Investigating mechanical properties of 3D-printed Engineered Cementitious Composites with ultra-high tensile strain capacity

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3D-Concrete Printing (ECC)

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Research question: The possibility of achieving structurally *sound rebar-free concrete structures* by using 3D-printing techniques.

Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Engineered Cementitious Composites (ECC)

Pre-installed reinforcement

Post-installed reinforcement

Phase I- Adjusting the mix design of ECC to achieve printable mix.

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Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

The quality of 3D-printed ECC was not acceptable

Large content of fiber reduces the dimension stability of 3D-printed component

Question:
How to improve the printing quality of ECC?

Viscosity Modifying Admixture (VMA) → Printable ECC mix

Phase I: Extensive experimental study to characterize the fresh properties of ECC mixes including extrudability, buildability and rheology tests

Introduction

- Title of study
- Statement of the Problem
- Objectives

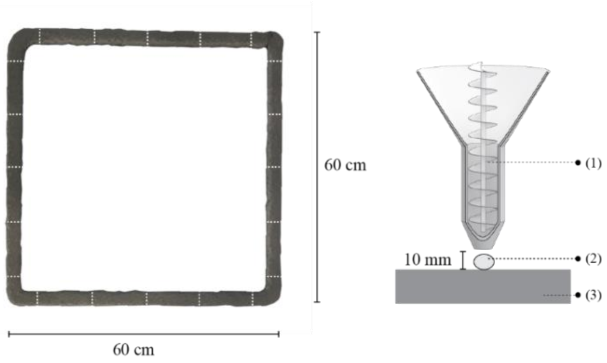
Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

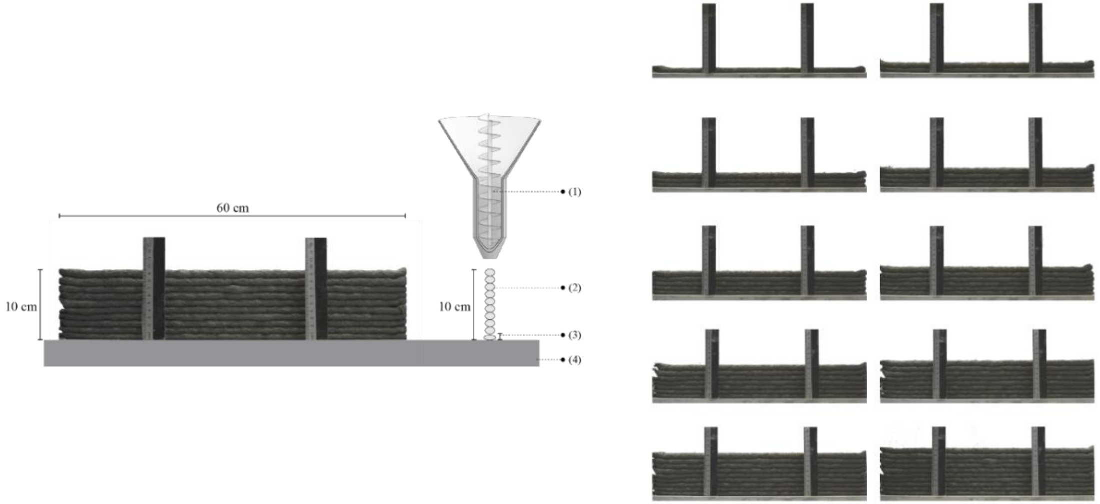
Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Buildable ----------> Extrudable



Extrudability Tests



Buildability Tests

Phase II: Extensive experimental study to characterize the mechanical properties of ECC mixes including compressive strength, direct tension, and bending tests

- Investigating the feasibility of using available materials from the local suppliers in region 6 to ECC.
- Designing ECC mixtures with sufficient compressive strength and suitable fresh properties for 3D-printing applications.
- Investigating the mechanical performance of selected ECC mixes from our previous studies and compare it with the cast-in-place ECC mixes with different fiber types (PVA vs. PE) and volumetric fiber.

The mechanical properties of ECC were studied as a function of SCMs (50% cement replacement), type and content of 8mm fibers

Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Chemical composition of mineral admixtures

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	TiO_2	Na_2O	Specific Gravity
C	19.24	4.75	3.35	65.80	2.20	3.61	0.54	0.21	-	3.13
S	30.80	11.45	2.26	47.50	3.65	3.03	0.38	-	0.17	2.91
SF	97.80	-	-	-	-	0.30	-	-	0.01	2.20
FA	61.27	23.18	5.09	2.11	1.19	0.30	1.43	-	1.44	2.09
MK	53.00	43.80	0.43	0.02	0.03	0.03	0.19	1.70	0.23	2.5

Properties of PVA and PE fibers

Material	Diameter (microns)	Length (mm)	Specific Gravity	Tensile Strength (MPa)	Flexural Strength (GPa)	Color
PVA Fibers	38	8	1.30	1600	40	White
PE Fibers	15	8	0.97	3000	100	White

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Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Mix design of different ECC mixtures

#	Mix ID	Fiber Type	C/B	FA/B	S/B	SF/B	MK/B	W/B	Adjusted W/B	RS/B	MC (%)[1]	HRWR (%)[1]	Fibers (Vol%)[3]
1	FA50	PVA	0.5	0.5	0	0	0	0.27	0.23	0.25	0.01	0.006	1.5
		PVA									0.01		2
		PE									0.01		2
2	S50	PVA	0.5	0	0.5	0	0	0.27	0.30	0.25	0.01	0.006	1.5
		PVA									0.01		2
		PE									0.01		2
3	FA40-SF10	PVA	0.5	0.4	0	0.1	0	0.27	0.27	0.25	0.01	0.006	1.5
		PVA									0.01		2
		PE									0.01		2
4	FA40-MK10	PVA	0.5	0.4	0	0	0.1	0.27	0.27	0.25	0.01	0.006	1.5
		PVA									0.01		2
		PE									0.01		2

Note: 1. %HRWR and MC dosage by weight of Binder

2. **C**: Cement; **FA**: Fly Ash; **S**: Slag; **MK**: Metakaolin; **SF**: Silica Fume; **W**: Water; **RS**: River Sand; **B**: Binder; **HRWR**: High Range Water Reducer, **MC**: Methyl Cellulose

3. all ratios are weight (wt) ratios but the volumetric fiber content.

