Elasticity and Load-Displacement Behavior of Engineered Cementitious Composites produced with Different Polymeric Fibers

Ikram Faraoun Al-Mulla
Civil Engineering Department, University of Baghdad, Iraq
ikram.faroun@coeng.uobaghdad.edu.iq (corresponding author)

Abbas Salim Al-Ameeri
Civil Engineering Department, University of Baghdad, Iraq
abbas.alameeri.eng@uobabylon.edu.Iq

Ammar Sabah Al-Rihimy
Civil Engineering Department, Middle Technical University, Iraq
ammar.alrihimy@mtu.edu.iq

Tareq Salih Al-Attar
Civil Engineering Department, University of Technology, Iraq
tareq.s.alattar@uotechnology.edu.iq

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ABSTRACT

Engineered Cementitious Composites (ECC) are ultra-ductile materials, and the fibers used provide superior flexibility and strain capacity. This study investigates the use of two different types of polymeric fibers, Polypropylene (PP) and Polyvinyl Alcohol (PVA), with volume fractions of 1 and 2%, and studies their effect on stress-strain relationships, load-displacement behavior, toughness, and elasticity of ECC mixes produced with two strength levels, 30 and 60 MPa. The results showed that mixtures with PVA fiber ionic coating had a better performance than those with PP fibers due to the chemical reaction between the PVA fibers and the ECC matrix. This performance was confirmed by Scanning Electronic Microscopy (SEM). For normal-strength concrete (30 MPa), the modulus of elasticity increased by 7.8 and 9.6% for mixes with PP and PVA fibers, respectively, while in high-strength mixes (60 MPa), it increased by 9.4 and 10.85%, respectively. Toughness increases with increasing matrix strength, which is associated with an increase in cement content and fiber fraction. This study also investigates the effect of incorporating a PVA solution in ECC mixes, which leads to an increase in yield stress. This behavior was observed in the stress-strain behavior of 60 MPa mixes with 2% fibers which were compared to 30 MPa mixes with 1% fibers.

Keywords-Engineered Cementitious Composite (ECC); Polypropylene (PP) fibers; Polyvinyl Alcohol (PVA) fibers; polyvinyl alcohol acetate; stress-strain behavior; load-deflection curve; modulus of elasticity

I. INTRODUCTION

Conventional concrete members are unyielding and have a strain capacity of at most 0.1%, producing high-brittleness concrete. The absence of normal concrete bendability is a notable cause of strain failure and is considered a controlling power in creating an elegant material, known as Engineered Cementitious Composite (ECC) concrete [1]. This type of concrete can exhibit intensely improved flexibility [2], as it is reinforced with tiny and disconnected polymer fibers that are micromechanical, specifically designed, and used up to 2% by volume [3]. Thus, ECC concrete deforms without breaking more than conventional concrete [4]. The formation of ECC concrete relies on the interaction between the matrix and the fibers, which is considered an essential factor for its behavior, as it results in a modification in the interfacial zone and provides an ideal property. Using appropriate mineral admixtures may prevent fiber pull-out from the matrix [3]. ECC concrete with 2% fibers improves tensile strain capacity by 3 to 7%. The diverse constituents of ECC concrete help resisting the subjected load and are 40 times lighter and 50 times more flexible than conventional concrete [4]. Instead of tension-softening, ECC experiences strain-hardening, which means that the material endures higher loads at a progressively imposed strain on the uniaxially tensioned specimen [4]. The addition of Polyvinyl Alcohol (PVA) acetate solution improves the durability and bonding strength of cementing materials [5]. PVA solutions are added directly to cement in the form of an aqueous solution to improve the properties of ECC concrete. Many studies have shown that adding a certain amount of PVA can improve the water retention and workability of ECC concrete in the fresh state [6]. Unlike FRC, the rising tensile deformation in ECC is nonlocalized, as it spreads from the first crack to multiple cracks that cover the specimen's volume. Increasing the number of microcracks and controlling the widths of the cracks to not exceed 100 μm increases the tensile ductility. ECC's strain-hardening increases with fiber volume content. Using silica fume with PVA fibers in ECC concrete mixes creates a surface coating that prevents fibers from slipping when loaded without fracturing [4]. According to [3], the increase in compressive strength between ECC concrete mixes made with Portland Limestone Cement (PLC), with and without fibers, was 36.11, 45.5, and 52.4% after 28, 56, and 90 days. In addition, its exceptional energy absorption makes ECC concrete suitable for use in seismic zones or microstructure tailoring [3].

