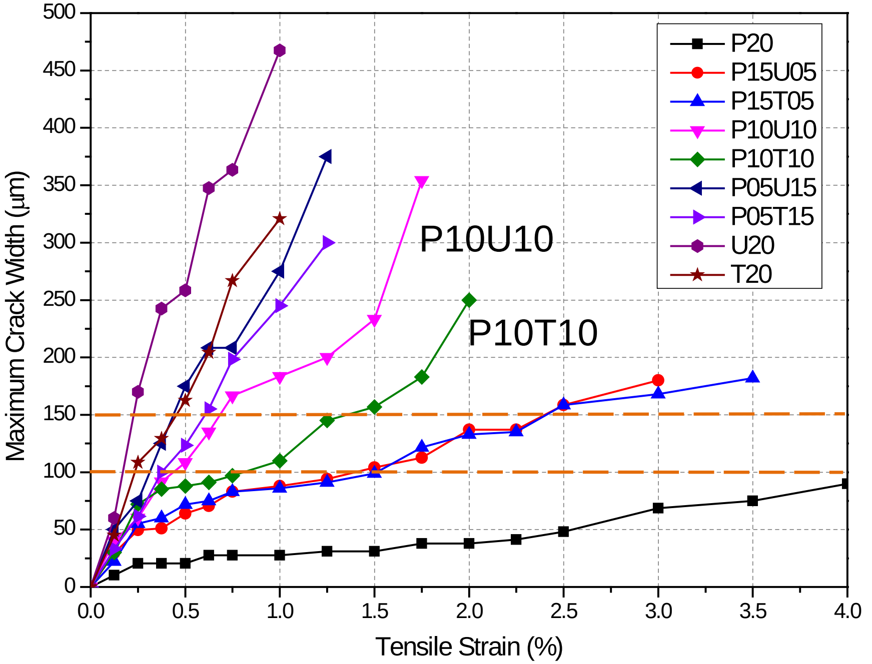




4. Mechanical Properties

Crack Control of ECC (28-day)