Introduction

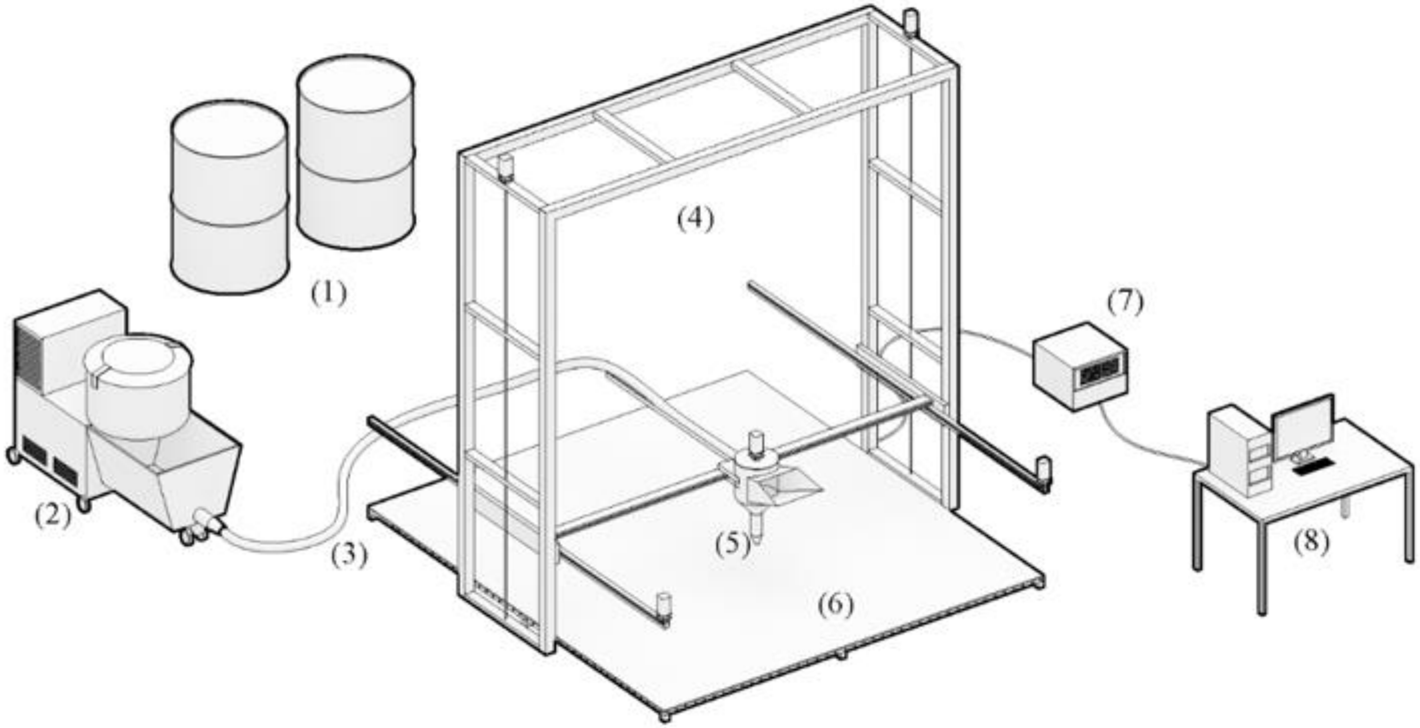
- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion



Raw materials (1), Mixer and Pump assembly (2), 3 inches diameter hose (3), 3D printer frame (4), Printing nozzle (5), 2x2 Printing bed (6), 3D printer processor (7), PC with software (8)

Introduction

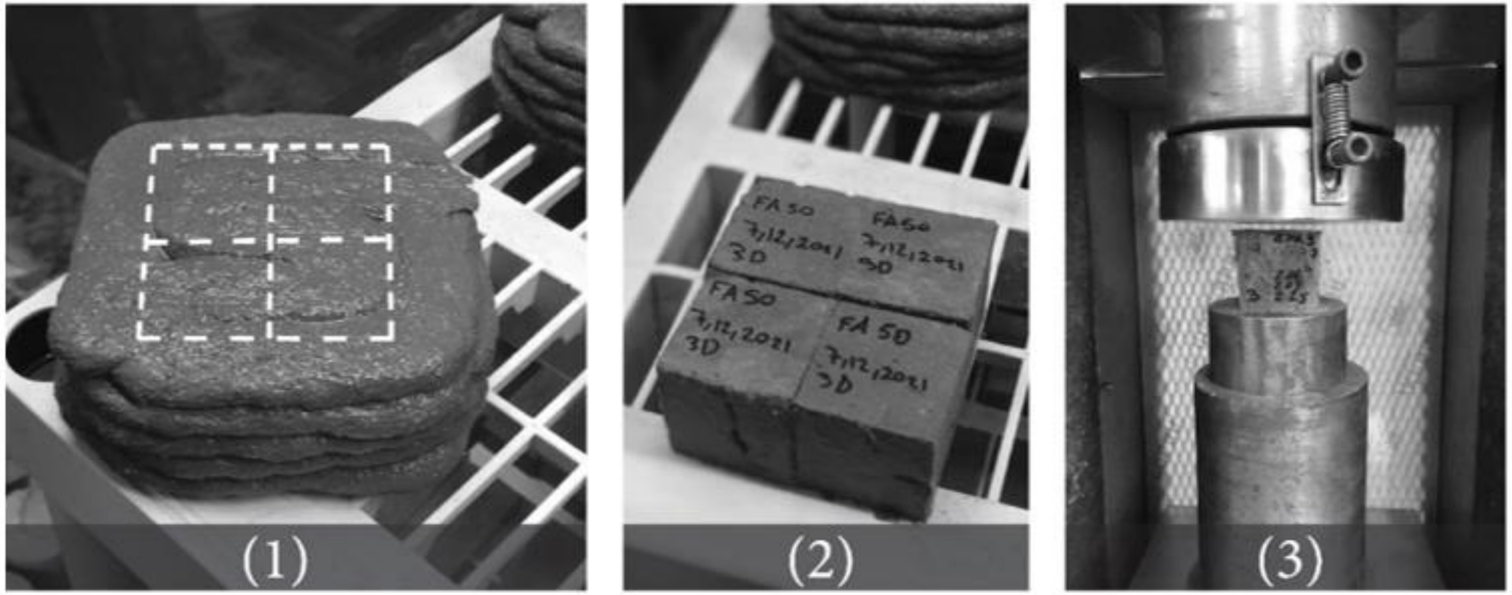
- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion



Primary 3D printed 150×150×60 mm sample with 20mm circular nozzle (1), four extracted 50×50×50mm cubic specimens from the primary sample (2), Compressive test setup with samples tested perpendicular to the loading direction (3)

Introduction

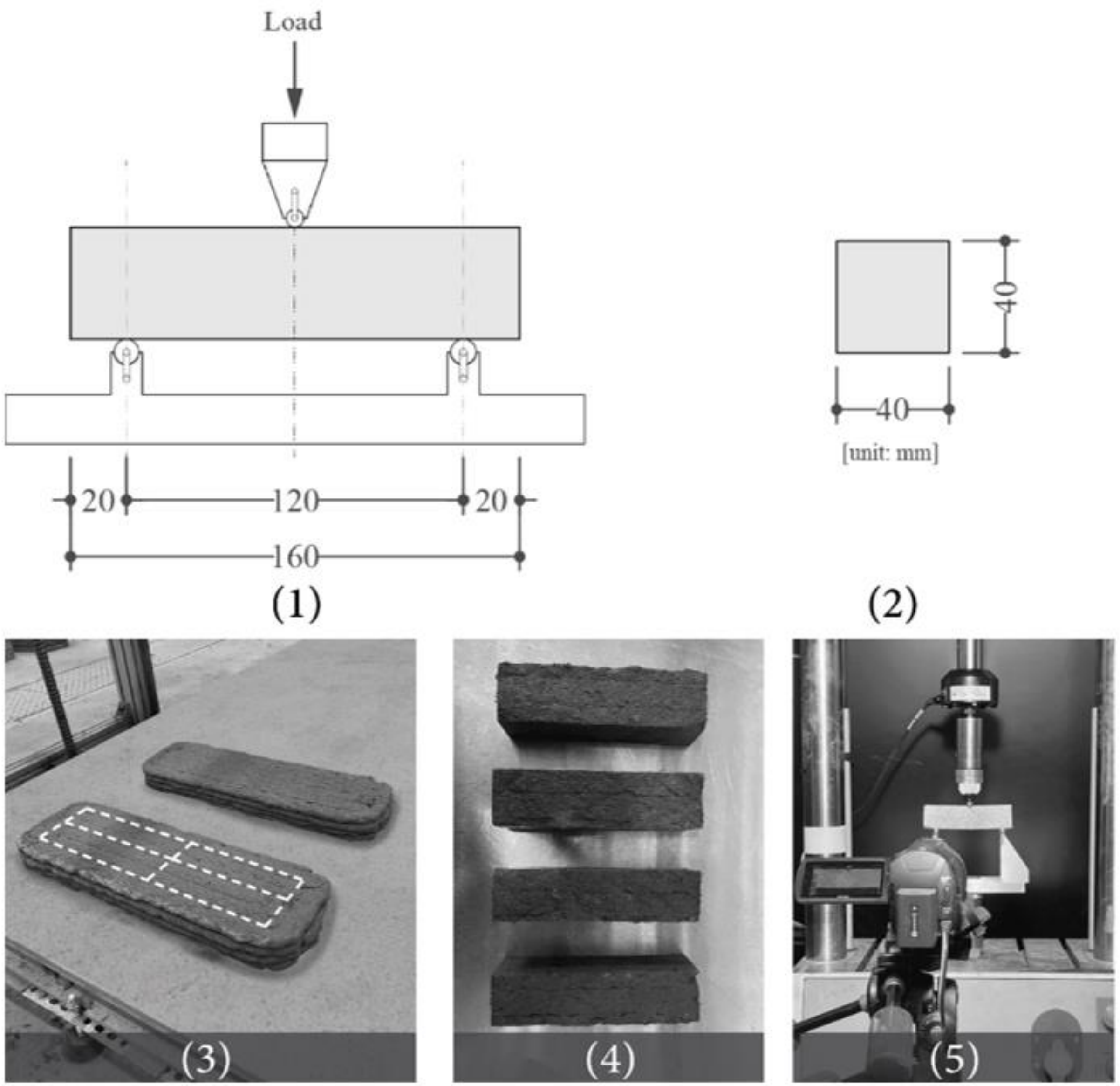
- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion



Three-point bending schematic test setup (1), the cross-section of the tested beam (2), primary 3D Printed slab of 100×350×50 mm with 20 mm circular nozzle (3), four extracted 140×40×40 mm beams from the primary slab (4), the third point bending test setup (5)

Introduction

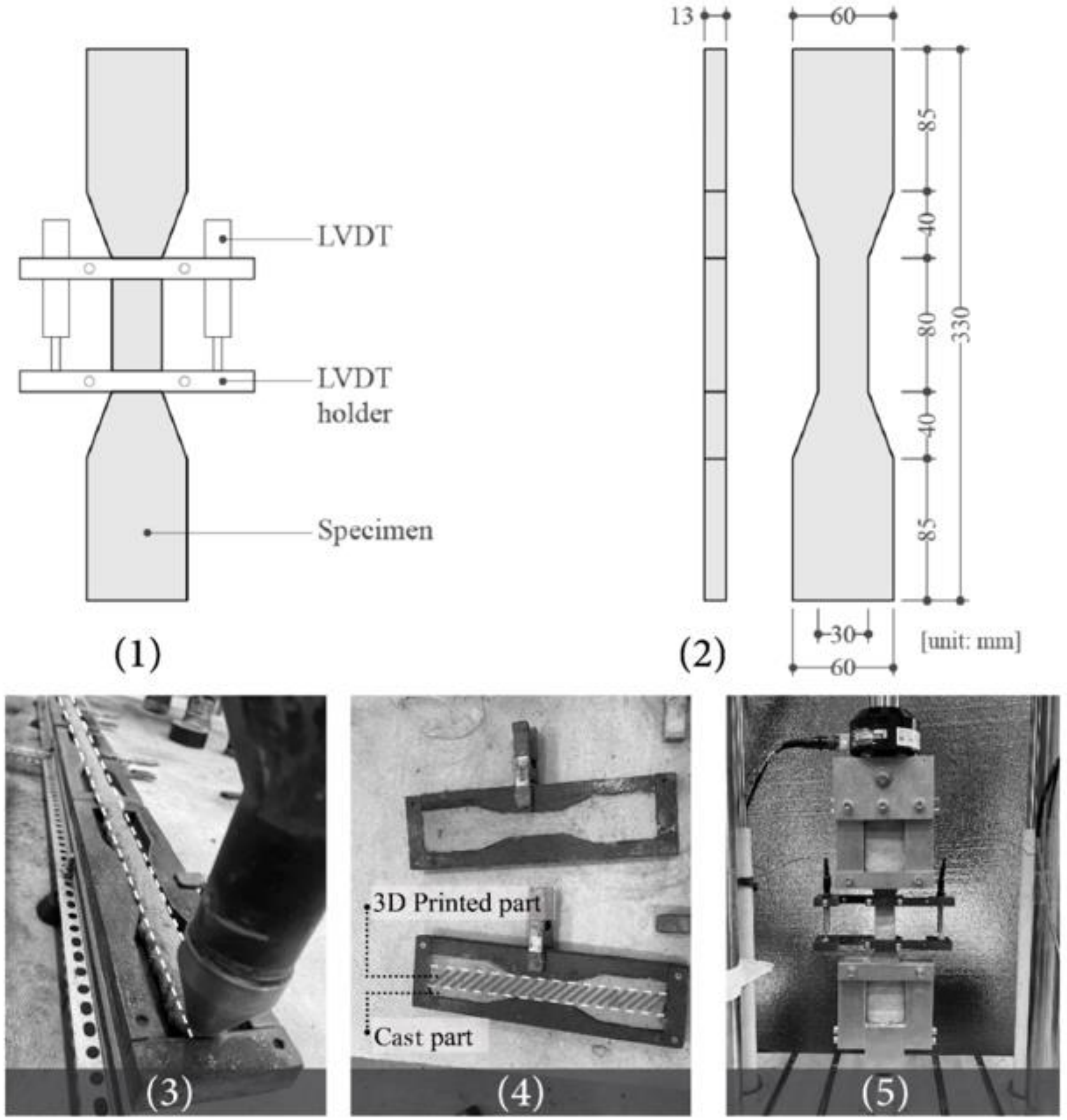
- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

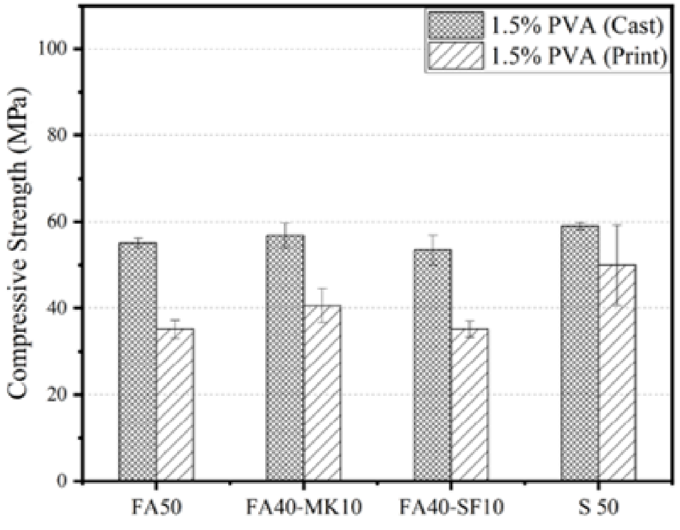
Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

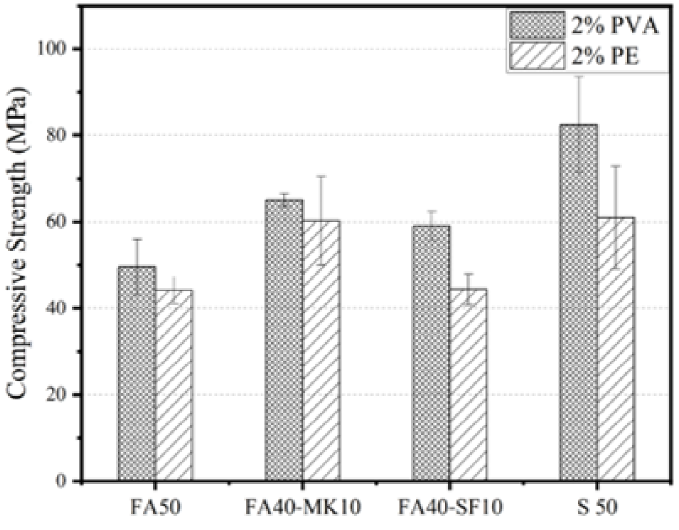


Uniaxial direct tensile test schematic test setup (1), dimension of dog-bone 3D printed samples (2), 3D printing the specimen inside the molds for under tension area (3), specimen showing 3D printed and cast part (4), test setup (5)

- Overall, the compressive strength of 3D printed cubes was lower compared to the cast ones.
- Increasing the PVA fiber quantity from 1.5% to 2% improves the compressive strength of ECC in all cases except FA50, which was reduced 10%.



