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Strain capacity and flexural strength behavior of bendable concrete produced with different polymeric fibers

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HIGHLIGHTS

- Engineered cementitious composite (ECC) can endure high tensile strength.
- Polyvinyl alcohol (PVA) and polypropylene (PP) fibers enhance ECC tensile behavior.
- PVA fibers improved flexural strength by 23% over PP fibers.
- Higher percentages of PVA fiber increased engineered cementitious composite strain capacity.

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ABSTRACT

The incorporation of fibers into engineered cementitious composite concrete imparts flexibility to the material. Therefore, using different types and contents of polymeric fibers would affect the behavior of such concrete types, and it is worth contemplating. The present research aims to study the flexural strength and the strain capacity of engineered cementitious composite concrete produced with polyvinyl alcohol fibers (PVA) and polypropylene fibers (PP) with different volume fractions (1%, 1.5%, and 2%). Six mixes of engineered cementitious composite concrete of three grades of strengths, 30, 45, and 60 MPa, were produced. Results revealed that mixes of 60 MPa with 2% PVA fibers recorded the highest strain capacity, which reached (17.6%) compared to mixes of 60 MPa with 2% PP fibers. The maximum enhancement in the flexural strength was (4.3%),(6%), and (23%) for mixes of 30 MPa, 45 MPa and 60 MPa. This enhancement may open the horizon for using high-strength engineered cementitious composite concrete reinforced with PVA fibers in structural applications exposed to flexural strength, providing a lighter weight due to the exclusion of bar reinforcement. Also, its high strain capacity reduces the tendency for microcracks formation. The standard deviation error bars for the average flexural strengths of bendable concrete mixes with different fiber contents and types show no differences when comparing the same strength and fiber types. For example, mixes of 60 MPa with PVA fibers give less than 2 MPa standard deviation when compared for different fiber volume fractions.

1. Introduction

The loss of bendability in regular concrete is the main reason and motive behind the invention of engineered cementitious composite-bendable concrete. The presence of fibers in bendable concrete gives it its exceptional ability to bend. The hydrophilic nature and adequate flexibility of the polymeric fibers have been recognized with extremely high tensile strength for the mixes included in them [1]; the geometry, types, volumetric concentration, distribution, and fiber orientation in the matrix are the main features that mark the mechanical performance of the concrete composites [2]. The fiber inclusion causes an intensification in the micropores, less than 50nm, because it reduces the porosity and the pores larger than 50 nm [3]. Fiber is usually adopted to increase the toughness and the mechanical strength of brittle matrices [4] therefore, an adequate volume fraction of fiber can improve both the strength and the toughness of concrete [5], but the high volumetric concentration of fiber might lead to some complications in the dispersion of fiber in the cementitious matrix [6]. A good fiber and matrix bonding leads to more productive fiber load transfer, resulting in a stiffer composite and strongly enhanced flexural strength [7-9]. If the crack flaws can be locally limited from being prolonged to the adjacent matrix, the initiation of tension cracking can be controlled, and higher concrete tensile strength will be achieved; this can be accomplished by using fibers in the concrete matrix [10]. The superior bendability in bendable concrete eliminates their failure under tensile stress [11]. This behavior is

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due to the rise of the interfacial frictional and chemical bonds, which increases strain rates [12]. The higher ability of fibers to bridge the cracks, the fiber strength, and the fiber/matrix interface strength are major reasons for the ultimate tensile strength of bendable concrete [13]. Bendable concrete characterizes a ductile feature, which is more flexible and weightier than traditional concrete. The matrix, fiber, and fiber/matrix interface structures are deliberately planned to interact with one another in a precise prescribed style when the composite is loaded. This particular design basis is the reason behind its appellation, "Engineered Cementitious Composites - ECC." However, Controlling the fiber/matrix interface is critical to preserve ductility under a high loading rate [14,15].

