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Mechanical and thermal performance of engineered cementitious composite concrete produced by using polyvinyl alcohol fibers

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HIGHLIGHTS

- PVA fibers reduce water absorption by about (17%) compared to traditional concrete.
- The inclusion of (PVA) fiber in ECC is essential for obtaining higher strengths.
- PVA fibers improved compressive strength by 19% compared to conventional concrete.
- Thermal insulation can be enhanced by incorporating higher percentages of PVA fiber.
- The higher tensile strain of (3.3)% can be achieved using (PVA) fiber up to (2)%.

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ABSTRACT

The inclusion of polyvinyl alcohol fiber (PVA) into an engineered cementitious composite (ECC) material is essential to impart mechanical and thermal properties, in addition to the enhancement of porosity and microstructural properties. Therefore, this improvement can be achieved by utilizing four different percentages of fiber (0.5, 1, 1.5, 2)%, replaced by volume. Five mixes of (PVA-ECC) of M25 grade strength were produced and tested at three different ages (7, 28, and 90) days. Because of the more porous structure of (PVA-ECC), the results demonstrated that adding 2% by weight of (PVA) fiber to (PVA-ECC) dramatically lowered its thermal conductivity by 36.5% compared to traditional concrete. However, more thermal energy can be captured and concentrated at the cement paste surface with the increasing amount of (PVA) fiber, causing an increment in thermal load and negatively affecting thermal insulating efficiency. Furthermore, compressive strength results revealed an upward trend as the fiber content increased up to 1.5% of (PVA) fiber, demonstrating the maximum improvement in strength. On the other hand, the achievement of 55% of the modulus of rupture by inclusion (2%) (PVA) fiber reveals that the modulus of rupture is mainly influenced by (PVA) fiber inclusion. Finally, there is confidence that the reduced thermal conductivity, hydrophobic surface nature, and improved mechanical characteristics of (PVA-ECC) can meet the demanding standards of environmentally friendly building construction.

1. Introduction

Ordinary cementitious composite (OCC) is a commonly used material in buildings. It exhibits adequate compressive strength at an acceptable cost but has low tensile strength, high density, high permeability, and poor chemical resistance. It is recognized as a brittle material that might experience sudden deterioration and catastrophic collapses in concrete structures due to its brittle nature [1]. Researchers aim to enhance the mechanical qualities of OCC by including additional materials such as polymeric compounds or micronized chemicals. Presently, high-performance concrete can be approximately divided into two categories based on its superior mechanical properties compared to conventional fiber-reinforced concrete: Certain types of high-performance fiber-reinforced cementitious composites (HPFRCCs), engineered cementitious composites (ECC), and strain-hardening cementitious composites (SHCC) are manifestations of high-compressive-strength and high-tensile-ductility concretes [2]. ECC is a unique high-performance fiber-reinforced concrete (HPFRC) formulated based on micromechanical principles [3]. Materials with high strength and flexibility have been created and thoroughly studied to address the brittleness issue in conventional concrete [4]. They display deflection-hardening behavior due to forming several closely spaced micro-cracks during deformation. ECCs have a significantly higher tensile strain capacity than typical concrete, reaching several hundred times (25%) depending on the type of fiber and the qualities of the matrix and interface [5]. In contrast, traditional concrete has a tensile strain capacity of around 0.01% and fractures with a localized crack of infinite width [6].

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ECCs were appropriate for applications that undergo seismic and impact stresses due to their high energy absorption and deformation capacity. The fibers were utilized in structural repairs as link slabs for jointless bridge decks and connecting beams for high-rise buildings [7]. Adding fibers is an effective technique for enhancing the strength and flexibility of conventional cement-based composites, leading to improved mechanical characteristics and longevity. Fiber-reinforced cementitious composites are created by evenly distributing discontinuous fibers within a matrix made of cementitious materials. Presently, the prevailing engineering fibers encompass steel, PVA, carbon, and polypropylene fibers [8]. The incorporation of steel fibers significantly enhances the performance of cementitious composites. However, this improvement is constrained by the accompanying increase in the weight of the material and the associated high cost. Furthermore, steel fibers are susceptible to corrosion in severe conditions, substantially reducing the strength and longevity of the cementitious composites [9,10]. Carbon fibers benefit from a high elastic modulus, low specific gravity, and robust toughness. Additionally, it enhances the mechanical properties of cementitious composites while it decreases the impact resistance and shear strength of these composites [9]. Polypropylene fiber enhances the flexible properties, flexural strength, and flexural toughness of cementitious composites, enabling them to withstand freeze-thaw cycles and high-temperature spalling. Nevertheless, polypropylene fiber has relatively low tensile strength and elastic modulus, which restricts its usefulness in cementitious composites [11]. Nevertheless, the PVA fibers exhibit favorable dispersion, may be evenly spread throughout the cementitious composites, and offer exceptional characteristics, including high strength, high elastic modulus, non-toxicity, hydrophilicity, and superior resistance to acid and alkali [12]. Furthermore, prior research has demonstrated that PVA-FRCC exhibits comparatively elevated compressive strength, ductility, toughness, and exceptional durability [13,14]. Hence, PVA fiber is a very appropriate fiber often used in ECC concrete due to its ability to bridge macro and micro-cracks in cement pastes [15]. Previous study indicates that the maximum strain of PVA fiber-reinforced ECC (PVA-ECC) under direct tension can range from 3% to 8% with cracks width consistently measuring less than 100 µm [16,17,18].

The ionic surface property (hydrophilic property) of (PVA) fiber, illustrated in Figure 1, results in a firm chemical connection with the cementitious matrix due to the higher quantities of hydroxyl groups, which can be used as a reinforcing filler [19,20]. Ensuring a strong chemical interaction between PVA and the cement matrix was essential for achieving high strength and ductility in ECC design [21]. The hydrophilic nature of PVA fiber significantly impacts the even distribution of fibers in the combination [22]. The influence of rheology (ECC concrete consistency) during processing was considered an essential aspect for getting the required mechanical behavior of ECC composite [23].

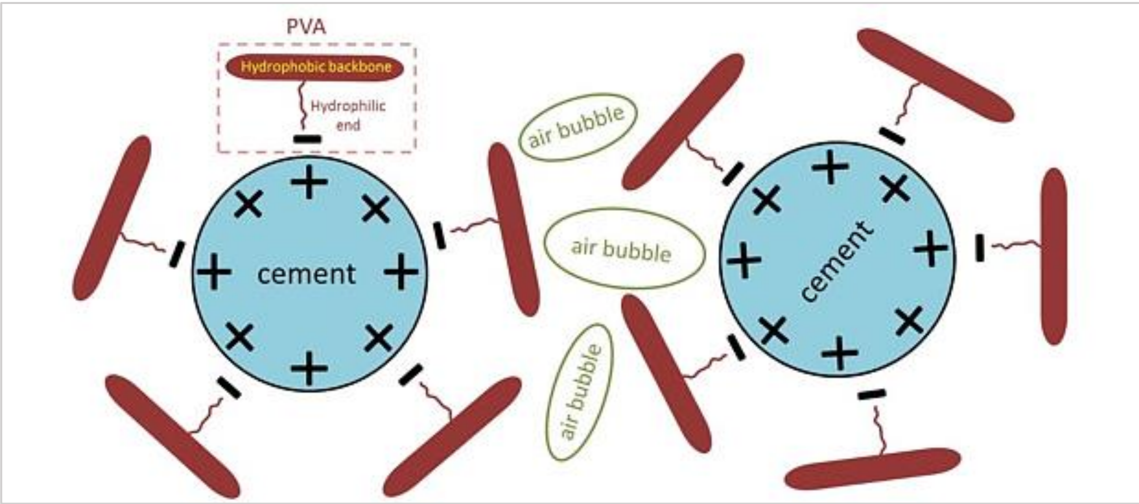

Figure 1: Mechanism of polyvinyl alcohol fiber (PVA) fiber [24]