Adding Polypropylene (PP) fibers with adequate tensile strength makes concrete more ductile, since it acts as a bridge at the matrix/fiber interface, making it more durable and robust and improving its bonding strength and microstructure [7]. The high density of high-strength concrete avoids water evaporation, leading to greater strength gain [8-9]. The modulus of elasticity of high-strength concrete reinforced with polymer grids shows greater improvement than normal-strength concrete due to its higher density and the use of high range water-reducing agents, leading to an increase in compressive strength [10]. This study investigates the modulus of elasticity behavior of ECC concrete with two grades of strength, normal (30 MPa) and high (60 MPa), reinforced with 1% and 2% PP and PVA fibers, and containing PVA solution and silica fume. This study also investigates the stress-strain behavior of ECC concrete and detects the load-displacement performance and the toughness of these mixes. SEM was used to identify the microstructural behavior of the engineered cementitious composite. The results of this study may open the horizon beyond the use of such mixes in constructions exposed to tensile stresses without the need to use traditional bar reinforcement.

II. MATERIALS

The ECC concrete used in this study was composed of ordinary Portland cement [11] with two cement content ratios: 275 and 450 kg/m^3, for 28-day concrete compressive strengths of 30 and 60 MPa, respectively. Fine aggregate (sand) sieve analysis grading confirmed IQS No.45/84, lying in zone II [12]. Silica fume with a strength activity index of 120% [13] was used. Table I shows the characteristics of the PP and PVA fibers. The PVA solution was used to reduce the porosity and enhance the density of ECC. The compressive strength test was performed after 28 days of water-curing, and the cylinders were tested according to [14]. The modulus of elasticity test was applied on a cylinder of 300×150 mm according to [15]. The stress-strain relationship was recorded for 300×150 mm cylinders at a curing age of 28 days. The test procedure was conducted according to [15]. Each cylinder's top surface was leveled using a diamond-stoned grinder to ensure a smooth and leveled surface. The load-displacement test was performed on a 100×100×400 mm prism in accordance with [16]. Tables II and III present the properties of the four mixes. Mixes of 30 MPa with a 1% volume fraction of fibers and 60 MPa with a 2% volume fraction of fibers were used to investigate modulus of elasticity, stress-strain relationship, toughness, and the load-displacement behavior of ECC-bendable concrete. These fiber ratios were chosen based on their better performance in the mixes to avoid the balling effect that occurs when using high-volume fractions of fibers with poor paste content.

TABLE I. CHARACTERISTICS OF POLYMERIC FIBERS

Characteristics	PVA	PP
Elongation, %	6	10
Length, mm	12	12
Diameter, μm	0.039	0.032
Color	Light yellow	White
Shape	Straight	Straight
Density, kg/m^3	1300	910
Tensile strength, MPa,	1620	600 - 700
Modulus of elasticity, GPa,	42.8	36

TABLE II. MIX PROPORTIONS BY WEIGHT

Materials	30 MPa	60 MPa
cement	1	1
sand	0.8	0.8
SF*	0.1	0.1
SP*	0.013	0.02
PVAs*	0.01	0.01
w/b*	0.42	0.3

*SP: superplasticizer percentage, *SF: silica fume percentage, *PVAs: polyvinyl alcohol solution, *w/b: water to binder ratio

TABLE III. DETAILS OF THE USED MIXES

Mix Designation	28-days compressive strength (MPa)	Fiber type	Fiber (%)
30P	30	PP	1
30V	30	PVA	1
60P	60	PP	2
60V	60	PVa	2

III. TEST METHOD AND STANDARDS

A. Modulus of Elasticity

A concrete cylinder of 150 mm diameter and 300 mm height was tested according to [17], to investigate the modulus of elasticity. The average modulus of elasticity of three specimens was calculated after 28, 60, and 90 days.