(1)



(2)

Compressive strength of specimen containing 1.5%PVA for cast and printed specimens at 28-day age (1), compressive strength of cast specimens containing 2%PVA and 2%PE for cast samples at 28 days of age (2)

Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

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Introduction

- Title of study
- Statement of the Problem
- Objectives

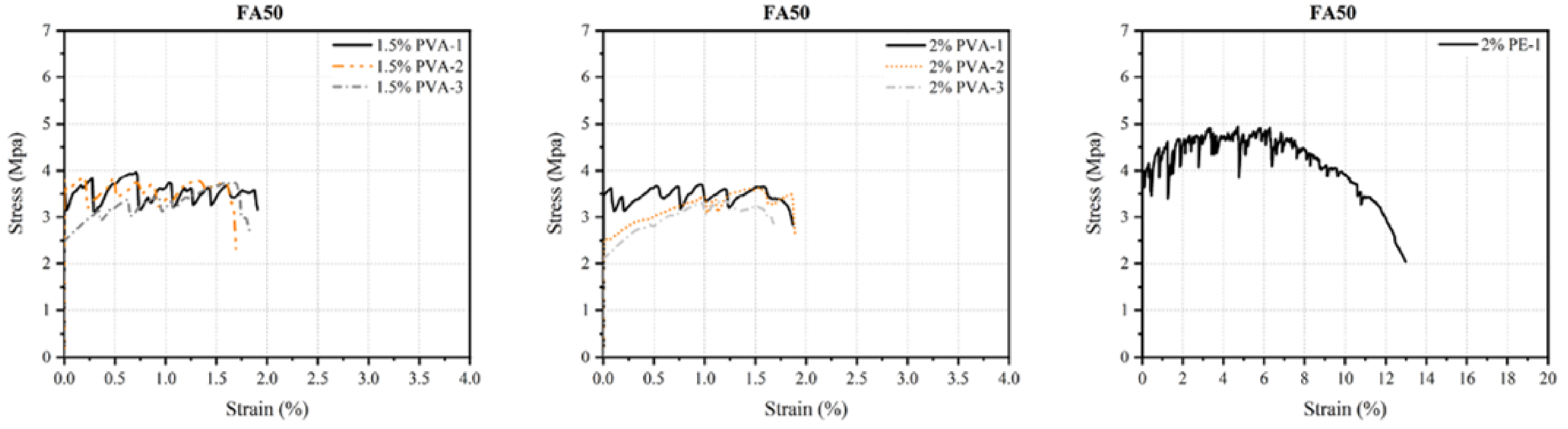
Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

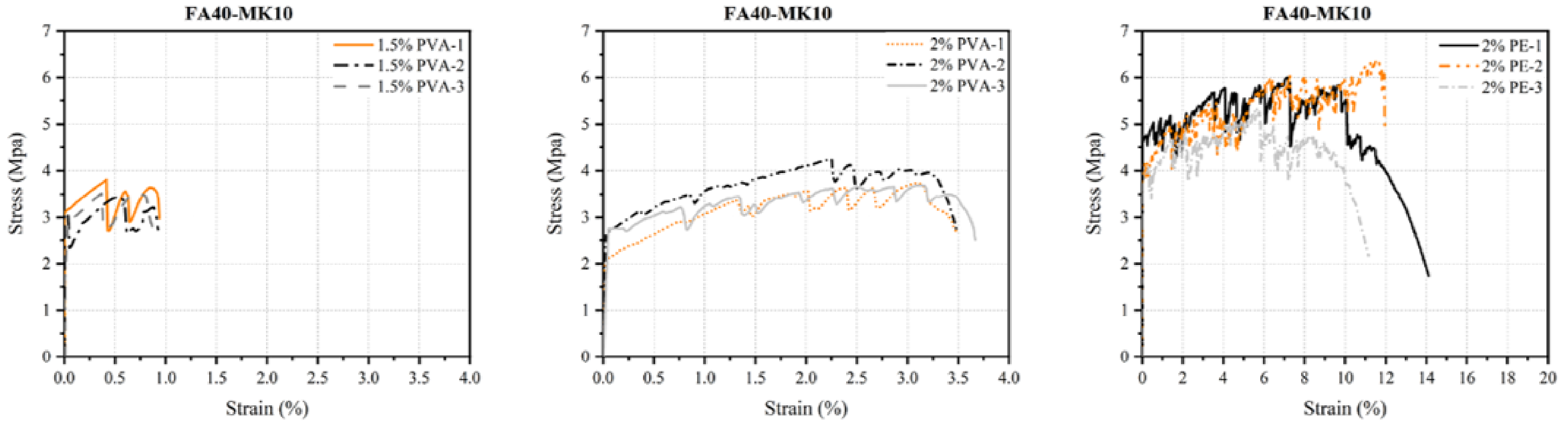
Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

- Notably, all the specimens exhibited pseudo-strain hardening behavior and multiple cracking.
- In case of 2% PE, Substituting 10% of MK with FA in FA50 resulted in almost similar ultimate tensile strength