The distribution of fibers, larger aspect ratio (length/diameter), and concentration in a mixture impact concrete property, leading to uneven distribution of fibers and fiber balling and causing poor points in ECC concrete. On the other hand, proper fiber properties and content significantly affect composites' mechanical properties due to their ability to bridge micro-cracks [25,26]. The prevention of fiber rupture is crucial to avoid the occurrence of significant cracking. Therefore, elastic concrete exhibits a significantly higher degree of deformation compared to conventional concrete while maintaining its structural integrity without undergoing breaking. The behavior of ECC concrete under flexural loading is depicted in Figure 2, which illustrates that the beam exhibits significant deformation without experiencing direct failure. The many constituents of concrete collaborate to distribute the imposed load. ECC concrete has demonstrated significantly more flexibility than conventional concrete, exhibiting a 50-time increase [27]. A study examined the impact of PVA fiber on the flexural behavior of ECC slabs. It was discovered that increasing the fiber content to 3% enhanced the flexural performance and deformability of the resulting ECCs [28]. An increase in fiber content and aspect ratio was shown to reduce the workability of cementitious composite material, as also mentioned by [29].

Until now, most studies have only revealed the influence of PVA polymer on cement-based materials' mechanical, microstructural, and engineering properties. However, PVA fiber should greatly influence the functionalization of cement-based materials, such as thermal properties, which benefit the improvement of cement-based materials in terms of thermal insulation and self-cleaning properties but has been rarely investigated. More importantly, it still lacks investigation on the relationship between the functional and mechanical properties of the PVA-modified cementitious materials. Therefore, in this study, the effect of PVA on the thermal properties of cement paste was first investigated by conducting a thermal conductivity test. The porosity of the PVA-modified cement paste widely affected thermal insulation properties. The present study investigates how the fiber volume content affects the compressive strength, rupture modulus, and ECC concrete's energy absorption behavior. PVA fibers were incorporated into the composite in varying volume fractions of 0.5%, 1%, 1.5%, and 2.0% to create ECC concrete with a compressive strength of 25 MPa with a higher deflection reach of approximately 10 mm. The mix design was assessed based on earlier research by Li [27]. The study's originality lies in providing results concerning the compressive strength and modulus of rupture behavior of the ECC concrete mixes by utilizing sand in zone two, emitting coarse aggregates containing PVA fibers with different volume fractions. It is also concerned with evaluating the tensile strain capacity, thermal characteristics, and microstructure investigation due to the most relevant and essential properties for identifying the behavior of fibers within the cement compound and the mechanics of bridging behavior.

Figure 2: Response of ECC under flexural loading [30]

2. Experimental work

2.1 Selection of materials

The formulation of engineered cementitious composite concrete mixtures was based on the standard mix proposed by Victor Li [27]. By employing an ECC concrete mixture of (1:0.8) (cement: sand) ratio with (0.36) (water/binder) ratio, it is achievable to produce ECC concrete with a strength of 45 MPa. Four fiber volume fractions were utilized to determine the ECC concrete with strength levels of 25 MPa, the mixtures were poured into their respective molds and cured in water at an ambient temperature of 21ºC for the following testing ages: 28, 60, and 90 days. Additionally, tensile strain capacity testing was performed on the mixtures after 28 days of water curing.

2.1.1 Cement

Ordinary Portland cement (Type I) was utilized consistently in the job. The physical properties (fineness higher than 2300 cm^2/gm and soundness equal to 0.12) and the chemical composition (loss on ignition lower than 3% and lime saturation factor lower than 1%) and main compounds of cement all these specifications conform to Iraqi Specification No.5 [31].

2.1.2 Fine aggregate

The experimental effort utilized natural sand as the fine aggregate. Table 1 visually represents sand's physical properties and chemical characteristics. The test results investigated that the sand gradation falls within zone two, and the sulfate percentage is measured at 0.37%, both of which comply with the specifications outlined in the Iraqi standard No. 45 [32].

Table 1: Specifications of fine aggregate

Sieve Size (mm)	Passing by Weight (%)	Limits of IQS (No.45) / Zone 2 [32]
9.51	100	100
4.75	97	90 - 100
2.36	89	75 - 100
1.18	78	55 - 90
0.6	56	35 - 59
0.3	20	8 - 30
0.15	5	0 - 10
	Fineness modulus = 2.8	
Property	**Test Results**	**Limits of IQS (No.45)**
Specific-gravity, SSD	2.5	-
Bulk Density (kg/m^3)	1713	-
Sulfate %	0.36	≤0.5
Absorption%	3.1	-

2.1.3 High range water reducing admixture (HRWRA)

SIKA Construction Chemicals produced the modified polycarboxylate-based high-performance superplasticizer concrete additive Visco-Crete 5930, which was used in the works. The manufacturer's recommended dosage ranges from 0.2 to 0.8 liters per unit weight of cement. This admixture adheres to the specifications established by ASTM C494 for types G and F [33].

2.1.4 Silica fume

The trade name (Mega Add MS(D)) refers to silica fume with an activity index of 112.8 percent. Silica Fume acts chemically and physically as a highly reactive pozzolan, as shown in Tables 2 and 3. The material underwent physical and chemical testing in accordance with the specifications given in ASTM C 1240 [34]. Silica fume is crucial for improving the microspores, density, and strength of ECC concrete mixes. Ten percent of the cement weight has been replaced with it in the mixture [35].

Table 2: Physical Properties of silica fume [34]

Sample No.	Accelerated Pozzolanic Strength Activity Index at Seven Days	Specification Limits the Percentage of Control
1	112.8	Min 105

Table 3: Chemical properties of silica fume [34]

Sample No.	SiO_2 (%)	Loss on Ignition (%)	Moisture Content (%)
1	92.84	1.59	0.33
Specification limits	85%, Min	6%, Max	3%, Max

2.1.5 Polyvinyl alcohol fiber (PVA) fiber

Higher (tensile strength and modulus of elasticity), non-toxic, acid, and alkali-resistant, and easily bonded with cement are the main properties of (PVA) fiber. This work uses high-strength PVA and high elastic modulus short fiber, provided by Sinopec group Sichuan Vigny nylon factory. Its physical performance indexes are shown in Table 4, and the PVA fiber is illustrated in Figure 3.

Table 4: Physical property index of PVA fiber

Properties	Units	Values
Length	mm	12-32
Diameter	mm	0.04
Density	Kg/cm^3	1310
Young Modulus	GPa	42.8
Tensile Strength	MPa	1600 – 2500
Poisson’s Ratio	-	0.42
Ultimate Elongation	%	4 – 9
Melting Point	℃	225
Specific Heat	J/gK	1.68

Figure 3: Polyvinyl alcohol fiber (PVA) fiber

2.1.6 Polyvinyl alcohol solution (PVA) solution

It is a synthetic polymer that is water soluble as well as biodegradable. It is an arid material that comes in both granule and powdered form. (PVA) The solution is a high-performance adhesive with exceptional bonding strength, film-forming, and emulsifying features. (PVA) The solution can be prepared according to Flinn Scientific [36] by used (40) grams of polyvinyl alcohol powder to one liter of warm water and homogenously mixed until all powder dissolved . Polyvinyl Alcohol powder and polyvinyl alcohol solution are illustrated in Figure 4 (a and b).

The PVA powder manufacturer characteristics were as shown below Bouling Chemical Co., Limited:

1) Hydrophobic fibers like polyester, nylon, polyester/cotton combined, and polyester/rayon combined fiber have a high binding and cohesion strength.
2) Viscosity stabilization in the solutions is perfect.
3) Non-toxic, tasteless, and harmless.
4) In partially hydrolyzed levels, the acetate category is substituted by the alcohol category by 86-89 mole percent.