The influence of continuous hydration on ECC's microscale and microstructure properties is the reason for the age dependence of the tensile strain capacity of ECC [16-18]. Increasing microcracks are formed throughout strain-hardening, whereas load capacity rises until the tensile strain capacity is exhausted. This happens after one of the multiple cracks develops a large crack because of the fiber bridging capacity loss on that crack plane [19]. The strain capacity of ECC may be defined as the maximum tensile strain at which concrete can endure without cracks continuously forming [20]. The tensile strain capacity of ECC ranges between (3-7) %, compared to 0.01% for ordinary Portland cement concrete; sudden excessive damage occurs when the strain exceeds this limit. Therefore, bendable concrete acts like a pliable material compared to the brittle nature of ordinary Portland cement concrete [21]. This research aims to investigate flexural strength behavior and the tensile strain capacity of bendable concrete by using two sorts of fibers, polyvinyl alcohol fibers (PVA) and polypropylene fibers (PP), with three different fiber percentages for each mix (1%,1.5%, and 2%) and three strength grades (30, 45 and 60) MPa. The mix design and proportions were based on the typical mix design applied by Professor Victor Li, the leader of the Michigan University team who invented the Engineered cementitious composite ECC [15].

The originality of the research lies in providing results concerning the flexural behavior of the bendable concrete mixes containing two types of polymeric fibers with different volume fractions and different strength levels. It also concerned evaluating the tensile strain capacity for different bendable concrete mixes and the effect of the fiber types and contents on it since the strain capacity of bendable concrete is considered the most relevant and important property for this type of concrete and is worth contemplating.

2. Experimental work

Engineered cementitious composite concrete mixes were designed according to Victor Li's typical mix [15]. Mixes details were tabulated in Table 2, and their proportions were reviewed in Table 3. Three strength levels were detected (30, 45, and 60) MPa, with three fiber volume fractions (1%, 1.5%, and 2%) for two types of polymeric fibers, polypropylene fibers PP and polyvinyl alcohol PVA fibers. The mixes were poured into their specific molds and cured in water at an ambient temperature of 21ºC until the age of testing. Six mixes of bendable concrete were applied to be tested for flexural strength (center point loading) according to the ASTM C293-02 [22] at ages 28, 60, and 90 days in water curing. The mixes were also conducted to be tested for tensile strain capacity after 28 days of water curing.

2.1 Materials

Portland cement type I (Ordinary Portland cement (OPC)) was used in this research; its physical and chemical characteristics confirmed the Iraqi specification [23]. The sieve analysis of Iraqi natural sand used in this research revealed that it lies in (zone 2). The fine aggregate's chemical and physical properties confirmed the Iraqi specification's requirements [24]. Silica fume was applied to this research as an essential constituent in refining the micropores, increasing the density and strength of the ECC concrete mixes. It has been added to the mix as a partial replacement by 10% of cement weight. It has been supplied from (Sika - Iraq) under the commercial name (CONMIX Mega Add MS (D)); it is a non-crystalline (amorphous phase) polymorph of silicon dioxide. Silica fume is an ultrafine powder collected as a by-product of silicon and ferrosilicon alloy production. It contains spherical particles with an average diameter of 150 nm and is used as pozzolanic material for high-performance concrete [25-28]. It acts chemically and physically as a highly reactive pozzolanic material to improve particle packaging of the concrete or mortar mixture and refine the microstructure pore size of concrete [13]. It has been physically and chemically tested and has a strength activity index (SAI) of 120%, which conforms to the requirements of (ASTM C 1240) [29]. Two types of fibers were used in this research (polypropylene fibers PP provided from Sika- Iraq, and polyvinyl alcohol fibers PVA which have been imported from China and are known as engineering mortar/concrete fibers; it has ionic coating to introduce chemical bond with the cement [21], the characteristics of the two fibers types are presented in Table 1. The superior characteristics of PVA fibers may reflect on the flexural properties of the bendable concrete mixes.