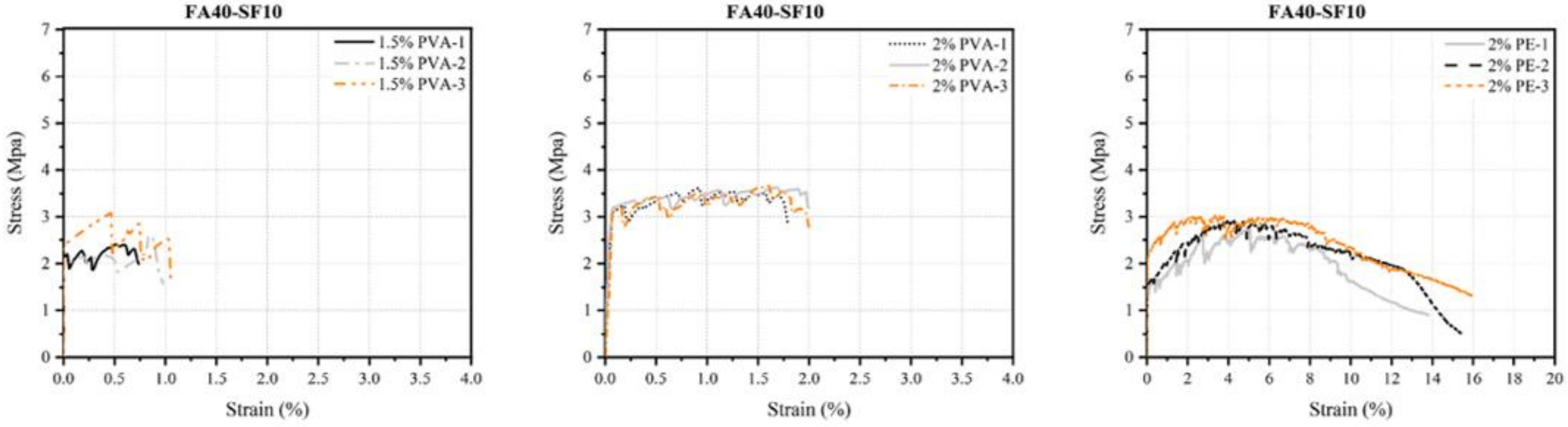


(1) FA50

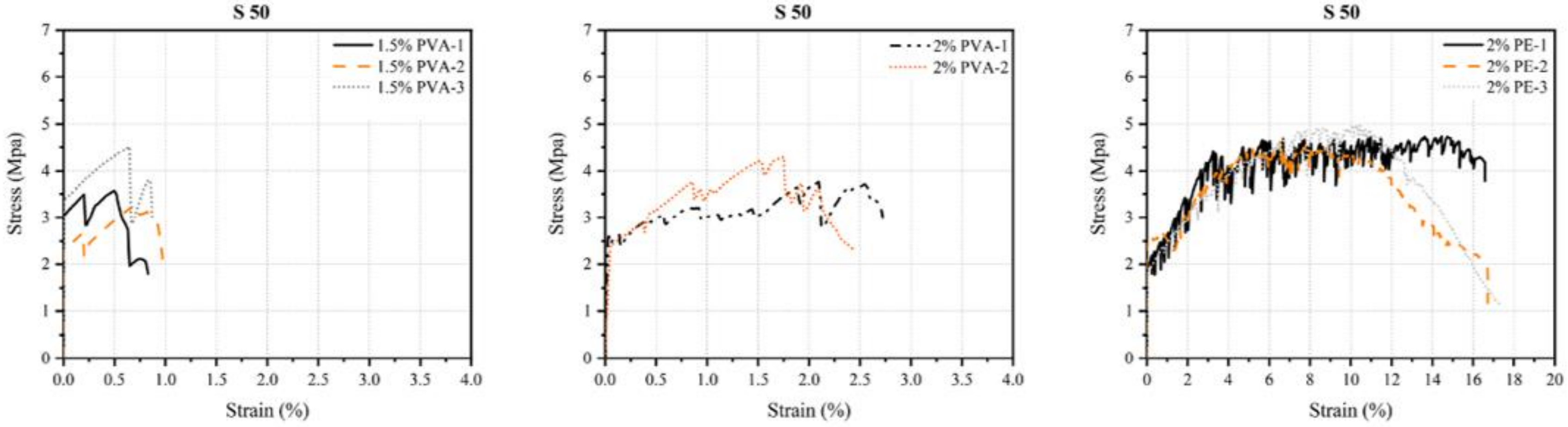


(2) FA40-MK10

- The stress-strain results of different ECC mixes indicate the higher ductility of S50 compared to other mixes.
- Substituting FA with SF led to lower tensile strength.



(3) FA40-SF10



(4) S50

Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

CONCRETE CONVENTION

Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Tensile properties of ECC mixes after 28 days under uniaxial direct tensile test

Mix ID	Fibers content	First cracking stress (MPa)	Ultimate tensile strength (MPa)	Strain Capacity (%)	Toughness (MPa)
FA50	PVA 1.5	3.13 (±0.50)	3.82 (±0.10)	1.76 (±0.11)	0.06 (±0.01)
	PVA 2	2.71 (±0.59)	3.51 (±0.13)	1.78 (±0.09)	0.06 (±0.01)
	PE 2	3.66 (±0.00)	4.91 (±0.00)	11.27 (±0.00)	0.52 (±0.00)
FA40-MK10	PVA 1.5	2.93 (±0.13)	3.76 (±0.15)	0.86 (±0.04)	0.03 (±0.00)
	PVA 2	2.39 (±0.24)	3.88 (±0.26)	3.59 (±0.23)	0.12 (±0.01)
	PE 2	3.99 (±0.43)	5.85 (±0.42)	11.21 (±0.9)	0.61 (±0.08)
FA40-SF10	PVA 1.5	2.05 (±0.14)	2.62 (±0.36)	1.02 (±0.05)	0.02 (±0.00)
	PVA 2	3.17 (±0.08)	3.61 (±0.04)	1.87 (±0.13)	0.07 (±0.01)
	PE 2	1.76 (±0.46)	2.95 (±0.28)	12.09 (±1.02)	0.31 (±0.04)
S50	PVA 1.5	2.95 (±0.45)	3.77 (±0.54)	0.83 (±0.04)	0.03 (±0.01)
	PVA 2	2.59 (±0.10)	4.03 (±0.27)	2.4 (±0.30)	0.09 (±0.02)
	PE 2	2.16 (±0.31)	4.73 (±0.15)	15.88 (±1.06)	0.60 (±0.09)

*Note: the values in parentheses indicate the standard deviation of three measurements

Introduction

- Title of study
- Statement of the Problem
- Objectives

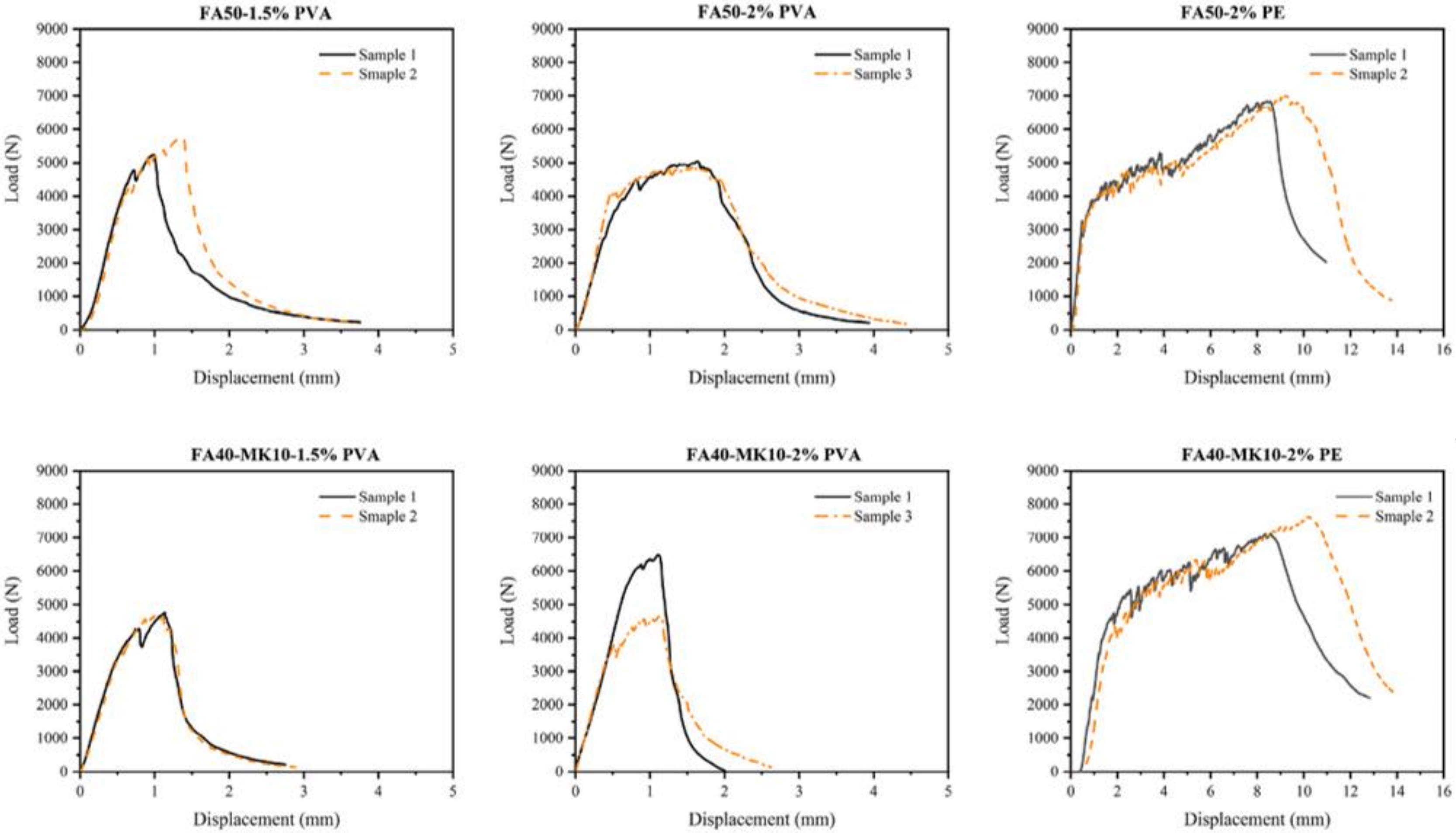
Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