(a)

(b)

Figure 4: Polyvinyl Alcohol solution (PVA) solution preparation.

2.2 Mix proportions

This research involves the production of concrete (PVA-ECC) using water with a cementitious (w/cm) ratio fixed at 0.41. The addition of (PVA) fiber was 0.5%, 1.0%, 1.5%, and 2.0%, by the weight of Cementitious materials. Mixes were created to achieve a compressive strength of 25 MPa at 28 days using PVA fibers, which could boost strength and higher strain, with a flow table measurement of 100±10 mm. The HRWRA dosage was adjusted to get the necessary flowability. A flow table test was conducted to assess workability, pouring freshly mixed concrete into molds and compacting it with an external vibrating table. The test specimens were cured by immersing them in lime-saturated water at a temperature of 20±2 °C until the testing date after being removed from the mold. Compared to conventional concrete, (PVA-ECC) concrete is a mortar-based composite lagging coarse aggregate typically containing two to three times more cementitious material [38]. Fundamentally, the mixed design of (PVA-ECC) concrete is predicated on the concept of micromechanics, which is determined by the interaction between fibers and matrices. This resulted in a bridging action that enhanced strength. The optimal mix proportions found in the literature on (PVA-ECC) concrete served as the guidelines for this investigation [27]. These proportions guided the determination of the appropriate amounts of different components to be included in the (PVA-ECC). The proportions of mixes ECC0.5, ECC1, ECC1.5, and ECC2 are shown in Table 5. According to this study, a (w/cm) ratio of 0.41 produces the most flexible concrete with a strength of 25 MPa. The objective was to achieve a mix with beneficial rheological properties through chemical admixtures and (PVA) Solutions, which produce practical mixtures.

Table 5: Constituents of (PVA-ECC) concrete

Mixes Symbols \ Mix Proportions	ECC0	ECC0.5	ECC1	ECC1.5	ECC2
Cement (kg/m^3)			265		
Sand (kg/m^3)			212		
Silica fume (%) by wt of cement			10		
(PVA) fiber (%), by volume	0	0.5	1	1.5	2
(PVA) Solution (%), by wt of cement			1		
HRWRA (%) by wt of cement	1	1	1.2	1.4	1.4
(w/cm)			0.41		

A mixer with 0.15 m^3 capacity is utilized to prepare the concrete mixes (PVA-ECC) [39]. The method and mechanism of mixing are summarized as follows: firstly, the dry constituents like cement, silica fume, and fine aggregate are mixed for two minutes, then water and HRWRA are collected together and added slowly into the dry mixture and mixed for another two minutes. Following this, the mixture was inspected, and any discovered clamping was broken to ensure an utterly heterogeneous mix. Mixing is maintained for an additional three minutes to ensure homogeneity. During this time, the (PVA) acetate and (PVA) fiber are gradually incorporated into the mortar mixture and mixed until the (PVA) fiber has effectively dissipated to prevent balling. [40]. The fresh ECC-PVA concrete was cast into cubes, cylinders, and beams of (100×100×100) mm, (200×100) mm, and (100×10×400) mm, respectively, which were vibrated by using a concrete vibrator. Specimens were remolded after 24 hours. The specimens were cured after being opened, and measurements of their modulus of rupture and compressive strength were taken at 7, 28, and 90 days.

3. Results and discussion

3.1 Properties of fresh mixes

It is crucial to ensure the homogeneous dispersion of (PVA) fibers to achieve PVA-ECC concrete with favorable mechanical characteristics. To achieve uniformly distributed cementitious composites, one can add a minimal quantity of fiber to the mixer several times and adequately prolong the mixing duration. A Flow Table test was conducted following the guidelines set by ASTM standards C-1437-15 [41]. This test assessed the workability of (PVA-ECC) concrete mixtures. Table 6 represents the flow table values. A higher percentage of (PVA) fiber causes a decrease in flow table values due to the presence of (PVA) fiber, which generates higher water absorption and internal friction of concrete ingredients. It requires additional water to get the same flow; thus, the workability of concrete containing (PVA) fiber was improved by adding High Range Water Reducing Admixture (HRWRA). Additionally, the viscosity of the (PVA-ECC) concrete mix was influenced by the presence of (PVA) fiber. To solve this problem, (PVA) Solution was added to enhance the mixture's viscosity.

Table 6: Flow table test results

Mix. ID	ECC0	ECC0.5	ECC1	ECC1.5	ECC2
Spread Dia. (mm)	212	202	195	170	158
Flow (%)	112	95	70	58	102

On the other hand, fresh density was calculated using the mean of three cubes measuring (100×100×100) mm in dimensions. This test was performed according to ASTM C567/C567M–19 [42]. Compared with the conventional mix, fresh density declined by (PVA) fiber addition for 1, 1.5, and 2 % by approximately 8.2, 9.1, and 11.1%, respectively. In comparison, (0.5%) of (PVA) fiber showed an insignificant difference for mixing density with (0%) replacement, as illustrated in Table 7.

Table 7: Fresh density test results

Mix. ID	(PVA) Fibre by Cement Weight (%)	HRWRA by Cement Weight (%)	Fresh Density (kg/m^3)
ECC0	0	1	2402
ECC0.5	0.5	1	2441
ECC1	1	1.2	2203
ECC1.5	1.5	1.4	2183
ECC2	2	1.4	2135

3.1.1 Mechanical properties

(PVA-ECC) concrete can be measured by determining the air-dried density and water absorption at (28) days of (100×100×100) mm cubes in accordance with BS EN 12390 [43] and ASTM C642-13, respectively. The water absorption and air-dried density test outcomes are illustrated in Table 8 and Figure 5. It has been observed that the air-dried density signifies an increase in the results with increasing (PVA) fiber content until (1.5)% due to the layer of $Ca(OH)_2$, which covers the fibers, making fiber surroundings denser, followed by a decrease in the results with increasing of (PVA) fiber percentages in the mix due to the increment of fiber volume.

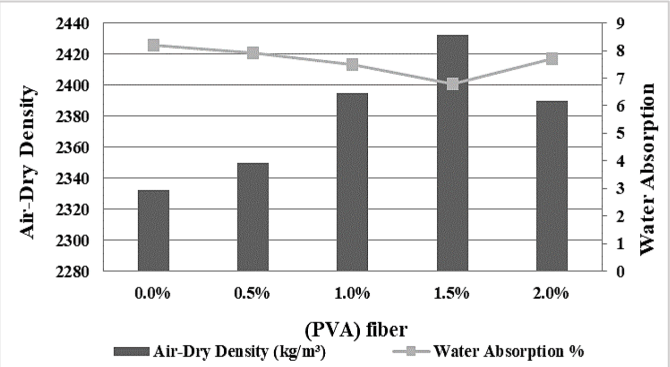

Figure 5: Results of density and water absorption of ECC-PVA

Table 8: Air-dry density and water absorption test results

Mix. ID	ECC0	ECC0.5	ECC1	ECC1.5	ECC2
Dry Density (kg/m^3)	2332	2350	2395	2432	2390
Water Absorption (%)	8.2	7.9	7.5	6.8	7.7

In addition, compressive strength tested at (7, 28, and 90) days of (100×100×100) mm cubes was confirmed to BS EN 12390 [43]. In addition, the modulus of rupture was conducted using prism specimens of (100×10×400) mm, in accordance with ASTM C293-2016 specification [44]. The test results reveal that as the curing process continues, there is a noticeable rise in strength as the curing age progresses. The result of all strengths of concrete mixtures with (PVA) fiber was higher than the conventional mix for all test ages. Mix with (1.5%) shows the optimum mix. The increment in strength, according to (PVA) fiber makes intricate clusters with the metal hydroxide of the cement matrix. It is caused by OH^- and Ca^+, two different ions in the cement slurry that are attracted by (PVA) fiber and form a layer of $Ca(OH)_2$ around the fibers, which are crucial for the bonding strength between the fiber and the matrix. In addition, increasing fiber percentages added to the concrete mixture will prevent them from expanding by preserving their volume.