B. Stress-Strain Relationship

The stress-strain behavior of ECC concrete using PVA and PP fibers with two volume fractions, 1% for 30 MPa and 2% for 60 MPa, was investigated for an age of 28 days.

C. Load-Displacement Test

The load-displacement test was performed using the third-point bending test on an ECC concrete beam of 100×100×400 mm, with a span length of 300 mm. The test procedure was determined according to [16]. Four mixes were detected for the load-deflection behavior, as described in Table III.

D. Field Emission–Scanning Electron Microscope (FE-SEM)

This test is used to inspect various materials and characterize their structure and composition, as it provides a stable, high-resolution platform that can meet most research needs from a collection of accurate and fast data: images of surface and composition can be combined with fast elemental analysis to determine the properties and the elemental composition of the material. This study used the FE-SEM test to determine the bond behavior between the PP and PVA polymeric fibers and the matrix, which has a great influence on the mechanical behavior of the ECC concrete mixes.

IV. RESULTS AND DISCUSSION

A. Strength and Elasticity

The compressive strength and modulus of elasticity test results in Table IV show that fiber type does not have a significant effect on compressive strength. Figure 1 shows that using PVA fiber for normal-strength concrete gives a higher modulus of elasticity than using PP. This behavior is attributed to the high tensile strength of PVA, which is 1620 MPa compared to the 700 MPa for PP. In addition, the higher modulus of elasticity of PVA fibers, reflects its effect on the modulus of elasticity of the ECC mixes. For normal-strength concrete, the increase in modulus of elasticity was 7.8 and 9.6% for mixes with PP and PVA fibers, respectively. For high-strength concrete, the increase in modulus of elasticity was 9.4 and 10.85% for mixes with PP and PVA fibers, respectively. For normal strength mixes, the increase in modulus of elasticity when using PVA compared to PP fibers was approximately 2.4% after 90 days. Furthermore, for high-strength concrete mixes after 90 days, the use of PVA fibers showed a 3.3% increase in modulus of elasticity compared to PP.

Figure 2 shows the error bars of the standard deviation of the modulus of elasticity for different fiber content and strength levels. The bar charts represent the average modulus of elasticity for each mix at 28, 60, and 90 days. There is an overlap between error bars in mixtures of the same strength, indicating that there are no huge differences in the modulus of elasticity for different fiber types. Also, it can be noticed that there is no overlap in the error bars between different mixes, indicating that there are obvious differences when using different fiber content and types. Mixes of 60 MPa with 2% PVA fibers recorded the highest modulus of elasticity over time, due to the high density, good fiber distribution, high cement content, high tensile strength of PVA fibers, high fiber content, and adequate chemical and mechanical bond between PVA fibers and matrix.

TABLE IV. TEST RESULTS OF CONCRETE MIXES

	Compressive strength (MPa)			Modulus of elasticity (GPa)		
Age (days)	**28**	**60**	**90**	**28**	**60**	**90**
30P	32	34	37	23	23.86	24.8
30V	34	36.4	38.7	24	24.6	26.3
60P	61.53	62	65.49	30.1	30.5	32.94
60V	62.79	63.23	69	30.67	31.27	34

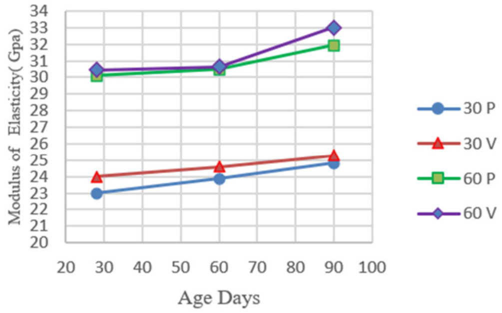

Fig. 1. The relationship of modulus of elasticity with age for the mixes.