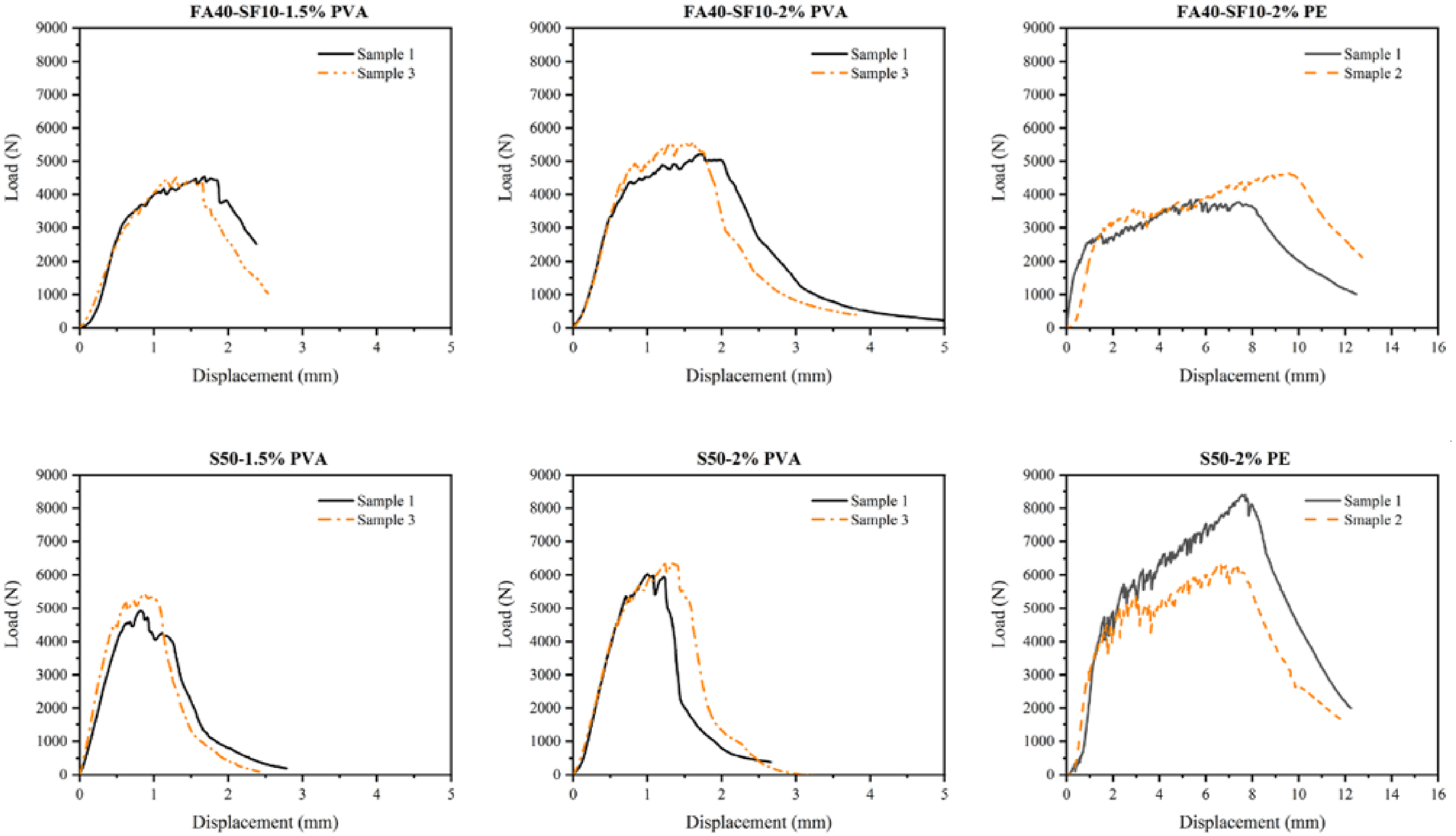
Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

- Substituting 10% of MK with FA in FA50 resulted in a nearly similar moment capacity.



- S50 had better performance in terms of moment capacity in different fiber contents among the four primary mix designs.
- Replacing FA with SF led to lower moment capacity (e.g., for 2%PE fiber ECC, FA50 has a 75% higher moment capacity compared to FA40-MK10).



Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Introduction

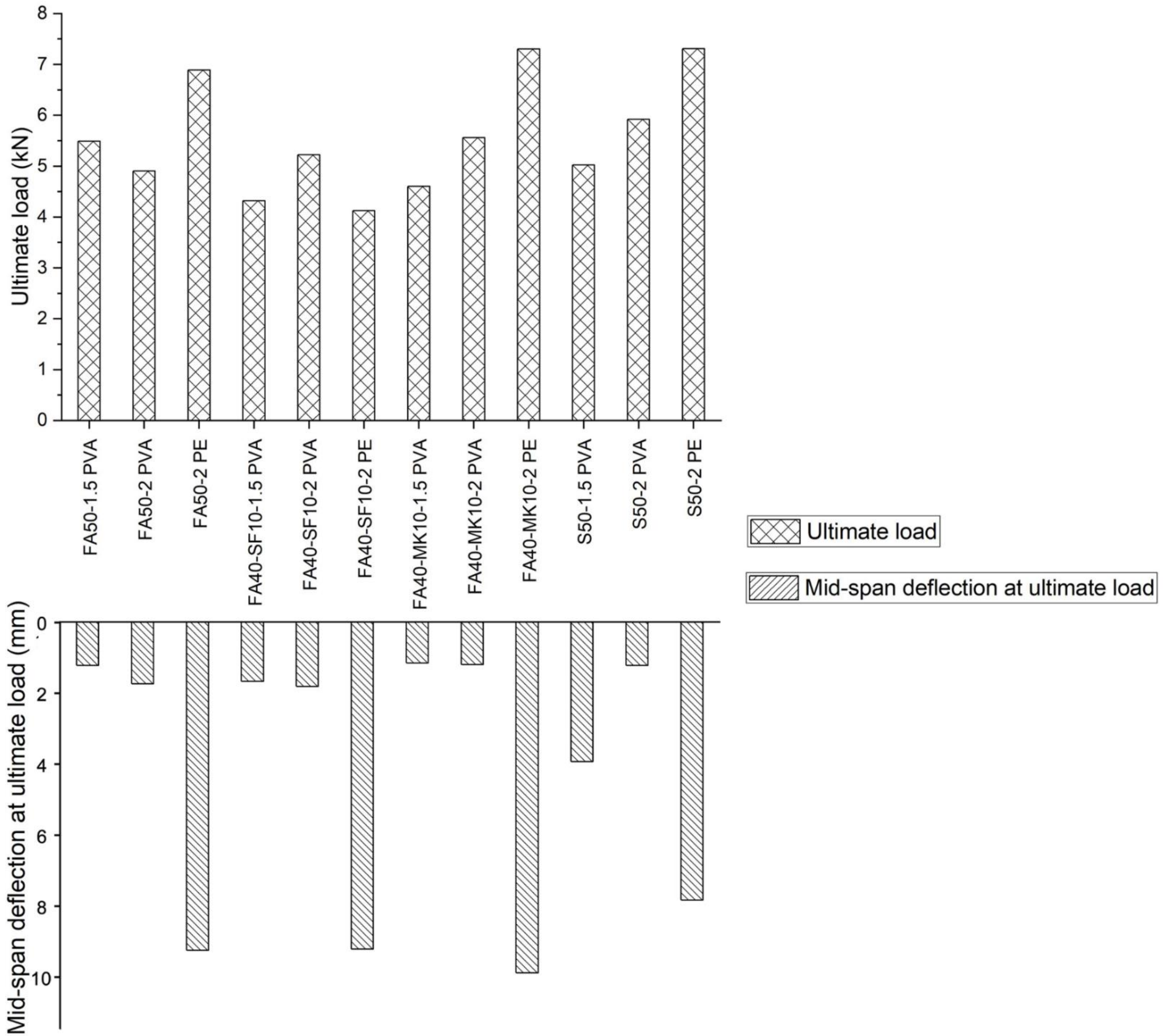
- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion



aci CONCRETE CONVENTION

Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Mix ID	Fiber's content	$M_{n\ Ave}$ (KN.m)	$Deflection_{Ave}$ (mm)	Failure Pattern
FA50	PVA 1.5	0.16	1.17 (±0.20)	
	PVA 2	0.15	1.66 (±0.03)	
	PE 2	0.21	8.87 (±0.42)	
FA40-MK10	PVA 1.5	0.14	1.10 (±0.01)	
	PVA 2	0.17	1.14 (±0.02)	
	PE 2	0.22	9.48 (±0.76)	