On the other hand, strength was diminished as the percentage of (PVA) fiber increased beyond 1.5%. This decrease in strength can be attributed to the loss of cohesion and the exceedingly poor binding of calcium-silicate-hydrate (C-S-H) gel to (PVA) fiber. Conversely, as illustrated in Table 9, the outcomes indicate that concrete mixes with (2%) fiber gave higher strength than the other percentages for all ages, followed by a decrease in strength with increasing fiber content.

Table 9: Strengths development of hardened concrete mixes

Mix. Symbol	Compressive Strength (MPa)			Modulus of Rupture (MPa)		
	7 Days	28 Days	90 Days	7 Days	28 Days	90 Days
ECC0	19.1	28.5	32.1	9.1	10.9	11.1
ECC0.5	19.7	28.9	33.4	11.2	13.2	14.1
ECC1	21.5	32.1	36.2	13.2	15.1	16.9
ECC1.5	24.2	35.3	40.2	14.5	16.9	17.5
ECC2	24.1	33.9	38.4	13.9	16.3	16.9

Finally, the load-displacement results were applied for the (100×10×400) mm prisms in accordance with ASTM C293-2016 [43], as presented in Figure 6. Cracking occurs when the strain in (ECC-PVA) exceeds its strain capacity. The load indicator stops recording when the first crack appears. At this point, the strain is measured by a strain gauge with an accuracy of 0.002 mm. The modulus of rupture responses of (PVA-ECC) under a one-point load illustrates deflection-softening for (PVA) fiber percentages that are lower than (2)%. Deflection-hardening can be achieved with additional percentages of (PVA) fiber up to (2)%, which means the load continues to increase even after the imitation of crack in the matrix leads to initiate multiple narrow cracks in the tension bottom zone of the beams, The same trend was illustrated by [27]. The testing procedure can be presented in Figure 7.

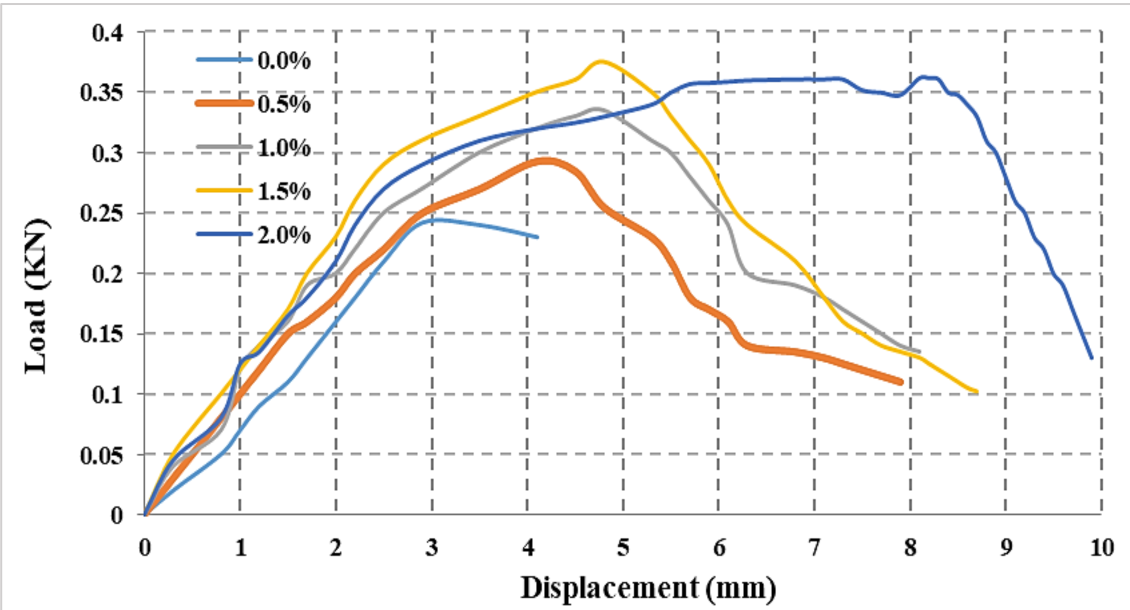

Figure 6: Load-displacement curve for (PVA-ECC) concrete tested at (28) days

Figure 7: (PVA-ECC) concrete plate tested at (28) days

3.1.2 Thermal characteristics

Thermal conductivity is determined by measuring the temperature gradient and heat flow through a concrete sample. Thermal characteristics such as thermal conductivity tests are essential in evaluating heat transfer rates. The samples were prepared to produce the required specimen with (100×100×100) mm. Two specimens were used for each mix and tested at (28 days). The thermal conductivity test was conducted using a rapid-thermal conductivity meter, specifically the ASTM C1113-90 Hot Wire Method (QTM 500, Kyoto-Electronics-Manufacturing, Japan) [44]. Before the thermal conductivity test, the testing specimen, which had reached 28 days of age, underwent an initial oven-drying process at 110 degrees Celsius for 8 hours, followed by a vacuum drying process lasting three days to eliminate moisture within the pores. The thermal conductivity testing results revealed increased cementitious material content, improving thermal conductivity. This increase in thermal conductivity indicates a decrease in thermal insulation. Including (PVA) fiber can fully or partially counteract the thermal-gradient effect by alleviating vapor pressure, even though an increase in thermal conductivity typically leads to a reduction in thermal gradient, which causes internal tensions and raises the danger of spalling.

The testing results indicate that the reference specimen, composed of standard cement paste without (PVA) fiber, has the highest conductivity. The decrease in conductivity can be attributed to the heightened porosity of the cement paste resulting from the inclusion of (PVA) fiber. Functioning as an anionic surfactant, it is comprised of a hydrophobic core and a hydrophilic end. However, as the (PVA) fiber content exceeds 2.0%, the thermal conductivity of the specimen fluctuates, indicating that a higher inclusion of (PVA) fiber has a detrimental impact on the thermal insulation properties of cement paste. The excessive volume fraction of (PVA) fiber in cement paste reduces the viscosity of the paste during mixing. When fresh, this negatively impacts the creation and stability of air bubbles in the paste, reducing porosity and thermal insulation abilities. The thermal conductivity outcomes are presented in Table 10 and Figure 8. The device used for testing thermal conductivity is illustrated in Figure 9.

Table 10: Results of thermal conductivity test

Mix. ID	(PVA) Fiber by Weight of Cement (%)	Thermal Conductivity (W/m.K)
BC0	0	0.8612
BC0.5	0.5	0.6918
BC1	1	0.5358
BC1.5	1.5	0.5034
BC2	2	0.5465