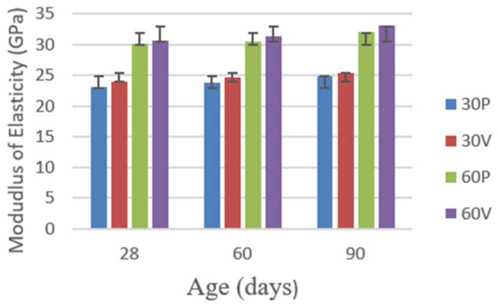

Fig. 2. Error bars for standard deviation for modulus of elasticity with age for different concrete mixes.

Figures 3 and 4 show the relationship between the compressive strength and the modulus of the elasticity of normal-strength concrete. The modulus of elasticity had low variation in normal-strength concrete despite using different fiber types.

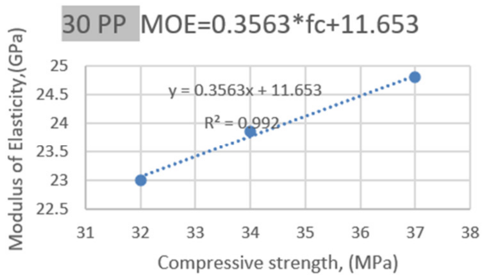

Fig. 3. Relationship between the modulus of elasticity and compressive strength for normal-strength concrete produced with PP fibers.

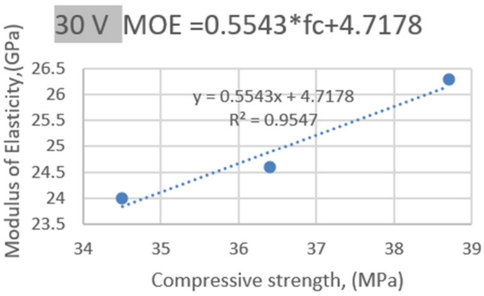

Fig. 4. Relationship between the modulus of elasticity and compressive strength for normal-strength concrete produced with PVA fibers.

Figures 5 and 6 show that in high-strength concrete, the mixes produced with PVA fibers had a greater increase in modulus of elasticity than the mixes made with PP. This performance may be due to the higher modulus of elasticity of PVA (42.8 GPa) compared to PP fibers (36 GPa) and the higher cement content for 60 MPa mixes, which provides better bonding with the fibers and better fiber distributions. The equations shown in Figures 3-6 have a high determination coefficient (R^2), which assures their suitability to predict the modulus of elasticity for each mix from its compressive strength. These equations were compared to the ACI 318 [18] and ACI 363 [19] equations:

ACI 318: $E_c = 4700 \times \sqrt{f'c}$ (1)

ACI 363 (Martines): $E_c = 3320 \times \sqrt{f'c}+6900$ (2)

ACI 363 (Radain): $E_c = 14495 + 2176 \times \sqrt{f'c}$ (3)

ACI 363 (NS 3473): $E_c = 9500 \times (f'c)^{0.3}$ (4)

Table V shows the relationships between the modulus of elasticity and compressive strength. The estimated results were compared to the results from the ACI equations, showing convergence with a variation between the ACI and the actual equation results of about 17, 14.5, 9, and 7.2% for mixes 30PP, 30V, 60PP, and 60V, respectively.

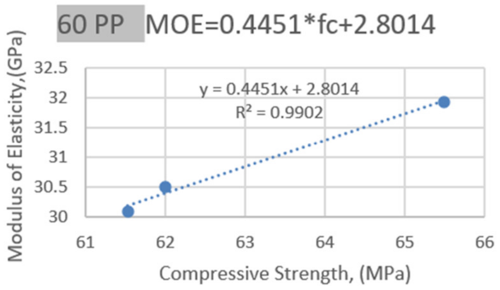

Fig. 5. Relationship between the modulus of elasticity and compressive strength for high-strength concrete produced with PP fibers.

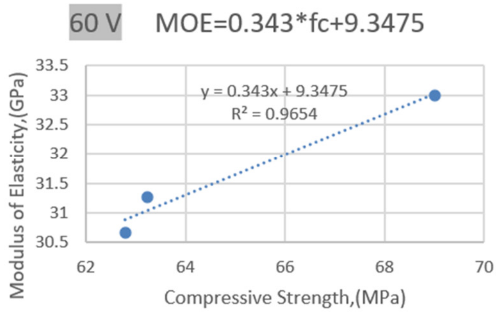

Fig. 6. Relationship between the modulus of elasticity and compressive strength for high-strength concrete produced with PVA fibers.