Table 1: 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

High-range water-reducing admixture HRWRA is an aqueous solution of adjusted polycarboxylates marketed under SikaViscocrete-5930; it was bought from Sika Company in Iraq and complies with (ASTM C-494) [30] types G and F requirements. It can obtain extreme water loss, superior flowability, and perfect cohesion [23]. Bendable concrete mixes also consist of Polyvinyl alcohol (PVA) solution, a synthetic polymer soluble in water and bio-degradable. It's a dry material that comes in both granule and powdered form and is considered a high-performance adhesive with exceptional bonding strength, film-forming, and emulsifying features [26]. It can be made in various ways, including hydrolysis and polymerization [27]. The PVA type (CDH) is partially hydrolyzed [28].

2.2 Mixes details

Six bendable concrete mixes were tested in this research; the main details of the mixes are tabulated in Table 2, while the mix proportions are tabulated in Table 3. The water-to-binder ratio for each mix is introduced in Table 2. The term binder refers to the weight of both cement and silica fume. Changing the fiber volume fractions (1%, 1.5%, and 2%) for both polypropylene and polyvinyl alcohol fibers aids in understanding the behavior of bendable concrete under the effect of flexural stress and in diagnosing the effect of these fibers on the strain capacity of the bendable concrete mixes. Also, changing the cement content in conjunction with the presence of fibers may affect the general tensile response of the bendable concrete mixes.

Table 2: Mixes Designation

Mixes	Targeted 28-compressive strength (MPa)	Fiber type	Fiber volume fraction %
30P	30	PP	1
30V	30	PVA	1
45P	45	PP	1.5
45V	45	PVA	1.5
60P	60	PP	2
60V	60	PVA	2

Table 3: Percentages of Mixes Proportions

Materials	30 MPa	45 MPa	60 MPa
cement	1	1	1
sand	0.8	0.8	0.8
SF*	0.1	0.1	0.1
SP*	0.013	0.015	0.02
PVAs*	0.01	0.01	0.01
w/b**	0.4	0.36	0.3
PP fiber	1%	1.5%	2%
PVA fiber	1%	1.5%	2%
Cement content (kg/m^3)	275	356	450

* PVA=polyvinyl alcohol solution **w/b= water to binder

2.3 Testing methods and standards

In this research, a flexural strength test (center point loading) is performed on (81) prism of (100×10×400 mm) according to ASTM C293-2002 [22] to test the effect of four variables (age, fiber volume fractions, fiber types, and strength levels) on the bendable concrete behavior. Curing age (28,60 and 90 days) for three fiber volume fractions (1%, 1.5%, and 2%) for both polypropylene and polyvinyl alcohol fibers and for three levels of strength (30, 45, and 60) MPa; the average of three specimens was tested for each variable. Also, the tensile strain capacity was applied for the (100×10×400 mm) prisms [19]. Cracking occurs when the tensile strain in concrete exceeds its tensile strain capacity. The load indicator stops recording when the first crack appears. At this point, the tensile strain is measured by a strain gauge with an accuracy of 0.01 mm; calculations are made to find the strain capacity. The specimens were applied for Inspect F50 FE- SEM to detect the micro-behavior of the different fiber types by using the scanning Electron Microscope Field Emission. All the tests in this research conformed to their related standards [29-34] as prescribed previously.

3. Results and discussion

3.1 Flexural strength test

The flexural strength behavior of bendable concrete mixes at 28 days of curing is presented in Table 4 using different fiber contents. Figure 1 shows the enhancement percentage in flexural strength when using PVA fibers compared to PP fibers, from which the maximum enhancement was (4.3%) for mix 30 MPa. Whereas for mix 45 MPa, the maximum enhancement in the flexural strength was (6%) and for the 60 MPa mix, the maximum enhancement in flexural strength was (23%). This behavior may be attributed to the excellent distribution of the fibers in the cement matrix, which is also related to the cement content in each mix. Mixes of 60 MPa produced with 2% PVA fibers show a higher enhancement in flexural strength. This behavior may be attributed to the adequate distribution of the PVA fibers in this mix due to its high cement content (450 kg/m^3) and the superior chemical bond between the matrix and PVA fibers. Mixes produced with PVA fibers have improved flexural strength behavior due to their better tensile ability than PP fibers. The flexural test results have diverged from the results obtained by