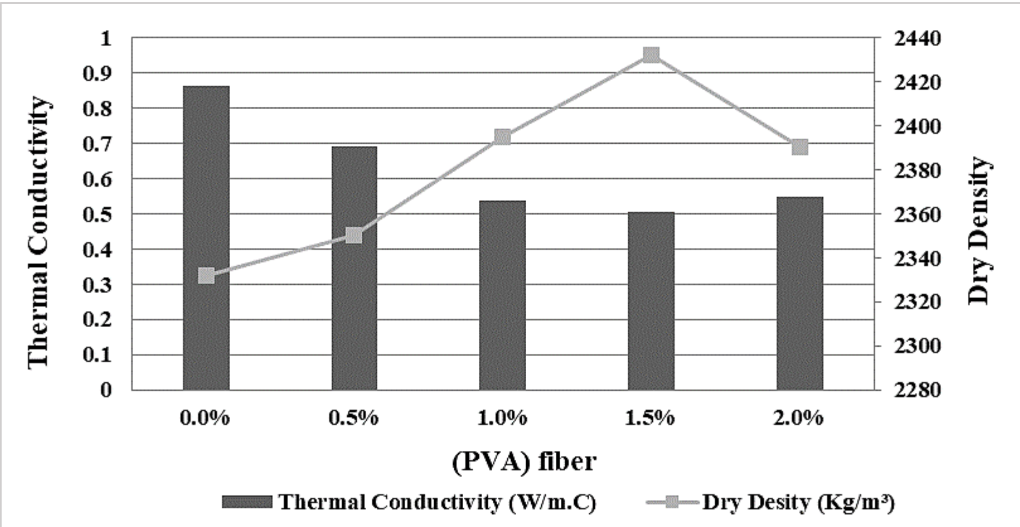

Figure 8: The Relation between thermal conductivity and air-dry density at 28 days

Figure 9: Thermal conductivity test by using cube (100×100×100) mm

3.1.3 Microstructure investigation

The fractured surface of the samples was analyzed using a Thermo-Scientific "Axia" Chemi-SEM scanning electron microscope equipped with a THERMOFISHER Scientific X-Flash 5030 source and detector. The microscope operates at a 1–30 kV voltage range and offers magnification between 5 and 1,000,000. Five SEM micrographs were obtained for each (PVA-ECC) mix, and the typical images of the observed microstructure were used in this manuscript. For this test, specimens must be prepared according to ASTM C 856-14 [45] with dimensions of (10×10×10) mm. All specimens were dried in the oven at 60 °C for seven days before testing to avoid the presence of water, which caused a disturbance in the photo. The subsequent step is submerging the sample in a low-viscosity epoxy resin. The epoxy was cured at 40 degrees Celsius for at least 24 hours. In the last step, the specimen is coated with a thin layer of conductive substance (gold liquid) to avoid the accumulation of electric charge during electron beam scanning, The steps of coated specimens by gold as demonstrated in Figure 10 (a and b).

(a) **(b)**

Figure 10: SEM sample preparation by gold liquid coating.

The microstructure, porosity, imperfections, impurities, interfaces, and microscale effect of PVA-ECC are all crucial factors in determining its ability to absorb electro-magnetic waves. Several researchers have found that the absorber's porous structure reduces the material's permittivity and permeability, improving the impedance matching between the absorber and air [47,48].

Introducing polyvinyl alcohol (PVA) fibers alters the pore distribution. It decreases the cement mixture's fluidity, preventing air bubbles from escaping and leading to more capillary holes. Adding polyvinyl alcohol (PVA), fibers fill the meso-pores and gel micro-pores with hydration products. Recent research has found that using PVA fibers results in both physical and chemical effects [49]. The high-density C-S-H gel predominantly forms in environments with a higher calcium-to-silica ratio (Ca/Si). Adding PVA fibers may increase the presence of high-density C-S-H gel, filling both meso-pores and gel micro-pores [49,50]. When the high-density C-S-H gel occupies the pore structure of the cementitious composites, it is logical that the pore volume and pore area of sample CF decrease [51].

The scanning electron microscopy investigations of the interfacial transition zone contrast the excellent bonding of (PVA) fiber with cement paste due to hydration products around the (PVA) fiber surface, as demonstrated in Figure 11. Thus, it causes a decline in tiny voids and porosity in the matrix. The compact matrix with fibers improved the mechanical strength of composites. On the other hand, Figures 12 and 13 illustrate a deboned between (PVA) fiber and matrix with less $CaCO_3$

content than reference specimens due to the transmigration of the carbonate composites, especially in the higher volume fraction of (PVA) fiber. The SEM figures illustrate some micro-cracks generated in the bonding zone between (PVA) fiber and cement paste, as illustrated in SEM Figures 14 and 15. Still, these cracks were arrested by fibers according to the crack bridging phenomenon, as distinguished in Figure 16. The presence of closed pores in the samples was increased with higher percentages of (PVA) fiber, which was also proved by [52].