TABLE V. COMPARISON BETWEEN THE ACTUAL RESULTS AND THE ACI RESULTS

	30 PP			30 V			60 PP			60 V		
	28 days	**60 days**	**90 days**	**28 days**	**60 days**	**90 days**	**28 days**	**60 days**	**90 days**	**28 days**	**60 days**	**90 days**
Compressive strength	32	34	37	34.5	36.4	38.7	61.53	62	65.49	62.79	63.23	69
Actual *Ec*	23	23.86	24.8	24	24.6	26.3	30.1	30.5	31.49	30.67	31.27	33
(1)	26.5	27.4	28.5	27.6	28.3	29.2	36.8	37	38	37.2	37.4	39
(2)	25.6	26.3	27	26.4	26.9	27.55	32.9	33	33.76	33.2	33.299	34.477
(3)	26.8	27.18	27.7	27.276	27.6	28	31.56	31.63	32	31.737	31.797	32.57
(4)	26.87	27.36	28	27.48	27.93	28.45	32.69	32.767	33.31	32.89	32.96	33.83

B. Stress-Strain Relationship

Figures 7-10 show the stress-strain behavior of ECC at the age of 28 days. The strain change reflects the matrix toughness and the interaction of the fiber/matrix properties [4].

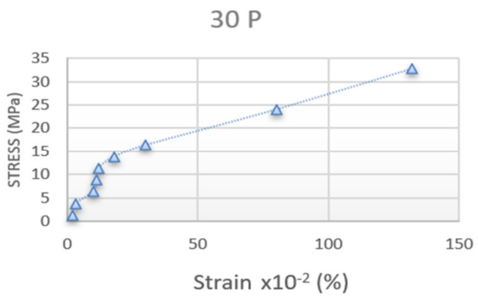

Fig. 7. Stress-strain curve for normal strength concrete reinforced with 1% PP fibers.

The stress-strain behavior for mix 30V is attributed to the ionic coating properties of the PVA fibers and the chemical interaction with the cement matrix that restricts concrete flaws and microcrack propagation. The same explanation also can be applied to the high-strength mixes in Figures 9-10. The elasticity of the mix is affected by the used fiber volume fraction and type. Therefore, it can be noticed that mixes with PVA fibers have higher elastic behavior than mixes with PP fibers. Also, mixes with 2% fiber content show a higher elastic trend than mixes with 1% fiber.

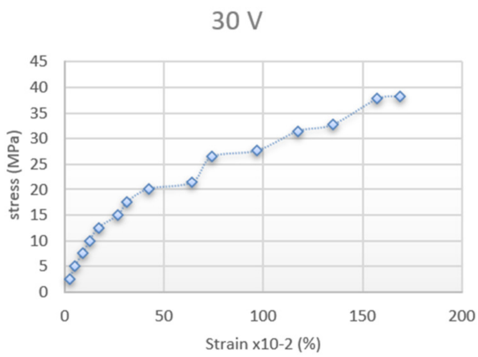

Fig. 8. Stress-strain curve for normal strength concrete reinforced with 1% PVA fibers.

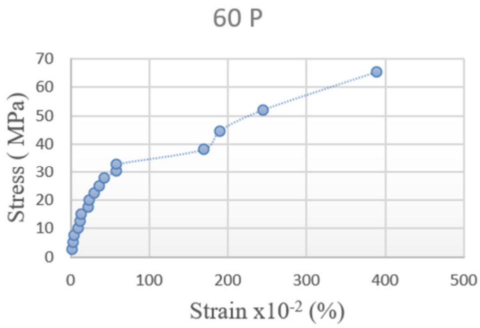

Fig. 9. Stress-strain curve for high-strength concrete reinforced with 2% PP fibers.