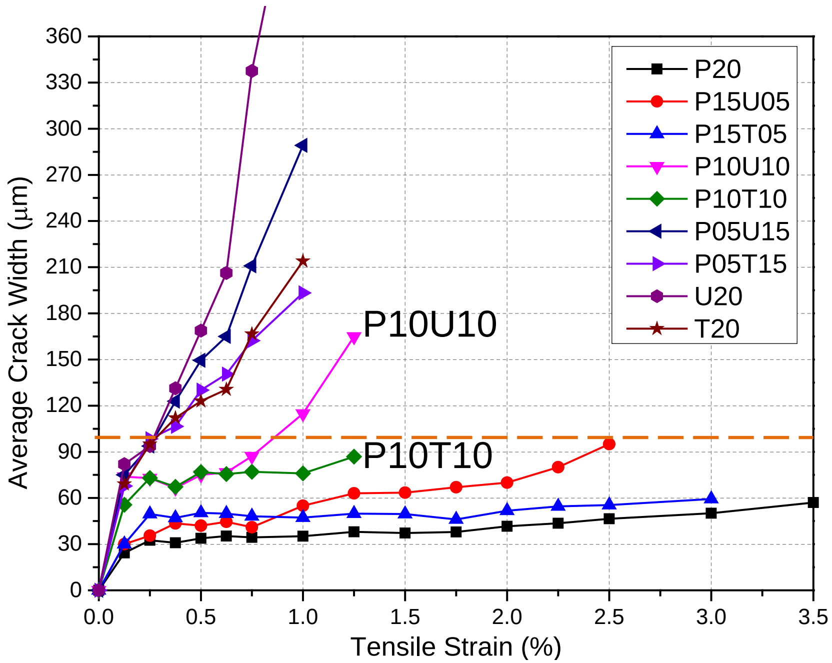


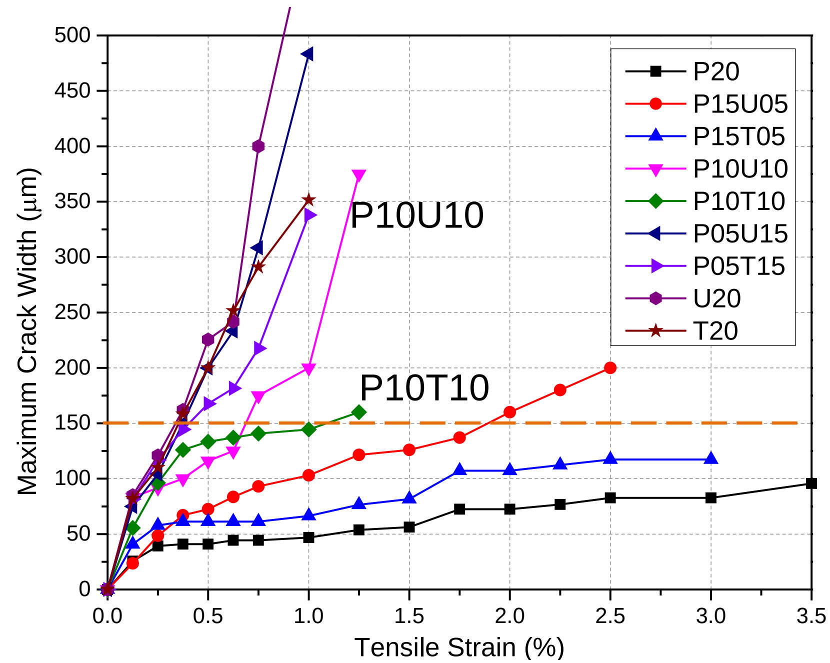
- P20 shows an average crack width under 60 μm and a maximum crack width under 100 μm up to 4%.

- Specimens with treated fibers shows better crack control ability. For P10U10, the average crack width is under 100 μm at 1.0%, and the maximum crack width is under 150 μm at 0.625%, while for P10T10, average crack width is under 100 μm at 1.75%, and the maximum crack width is under 150 μm at 1.25%, and under 100 μm at 0.75%.

4. Mechanical Properties

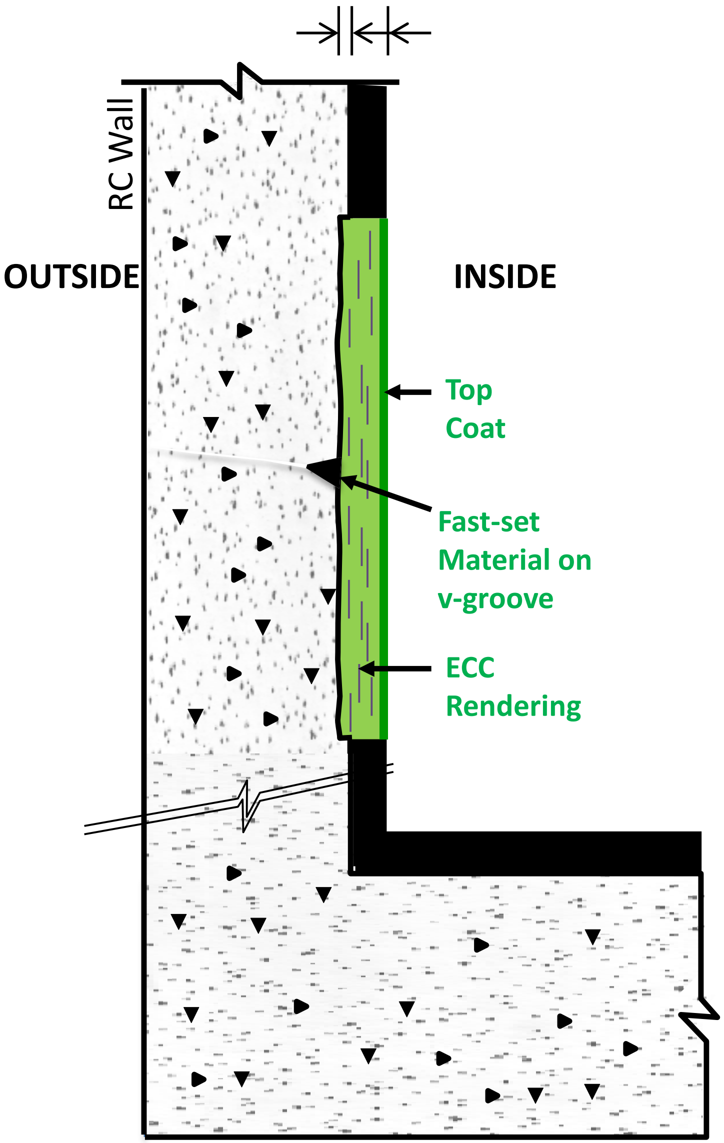
Crack Control of ECC (Accelerated Aging)