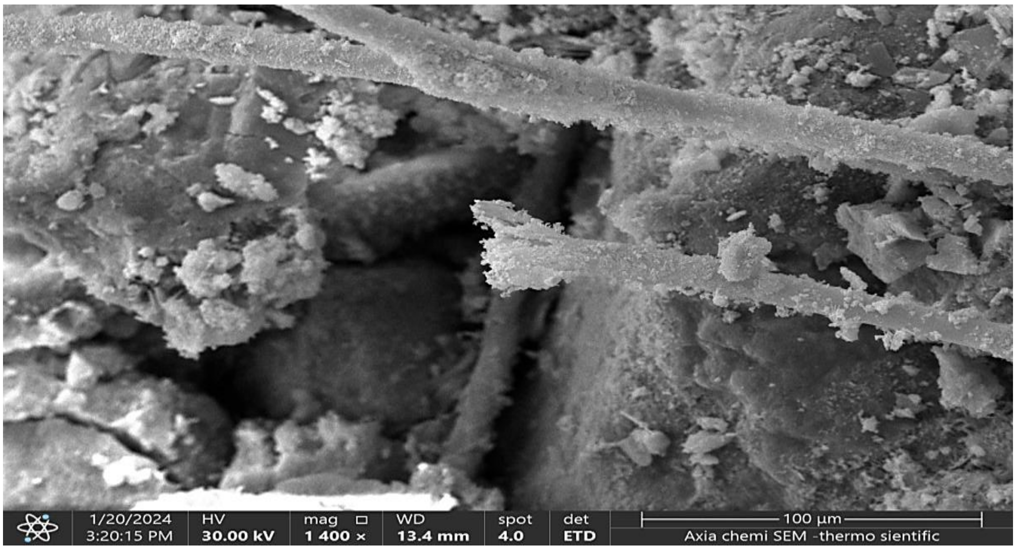

Figure 11: SEM micrograph of hydration product around fiber

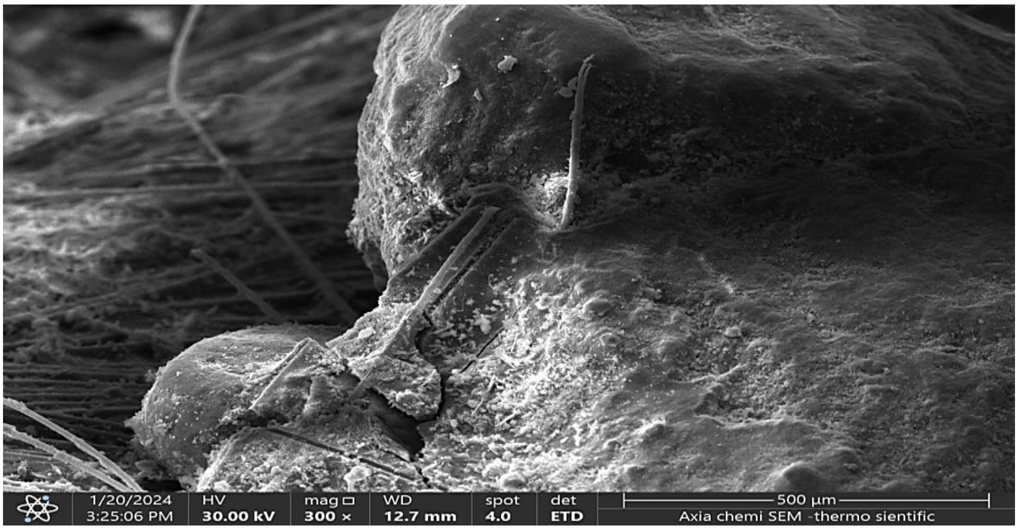

Figure 12: SEM micrograph of de-bonding between fiber and matrix

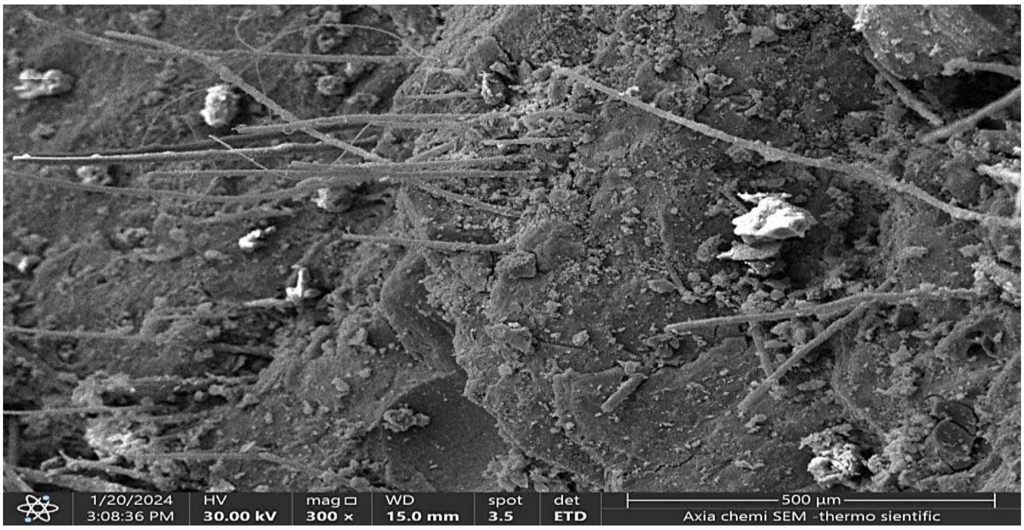

Figure 13: SEM micrograph of de-bonding between fiber and matrix

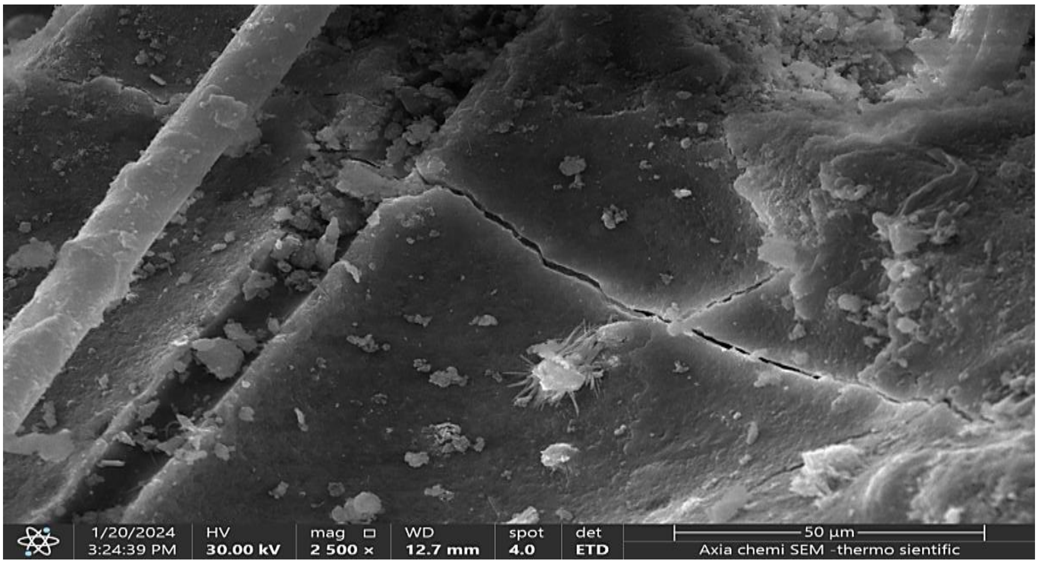

Figure 14: SEM Micrograph of micro-cracks in matrix

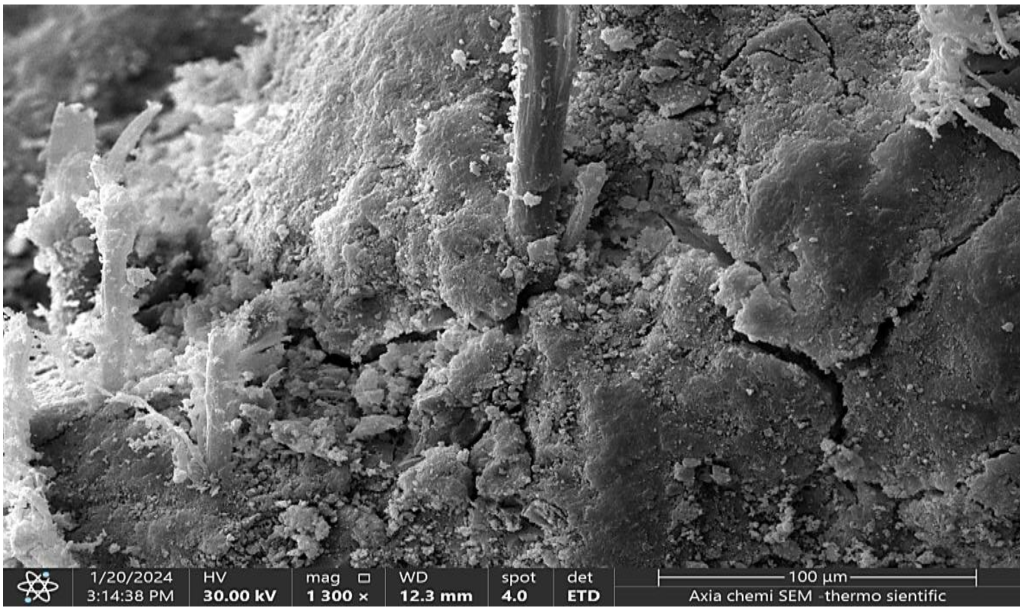

Figure 15: SEM micrograph of micro-cracks in matrix

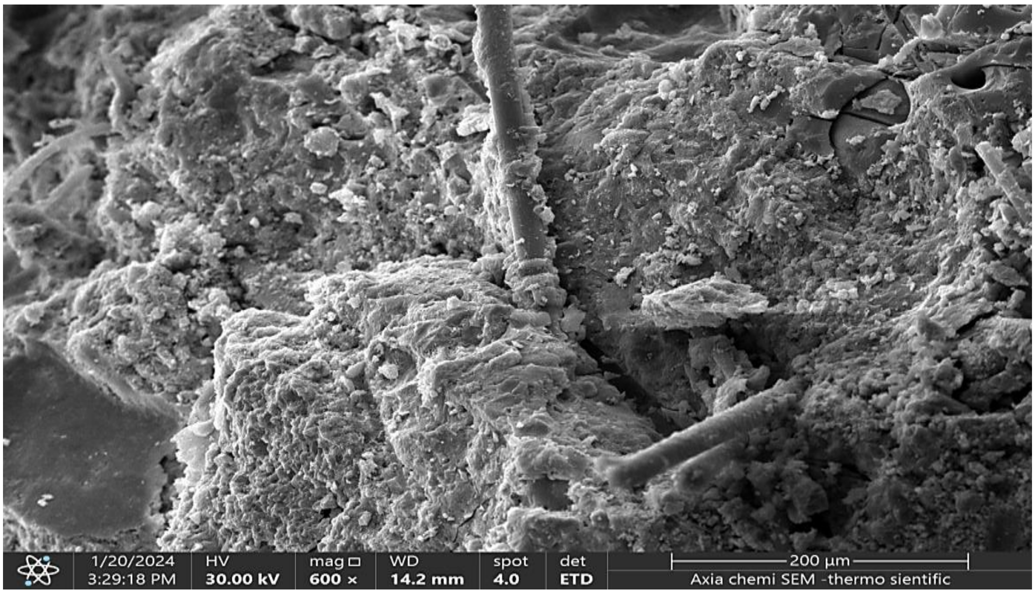

Figure 16: SEM micrograph of bridging phenomenon of fiber

4. Conclusion

The conclusions illustrate research regarding the laboratory works and the importance of adding (PVA) solution and (PVA) fiber with composite mortar. For these investigations, the conclusion explains in several points:

1) The inclusion of polyvinyl alcohol solution (PVA acetate), which imparts desirable cohesion properties, and (PVA) fiber, which possesses sufficient tensile strength, enhance the elasticity of engineered cementitious composite concrete.
2) The fiber volume fraction influences the elasticity of (PVA-ECC) concrete. Hence, it is evident that the (PVA-ECC) mixture containing 2% fiber exhibits a greater tendency towards elasticity than the mixture containing 1.5% fiber fraction.
3) Increased (PVA) fiber percentage causes a gradual decrease in water absorption. The mix of 1.5% (PVA) fiber can decrease water absorption to 17% more than ECC without fiber, but additional percentages of (PVA) fiber cause an increment in water absorption results.
4) The density test of concrete does not show a lot of variations between mixes. (PVA-ECC) offers a slightly higher density than the reference mix.
5) (PVA-ECC) illustrates higher results in compressive strength than the corresponding reference mix by approximately (1.4, 12.6, and 23.8)% for (0.5, 1, and 1.5)% of (PVA) fiber, respectively. But at (2)%, the fiber fraction gives a result higher than the result at (1.5)% by the fiber fraction.
6) Due to good bonding behavior between fibers and matrix, a higher strain capacity was gained when using (PVA) fiber in a mix of 25 MPa strength.
7) Using (PVA) fiber caused a reduction in the values of thermal conductivity up to 1.5% (PVA) fiber for 25 MPa compressive strength. The test results of thermal conductivity at 28 days of all mixes range between (0.5034 to 0.8612) W/m.K.
8) The laboratory SEM figures support the behavior of the fiber within the matrix and the obtained results.

Author contributions

Conceptualization, H. AL-Masraf. T. AL-Attar and Q. Freyyah; data curation, H. AL-Masraf. T. AL-Attar and Q. Freyyah.; formal analysis, H. AL-Masraf. T. AL-Attar and Q. Freyyah.; investigation H. AL-Masraf.; methodology, H. AL-Masraf. T. AL-Attar and Q. Freyyah.; resources, H. AL-Masraf.; supervision, T. AL-Attar and Q. Freyyah.; validation, H. AL-Masraf. T. AL-Attar and Q. Freyyah.; visualization, H. AL-Masraf. T. AL-Attar and Q. Freyyah.; writing—original draft preparation, H. AL-Masraf. T. AL-Attar and Q. Freyyah.; writing—review and editing, H. AL-Masraf. T. AL-Attar and Q. Freyyah. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] S. Hamoush, T. Abu-Lebdeh, and T. Cummins, Deflection behavior of concrete beams reinforced with PVA micro-fibers, Constr. Build. Mater., 24 (2010) 2285–2293. https://doi.org/10.1016/j.conbuildmat.2010.04.027

[2] J. Yu, J. Lin, Z. Zhang, and V. C. Li, Mechanical performance of ECC with high-volume fly ash after sub-elevated temperatures, Constr. Build. Mater., 99 (2015) 82–89. http://dx.doi.org/10.1016/j.conbuildmat.2015.09.002

[3] V. C. Li and S. Wang, Microstructure variability and macroscopic composite properties of high-performance fiber reinforced cementitious composites, Probabilistic Eng. Mech., 21 (2006) 201–206. https://doi.org/10.1016/j.probengmech.2005.10.008

[4] K. Tosun-Felekoğlu, B. Felekoğlu, R. Ranade, B. Y. Lee, and V. C. Li, The role of flaw size and fiber distribution on tensile ductility of PVA-ECC, Compos. Part B Eng., 56 (2014) 536–545. http://dx.doi.org/10.1016/j.compositesb.2013.08.089

[5] E. Özbay, O. Karahan, M. Lachemi, K. Hossain, and C. Atis, Investigation of Properties of Engineered Cementitious Composites Incorporating High Volumes of Fly Ash and Metakaolin, ACI Mater. J., 109 (2012) 302–315. https://doi.org/10.14359/51684088

[6] B. Felekoglu, K. Tosun-Felekoglu, R. Ranade, Q. Zhang, and V. C. Li, Influence of matrix flowability, fiber mixing procedure, and curing conditions on the mechanical performance of HTPP-ECC, Compos. Part B Eng., 60 (2014) 359–370. http://dx.doi.org/10.1016/j.compositesb.2013.12.076

[7] V. Mechtcherine et al., Behaviour of strain-hardening cement-based composites under high strain rates, J. Adv. Concr. Technol., 9 (2011) 51–62. http://dx.doi.org/10.3151/jact.9.51

[8] B. Liu, X. Zhang, J. Ye, X. Liu, and Z. Deng, Mechanical properties of hybrid fiber reinforced coral concrete, Case Stud. Constr. Mater., 16 (2022) e00865. http://dx.doi.org/10.1016/j.cscm.2021.e00865

[9] A. Dehghani and F. Aslani, The effect of shape memory alloy, steel, and carbon fibres on fresh, mechanical, and electrical properties of self-compacting cementitious composites, Cem. Concr. Compos., 112 (2020) 103659. http://dx.doi.org/10.1016/j.cemconcomp.2020.103659

[10] S. M. S. M. K. Samarakoon, P. Ruben, J. Wie Pedersen, and L. Evangelista, Mechanical performance of concrete made of steel fibers from tire waste, Case Stud. Constr. Mater., 11 (2019) e00259. http://dx.doi.org/10.1016/j.cscm.2019.e00259

[11] D. Akhmetov et al., Effect of low-modulus polypropylene fiber on physical and mechanical properties of self-compacting concrete, Case Stud. Constr. Mater., 16 (2021) e00814. http://dx.doi.org/10.1016/j.cscm.2021.e00814

[12] H. R. Pakravan, M. Latifi, and M. Jamshidi, Hybrid short fiber reinforcement system in concrete: A review, Constr. Build. Mater., 142 (2017) 280–294. http://dx.doi.org/10.1016/j.conbuildmat.2017.03.059

[13] S. Liu, R. Bai, J. Zhang, C. Yan, and X. Wang, Flexural load-deflection performance of polyvinyl alcohol fiber reinforced cementitious composite beams, Constr. Build. Mater., 223 (2019) 1135–1144. http://dx.doi.org/10.1016/j.conbuildmat.2019.07.215

[14] J. Zhao, C. Yan, S. Liu, J. Zhang, S. Li, and Y. Yan, Effect of solid waste ceramic on uniaxial tensile properties and thin plate bending properties of polyvinyl alcohol engineered cementitious composite, J. Clean. Prod., 268 (2020) 122329. http://dx.doi.org/10.1016/j.jclepro.2020.122329

[15] Z. Zhang and Q. Zhang, Matrix tailoring of Engineered Cementitious Composites (ECC) with non-oil-coated, low tensile strength PVA fiber, Constr. Build. Mater., 161 (2018) 420–431. http://dx.doi.org/10.1016/j.conbuildmat.2017.11.072

[16] Z. Pan, C. Wu, J. Liu, W. Wang, and J. Liu, Study on mechanical properties of cost-effective polyvinyl alcohol engineered cementitious composites (PVA-ECC), Constr. Build. Mater., 78 (2015) 397–404. http://dx.doi.org/10.1016/j.conbuildmat.2014.12.071