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Introduction

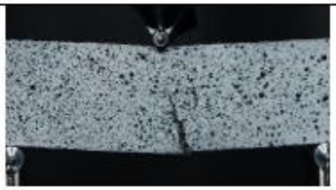
- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Mix ID	Fiber's content	$M_{n\ Ave}$ (KN.m)	$Deflection_{Ave}$ (mm)	Failure Pattern
FA40-SF10	PVA 1.5	0.13	1.6 (±0.17)	
	PVA 2	0.16	1.74 (±0.18)	
	PE 2	0.12	8.84 (±0.86)	
S50	PVA 1.5	0.15	0.87 (±0.08)	
	PVA 2	0.18	1.17 (±0.16)	
	PE 2	0.22	7.51 (±0.17)	

Introduction

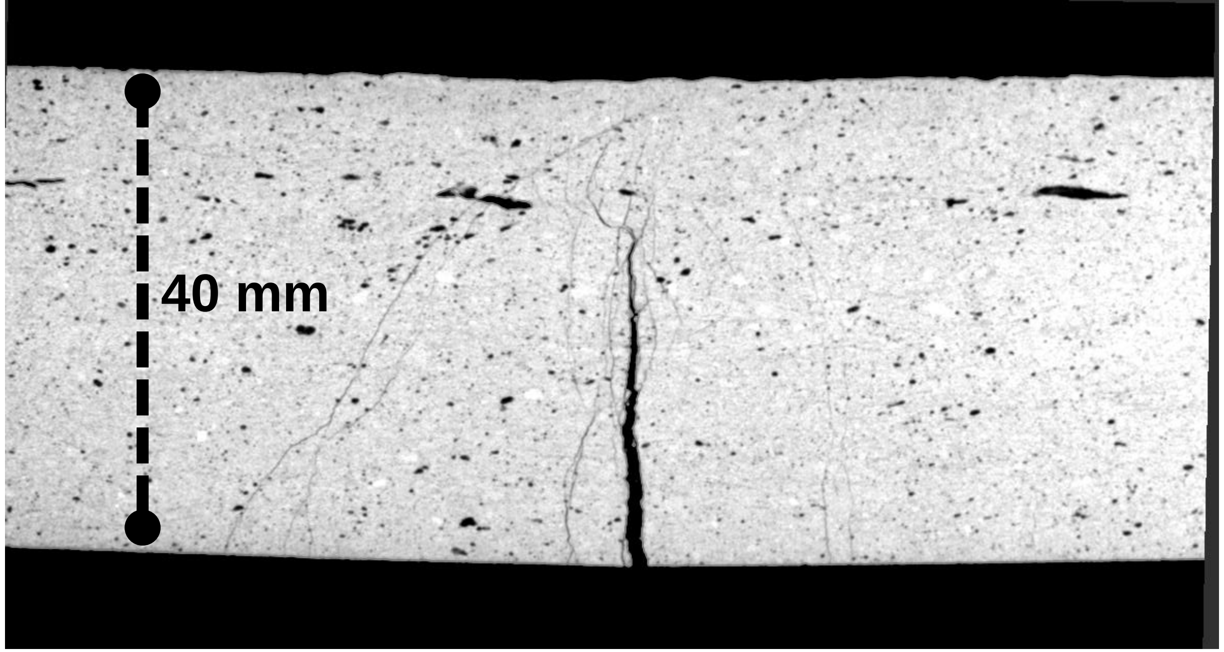
- Title of study
- Statement of the Problem
- Objectives

Methodology

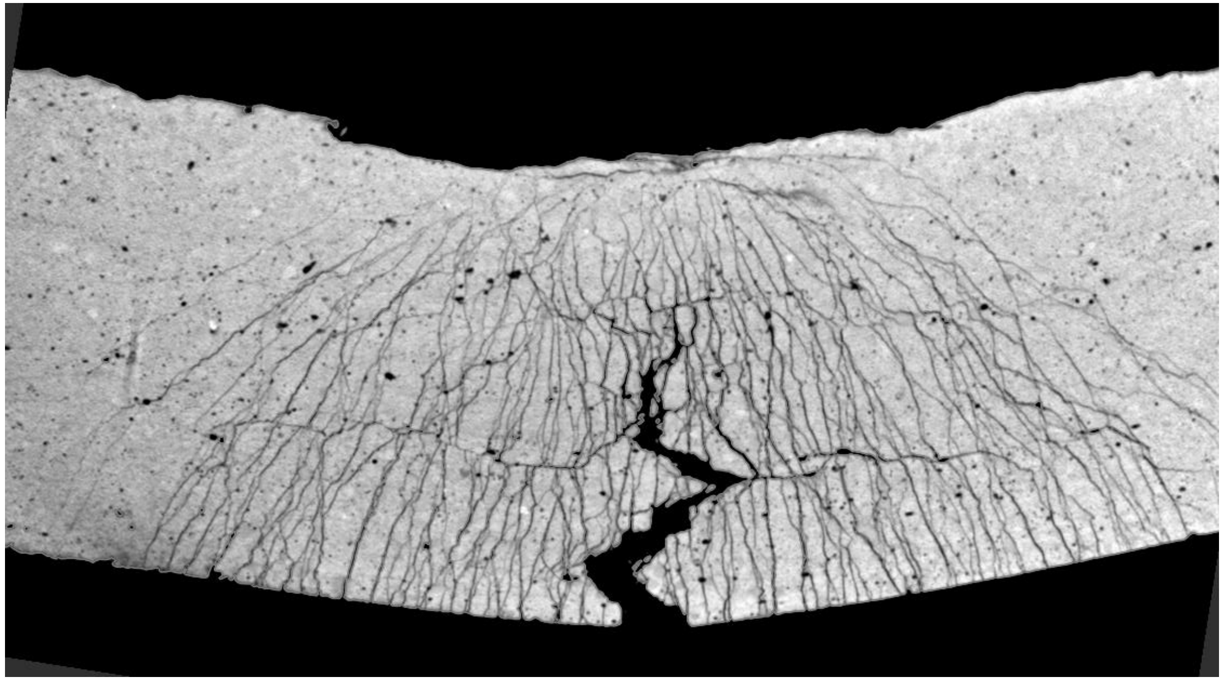
- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion



S50-2%PVA



S50-2%PE

Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Introduction

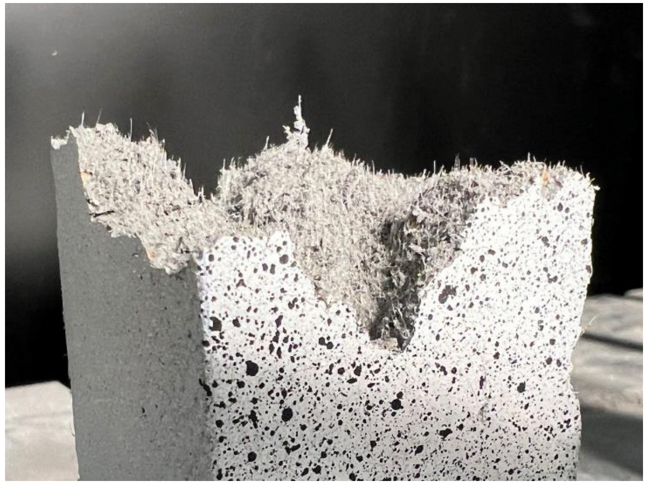
- Title of study
- Statement of the Problem
- Objectives