- The overall crack control ability decreases slightly after aging
- for P10U10, the average crack width is under 100 μm at 0.75%, and the maximum crack width is under 150 μm at 0.625%, while for P10T10, average crack width is under 100 μm at 1.25%, and the maximum crack width is under 150 μm at 1.0%

Field Trial in a Basement with Water Leakage



ECC applied in two areas (roughly 1m x 1m) with severe water leakage

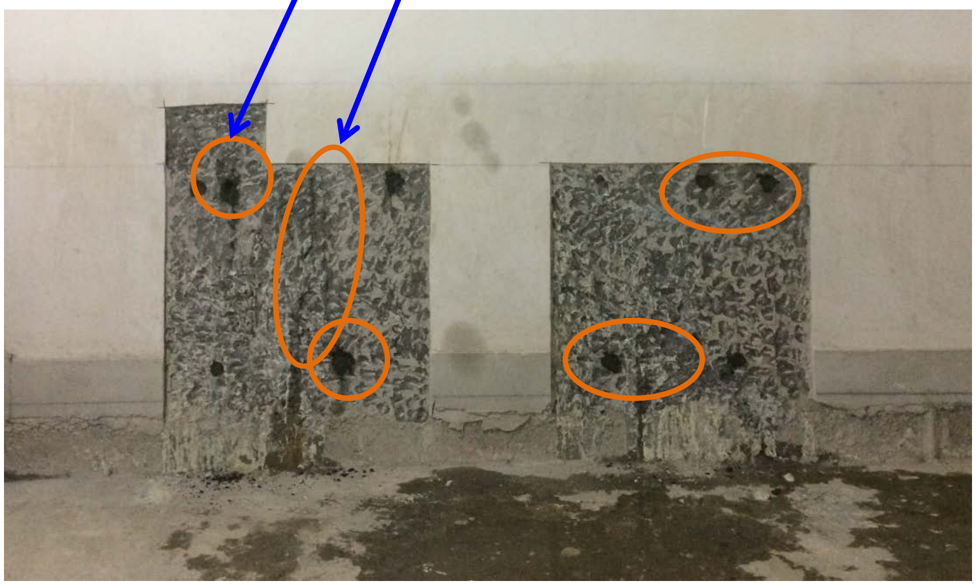
Key Steps:

- Concrete surface is roughened
- Standing water and dust are wiped off
- V-groove is made at seepage points
- Fast-set material is applied or grout is injected to stop water temporarily
- ECC is applied
- Top Coat is applied after ECC is hardened