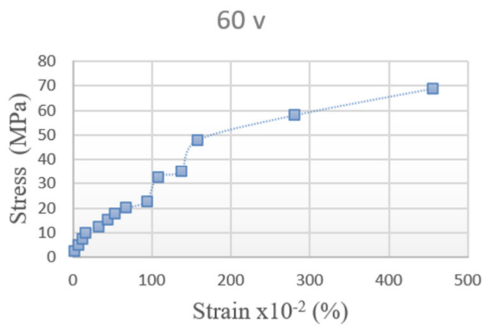

Fig. 10. Stress-strain curve for high-strength concrete reinforced with 2% PVA fibers.

C. *Load-Displacement Relationship*

Figures 11 and 12 show the flexural responses of PP and PVA ECC cement under loading. These figures show a deflection hardening behavior, indicating that the load grows even after the initiation of the crack in the matrix.

The load-displacement curve of high-strength ECC concrete mixes indicates that the distributed tensile deformation causes the spread of a strain in the compressive zone of the beam. In ordinary concrete mixes, concentrating strain in the compressive zone of the beam leads to brittle spalling [4]. The key differences in ECC's elasticity and load-displacement behavior produced with PP and PVA fibers are that PVA improves the elasticity behavior of the ECC mixes and increases their capacity to bear the applied load, compared to PP which gives the same enhancement in an inferior degree.

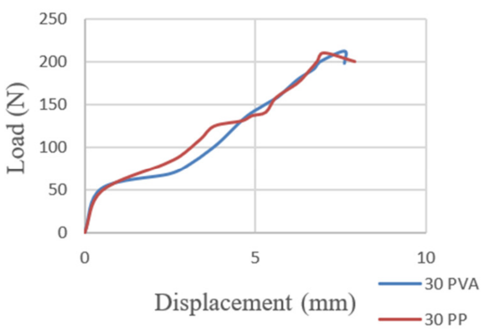

Fig. 11. Load-displacement curve for normal-strength concrete with PVA and PP fibers.

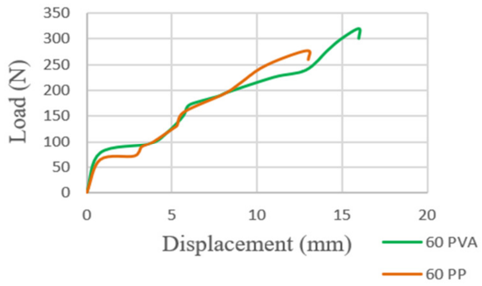

Fig. 12. Load-displacement curve for high-strength concrete with PVA and PP fibers.

D. *Toughness*

Table VI shows the areas under the load-displacement curves, which are defined as the ECC concrete toughness.

TABLE VI. TOUGHNESS OF THE ECC CONCRETE MIXES

Mixes	Toughness (J/m^3)
30P	856
60P	2095
30V	958
60V	2880

The toughness of the ECC matrix is ruled by its ingredients. When the maximum energy exceeds the matrix toughness, crack propagation is achieved after the crack starts from a defective site [4]. This can be realized by restricting the matrix toughness, which can be achieved by varying the matrix ingredients. Table VI shows that as the strength of the matrix increases, which is related to an increase in cement and fiber content, the toughness of the mixes increases. For normal-strength concrete, the toughness of the 30V mixes was about 12% higher than that of the 30P mixes. The same behavior can be observed in 60V mixes compared to 60P mixes, where the toughness increase was 37%. This behavior may be related to the increase in fiber content in high-strength mixes. The degree of ductility depends on the fiber type and is directly proportional to the fiber content. This explanation agrees with [20], which concluded that the higher fiber content in FRC leads to a lower corresponding post-crack load drop.

E. *Field Emission-Scanning Electron Microscope (FE-SEM)*

SEM analysis is characterized by easy sampling, a variety of accessible knowledge, and good resolution [21]. PVA fibers provided better behavior than PP fibers in the ECC, because of the chemical bond between their ionic coating and the cement matrix. Figure 13 represents the bond area between the PVA fibers and the cement matrix for 500×(200 μm) magnification. Figure 14 represents the bond situation between the PP fibers and the cement matrix for 600× magnification. In general, adding polymeric fibers to concrete mixes leads to a remarkable improvement in its behavior, especially its flexural strength, which is consistent with the conclusions of [22].