[17] D. Meng, T. Huang, Y. X. Zhang, and C. K. Lee, Mechanical behaviour of a polyvinyl alcohol fibre reinforced engineered cementitious composite (PVA-ECC) using local ingredients, Constr. Build. Mater., 141 (2017) 259–270. http://dx.doi.org/10.1016/j.conbuildmat.2017.02.158

[18] M. Şahmaran and V. C. Li, Durability properties of micro-cracked ECC containing high volumes fly ash, Cem. Concr. Res., 39 (2009) 1033–1043. http://dx.doi.org/10.1016/j.cemconres.2009.07.009

[19] J. H. Kim and R. E. Robertson, Prevention of air void formation in polymer-modified cement mortar by pre-wetting, Cem. Concr. Res., 27 (1997) 171–176. http://dx.doi.org/10.1016/S0008-8846(97)00001-X

[20] A. Noushini, B. Samali, and K. Vessalas, Effect of polyvinyl alcohol (PVA) fibre on dynamic and material properties of fibre reinforced concrete, Constr. Build. Mater., 49 (2013) 374–383. http://dx.doi.org/10.1016/j.conbuildmat.2013.08.035

[21] V. C. Li, C. Wu, S. Wang, A. Ogawa, and T. Saito, Interface tailoring for strain-hardening polyvinyl alcohol-engineered cementitious composite (PVA-ECC), ACI Mater. J., 99 (2002) 463–472. http://dx.doi.org/10.14359/12325

[22] H. R. Pakravan, M. Jamshidi, and M. Latifi, Study on fiber hybridization effect of engineered cementitious composites with low- and high-modulus polymeric fibers, Constr. Build. Mater., 112 (2016) 739–746. http://dx.doi.org/10.1016/j.conbuildmat.2016.02.112

[23] M. Li and V. C. Li, Rheology, fiber dispersion, and robust properties of engineered cementitious composites, Mater. Struct. Constr., 46 (2013) 405–420. http://dx.doi.org/10.1617/s11527-012-9909-z

[24] Z. Lu, A. Hanif, C. Lu, G. Sun, Y. Cheng, and Z. Li, Thermal, mechanical, and surface properties of poly(vinyl alcohol) (PVA) polymer modified cementitious composites for sustainable development, J. Appl. Polym. Sci., 135 (2018) 1–8. http://dx.doi.org/10.1002/app.46177

[25] E. Yang, Designing Added Functions in Engineered Cementitious Composites, 2008.

[26] B. Y. Lee, J. K. Kim, J. S. Kim, and Y. Y. Kim, Quantitative evaluation technique of Polyvinyl Alcohol (PVA) fiber dispersion in engineered cementitious composites, Cem. Concr. Compos., 31 (2009) 408–417. http://dx.doi.org/10.1016/j.cemconcomp.2009.04.002

[27] Li, V. C., Engineered Cementitious Composites (ECC) bendable concrete for sustainable and resilient infrastructure, 2019.

[28] S. Said, H. Abdul Razak, and I. Othman, Flexural behavior of engineered cementitious composite (ECC) slabs with polyvinyl alcohol fibers, Constr. Build. Mater., 75 (2025) 176–188. https://doi.org/10.1016/j.conbuildmat.2014.10.036

[29] L. Martinie, P. Rossi, and N. Roussel, Rheology of fiber reinforced cementitious materials: classification and prediction, Cem. Concr. Res., 40 (2010) 226–234. http://dx.doi.org/10.1016/j.cemconres.2009.08.032

[30] Li, V. C., Can concrete be bendable, American Scientist the magazine of Sigma Xi, The Scientific Research Society,100, 2012.

[31] IOS., Portland cement, Minist. Planning, Cent. Organ. Stand. Qual. Control, 5, 2019.

[32] IOS, Aggregates from natural sources for concrete and building constructions, Minist. Planning, Cent. Organ. Stand. Qual. Control, 45, 1980.

[33] ASTM C494/C494M, Standard Specification for Chemical Admixtures for Concrete, Am. Soc. Test. Mater., 2017.

[34] ASTM C1240, Standard Specification for Silica Fume Used in Cementitious Mixtures 1, Am. Soc. Test. Mater., 2015.

[35] S. A. Al Kareem and I. F. Ahmed, Impact Resistance of Bendable Concrete Reinforced with Grids and Containing PVA Solution, Eng. Technol. Appl. Sci. Res., 11(2021) 7709–7713. http://dx.doi.org/10.48084/etasr.4440

[36] J. Sherman, Polyvinyl Alcohol Prep and Activities, 103959(2016)1–4.

[37] M. G. Muktadir, M. I. F. Alam, A. Rahman, and M. R. Haque, Comparison of Compressive Strength and Flexural Capacity between Engineered Cementitious Composites (Bendable Concrete) and Conventional Concrete used in Bangladesh, 7 (2020) 73–82.

[38] ASTM C305, Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency1, Am. Soc. Test. Mater., 1–3, 2015.

[39] ASTM C1609/C1609M, Standard test method for flexural performance of fiber reinforced concrete (using beam with third point loading, Am. Soc. Test. Mater., 2012,1-9.

[40] ASTM C143/C143M, Standard Test Method for Slump of Hydraulic-Cement Concrete, Astm C143, 2015,1-4.

[41] ASTM C567/C567M, Standard Test Method for Determining Density of Structural Lightweight Concrete 1, Am. Soc. Test. Mater., 2019,1-4.

[42] BS EN 12390-3, Testing hardened concrete, British Standard: London, UK, 2019.

[43] ASTM C293, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) Am. Soc. Test. Mater., 2016,1-4.

[44] ASTM C1113/C1113M-09, Standard Test Method for Thermal Conductivity of Refractories by Hot Wire (Platinum Resistance Thermometer Technique), Am. Soc. Test. Mater., 2013,1-6.

[45] ASTM C856, Standard Practice for Petrographic Examination of Hardened Concrete, Am. Soc. Test. Mater., 2014,1-17.

[46] L. Baoyi, D. Yuping, Z. Yuefang, and L. Shunhua, Electromagnetic wave absorption properties of cement-based composites filled with porous materials, Mater. Des., 32 (2011) 3017–3020. http://dx.doi.org/10.1016/j.matdes.2010.12.017

[47] X. G. Chen, J. P. Cheng, S. S. Lv, P. P. Zhang, S. T. Liu, and Y. Ye, Preparation of porous magnetic nanocomposites using corncob powders as template and their applications for electromagnetic wave absorption, Compos. Sci. Technol., 72 (2012) 908–914. http://dx.doi.org/10.1016/j.compscitech.2012.03.001

[48] A. R. Sakulich and V. C. Li, Nanoscale characterization of engineered cementitious composites (ECC), Cem. Concr. Res., 41 (2011) 169–175. http://dx.doi.org/10.1016/j.cemconres.2010.11.001

[49] Q. Li, X. Gao, and S. Xu, Multiple effects of nano-SiO2 and hybrid fibers on properties of high toughness fiber reinforced cementitious composites with high-volume fly ash, Cem. Concr. Compos., 72 (2016) 201–212. http://dx.doi.org/10.1016/j.cemconcomp.2016.05.011

[50] Y. Shen, Q. Li, S. Xu, and X. Liu, Electromagnetic wave absorption of multifunctional cementitious composites incorporating polyvinyl alcohol (PVA) fibers and fly ash: Effects of microstructure and hydration, Cem. Concr. Res., 143 (2021). http://dx.doi.org/10.1016/j.cemconres.2021.106389

[51] P. Zhang, S. Wei, J. Wu, Y. Zhang, and Y. Zheng, Case Studies in Construction Materials Investigation of mechanical properties of PVA fiber-reinforced cementitious composites under the coupling effect of wet-thermal and chloride salt environment, Case Stud. Constr. Mater., 17 (2022) e01325. http://dx.doi.org/10.1016/j.cscm.2022.e013250