Before Repair

After Repair

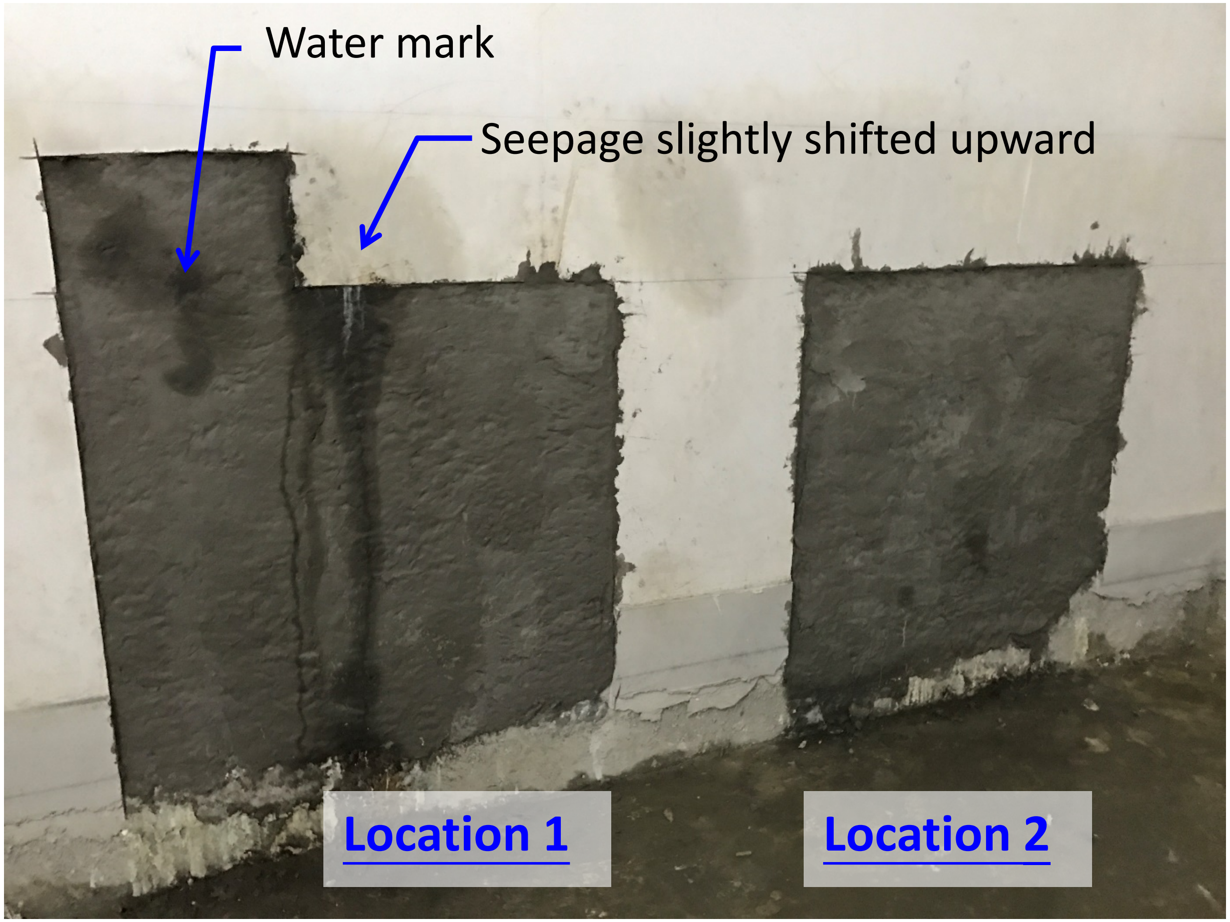
- Water leakage from big cracks in these regions
- Attempt to seal cracks before applying ECC



Location 1

Location 2

Inspection after about One Month



- Water Leakage stops at one of the locations but persists in another location
- Additional work on stopping running water before ECC hardening is needed

5. Concluding Remarks

- A matrix with very good waterproofing ability and low drying shrinkage can be obtained by introducing the WPA and SRA, and replacing a small percentage of OPC by SAC.

- A surface treatment method to enhance the fiber/matrix bonding and improve the alkali resistance of recycled PET fibers has been developed.

- Very good mechanical performance can be achieved with up to 50% of PVA fibers replaced by recycled PET. The replacement of PVA fibers with recycled PET fibers reduces the material cost and the environmental impact significantly.

- Field demonstration shows some success but additional work required for the situation when existing water leakage is severe

THANK YOU

Acknowledgement

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