V. CONCLUSIONS

1. Engineered high-strength (60 MPa) cementitious composite concrete containing 2% PVA fibers showed the highest results in modulus of elasticity, and its load-displacement curves showed higher yield stress levels.

Fig. 13. The bond between PVA fibers and the matrix.

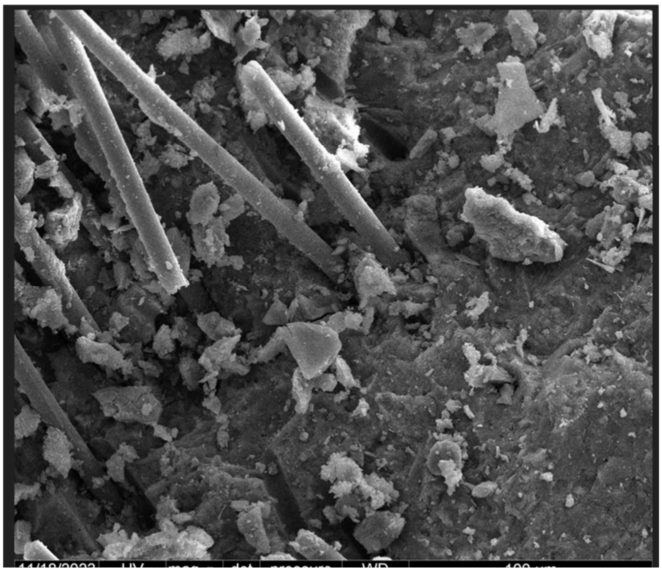

Fig. 14. The bond between polypropylene fibers and concrete matrix.

2. The presence of a PVA solution provides good cohesion strength, and the presence of polymeric fibers, having adequate tensile strength, makes the engineered cementitious composite concrete more ductile.
3. The elasticity of the mixture is affected by the type and fraction of fibers used. Therefore, it can be noticed that ECC mixes with PVA fibers had a higher elastic behavior than mixes with PP. In addition, mixes with 2% fiber content showed a higher elastic trend than mixes with 1% fiber.
4. The higher modulus of elasticity of PVA fibers compared to PP reflects its effect on the modulus of elasticity of the ECC mixes.
5. The flexural responses of PP and PVA ECC concrete under loading show deflection hardening behavior.
6. The toughness of the ECC matrix is ruled by its material components and the matrix strength, which is related to an increase in cement content and fiber volume fraction. Therefore, the matrix toughness increases as the strength and fiber content increase.
7. For normal-strength concrete (30 MPa), mixes containing PVA fibers exhibit an increase of approximately 12% in comparison with the mixes containing PP fibers. The same behavior can be observed for high-strength concrete (60 MPa), where mixes containing PVA fibers showed an increase in toughness of approximately 37% higher than ECC concrete mixes containing PP fibers.
8. The superior behavior of PVA fibers is related to their higher modulus of elasticity and their ionic coating, which provides good chemical bonding with the cement matrix, leading to an increase in the toughness and elasticity behavior of the ECC concrete mixes.
9. SEM revealed the bond behavior between the polymeric fibers and the ECC concrete matrix.
10. SEM showed that microcracks below 50 μm were controlled by polymeric fibers and the sequence of developing microcracks leads to an improved strain capacity of the ECC mixes.

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CONFLICTS OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

REFERENCES

[1] S. Gadhiya, T. N. Patel, and D. Shah, "Bendable Concrete: A Review," *International Journal of Structural and Civil Engineer Research*, vol. 4, no. 1, pp. 141–146, 2015.

[2] I. F. Al-Mulla, A. S. Al-Rihimy, and M. S. A. Alameer, "Properties of engineered cementitious composite concrete (bendable concrete) produced using Portland limestone cement," *IOP Conference Series: Materials Science and Engineering*, vol. 671, no. 1, Jan. 2020, Art. no. 012131, https://doi.org/10.1088/1757-899X/671/1/012131.

[3] S. A. A. Kareem and I. F. Ahmed, "Impact Resistance of Bendable Concrete Reinforced with Grids and Containing PVA Solution," *Engineering, Technology & Applied Science Research*, vol. 11, no. 5, pp. 7709–7713, Oct. 2021, https://doi.org/10.48084/etasr.4440.