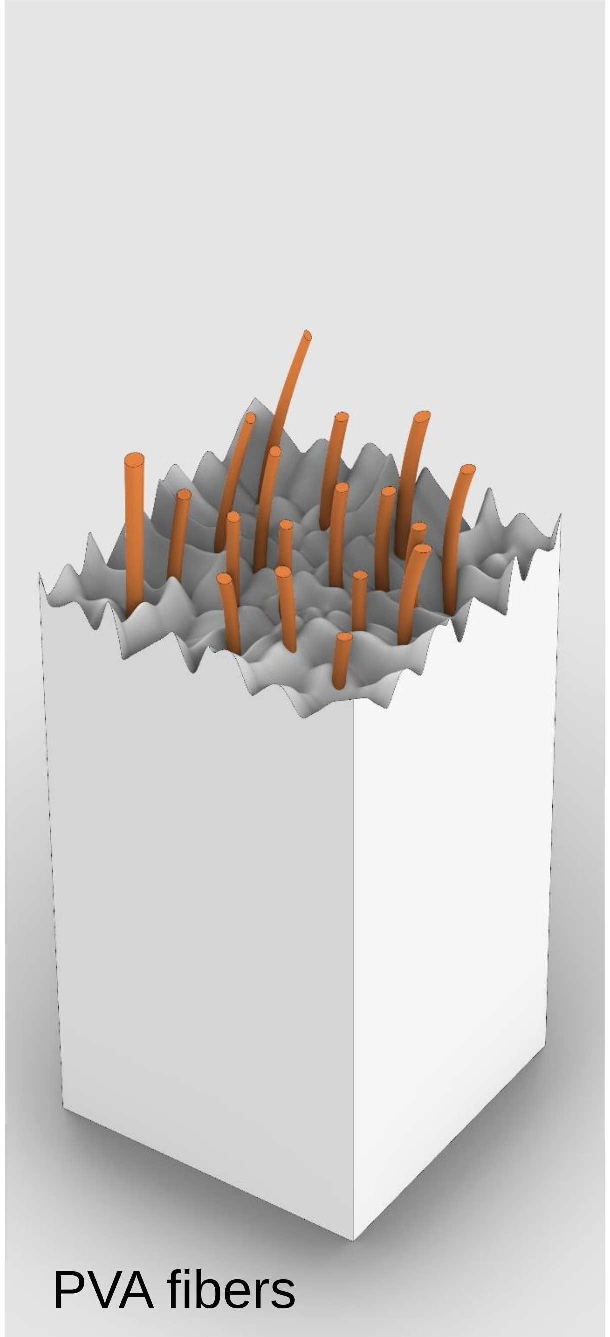
Methodology

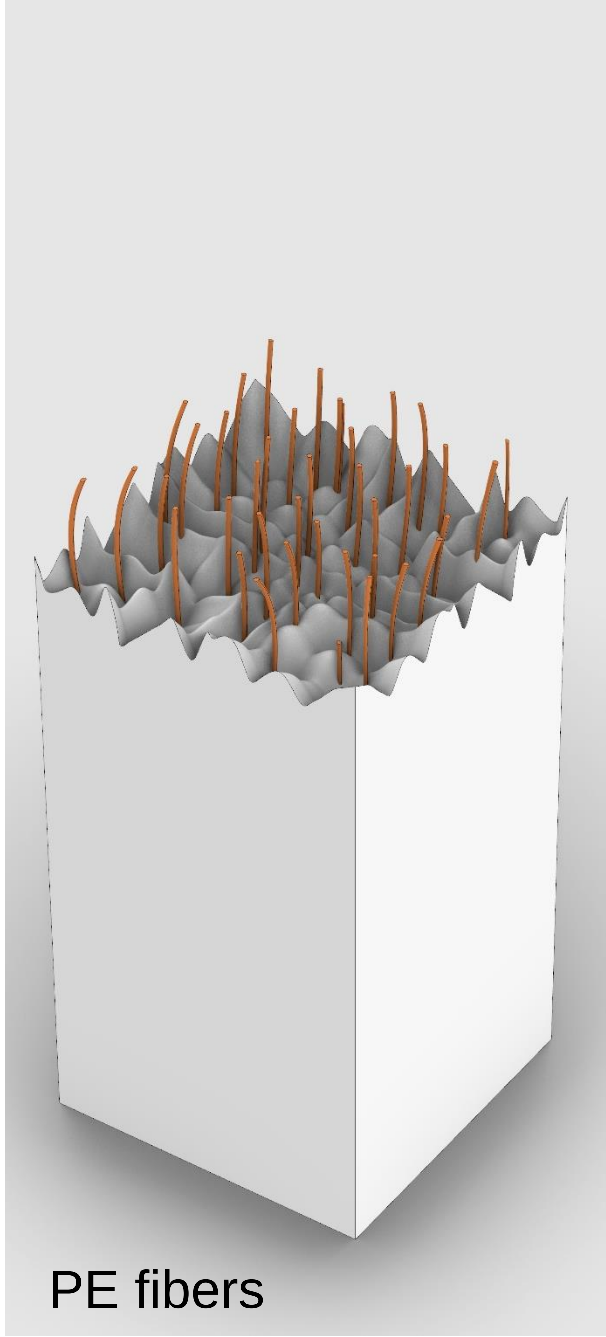
- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion







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1. The considerable gap between the deflection of PE and PVA samples can be attributed to the physical difference in utilized fibers and interfacial frictional force acting on the fibers.
2. All specimens containing PE fibers exhibited a high ductility and can be regarded as ultra-high ductile ECC with strain capacity over 10%.
3. Regarding the fiber length, ECCs with 8mm PVA fibers could not achieve the desired strain capacity, whereas ECCs with 8mm PE fibers could surpass anticipations and achieve a strain capacity of over 10%.
4. In this paper, some of the mixes, such as the S50-2%PE, demonstrated superior performance with 15.8% strain capacity and S50-2%PVA with 82.47 MPa compressive strength. According to this paper, it is possible to design an improved ECC with ultra-high ductile characteristics with locally available materials.

Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

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Introduction

- Title of study
- Statement of the Problem
- Objectives

Methodology

- Solid Materials
- Mix Design of ECC Mixtures
- Test Methods

Results

- Compressive strength test result
- Direct Tensile test
- Flexural strength test
- Conclusion

Studies on tensile properties of 3DP-ECC.

Authors	Process	Binder	Fiber type	Fiber length [mm]	Fiber content [%]	Tensile strength [MPa]	Tensile ductility [%]
Soltan & Li [12]	Caulk gun	OPC, FA, CAC, silica sand, VMA (NC & HPMC), SP	PVA	12	2	2–4	2–4
Bao et al. [21]	Caulk gun	OPC, FA, CAC, silica sand, VMA (NC & HPMC), SP	PVA	8	2	4.7–5.5	2.4–3.6
Yu & Leung [18]	Caulk gun	OPC, FA, silica sand, VMA, SP	PVA	12	2	2.5–3.5	5–6
Chaves Figueiredo et al. [19,45]	Gantry with down-flow nozzle	- OPC, slag, limestone aggregates, VMA, SP;	PVA	8	2	1.5–2.5	0.05–0.15
		- OPC, FA, limestone, sand aggregates, VMA, SP				1.0–1.5	0.05–0.15
Ogura et al. [20]	Gantry with rect. nozzle	OPC, silica fume, FA, sand aggregates, SP	HDPE	6	1–1.5	4–5	1–3
Zhu et al. [17]	Gantry with down-flow round nozzle	OPC, FA, SAC, silica sand, VMA (NC & HPMC), SP	HDPE	12	1–2	~5 Flexural strength 13–19 MPa	3.6–11.4

OPC: ordinary Portland Cement; FA: fly ash; NC: nanoclay; CAC: calcium aluminate cement; VMA: viscosity modifying agent, HPMC: high performance methylcellulose; SP: superplas

Victor Li (2020)