[4] V. C. Li, Engineered Cementitious Composites (ECC): Bendable Concrete for Sustainable and Resilient Infrastructure. Springer, 2019.

[5] P. E. Stutzman, "Scanning Electron Microscopy in Concrete Petrography," in *The Role of Calcium Hydroxide - American Ceramic Society Workshop*, Nov. 2000.

[6] F. Liu, B. Wang, Y. Xing, K. Zhang, and W. Jiang, "Effect of Polyvinyl Alcohol on the Rheological Properties of Cement Mortar," *Molecules*, vol. 25, no. 3, Jan. 2020, Art. no. 754, https://doi.org/10.3390/molecules25030754.

[7] S. S. Saeed, N. M. Fawzi, and I. F. Ikram, "A-mechanical properties of engineered cementitious composite concrete produced from Portland

limestone cement," *Association of Arab Universities Journal of Engineering Sciences*, vol. 29, no. 2, pp. 19–26, Jul. 2022, https://doi.org/10.33261/jaaru.2022.29.2.003.

[8] E. M. Bezerra, A. P. Joaquim, and H. Savastano Jr, "Some Properties of Fiber-Cement Composites with Selected Fibers," presented at the Conferência Brasileira de Materiais e Tecnologias Não- Convencionais: Habitações e Infra-Estrutura de Interesse Social Brasil-NOCMAT, Pirassununga, Brazil, Oct. 2004.

[9] A. S. A. Al-Rihimy, "Experimental Evaluation and Modeling of Time-dependent Deformations of self-compacting Concrete," Ph.D. dissertation, University of Technology, Baghdad, Iraq, 2018.

[10] A. F. Ikram, "Behavior of concrete units containing polymer grids," MSc Thesis, University of Technology, Iraq, 2002.

[11] "ASTM C150-07: Standard Specification for Portland Cement." American Society for Testing and Materials, 2007, https://doi.org/ 10.1520/C0150-07.

[12] "IQS 45/1984: Aggregate from natural sources for concrete and construction." Central Organization for Standardization and Quality Control, Baghdad, Iraq, 1984.

[13] "ASTM C1240-15: Standard Specification for Silica Fume Used in Cementitious Mixtures." American Society for Testing and Materials, https://doi.org/10.1520/C1240-15.

[14] "ASTM C39/C39M-18: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." American Society for Testing and Materials, https://doi.org/10.1520/C0039_C0039M-18.

[15] "ASTM C469-02e1: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." 2002, https://doi.org/10.1520/C0469-02E01.

[16] "ASTM C1609/C1609M-07: Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)." American Society for Testing and Materials, https://doi.org/10.1520/C1609_C1609M-07.

[17] "ASTM C192/C192M-15: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory." American Society for Testing and Materials, https://doi.org/10.1520/C0192_C0192M-15.

[18] "ACI CODE-318-14: Building Code Requirements for Structural Concrete and Commentary." American Concrete Institute, 2014.

[19] "363R-10: Report on High-Strength Concrete," American Concrete Institute, 363R–10, Jan. 2010. [Online]. Available: https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/51663590.

[20] V. Ramakrishnan, G. Y. Wu, and G. Hosalli, "Flexural Behavior and Toughness of Fiber Reinforced Concretes," *Transportation Research Record*, vol. 1226, pp. 69–77, 1989.

[21] B. Uzbas and A. C. Aydin, "Microstructural Analysis of Silica Fume Concrete with Scanning Electron Microscopy and X-Ray Diffraction," *Engineering, Technology & Applied Science Research*, vol. 10, no. 3, pp. 5845–5850, Jun. 2020, https://doi.org/10.48084/etasr.3288.

[22] M. T. Lakhiar, S. Sohu, I. A. Bhatti, N. Bhatti, S. A. Abbasi, and M. Tarique, "Flexural Performance of Concrete Reinforced by Plastic Fibers," *Engineering, Technology & Applied Science Research*, vol. 8, no. 3, pp. 3041–3043, Jun. 2018, https://doi.org/10.48084/etasr.2084.