Al-Rhimy et al. [16] since they found that using polyethylene fibers in bendable concrete leads to flexural stress of (10 MPa) compared to the results of the current research (12.48 MPa) when using high strength bendable concrete mixes, these results in flexural test may be attributed to the higher fiber bridging capacity and higher strain capacity of the polyethylene fibers [21].

Table 4: The flexural strength of bendable concrete mixes with different fiber contents at 28 days

Strength (MPa)	PP fibers (%)			PVA fibers (%)			Cement content (kg\m^3)
	1	1.50	2	1	1.50	2	
30	9.46	8.7	7.95	9.54	9	8.33	275
45	9.6	9.8	10.1	10.21	10.33	10.43	350
60	9.8	10.97	12.48	12.1	12.48	14.37	450

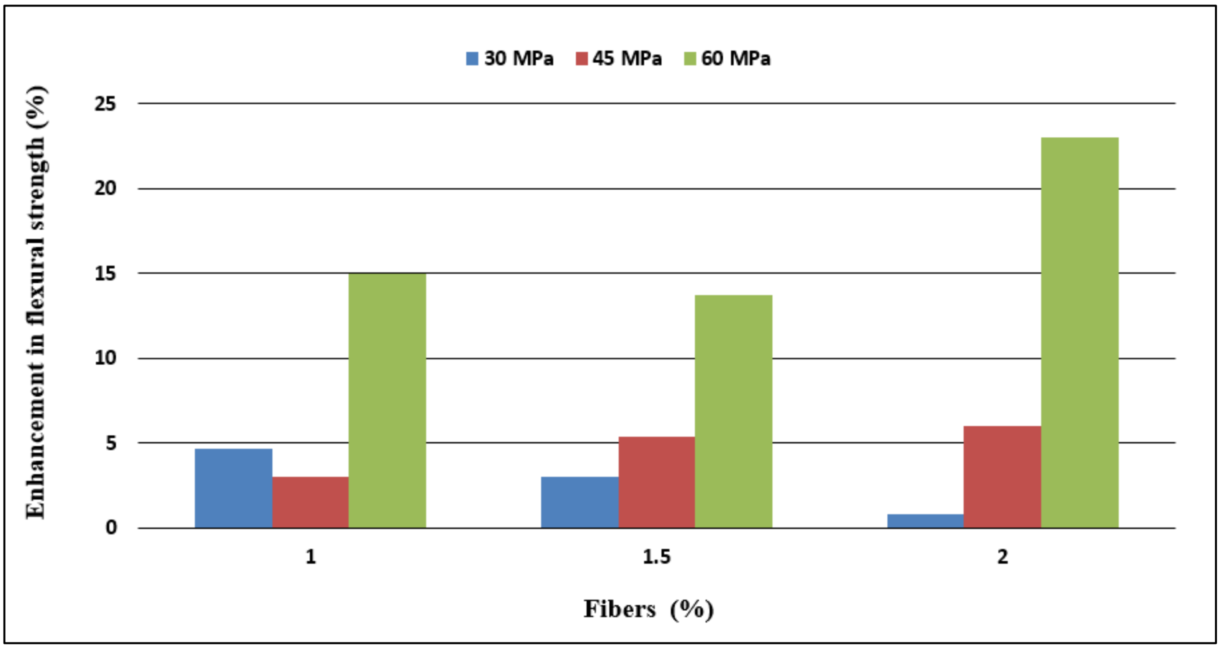

Figure 1: Enhancement percentage in flexural strength of bendable concrete mixes with PVA fibers compared to mixes with PP fibers

It can be noticed from Table 5 and Figure 2 that high-strength mixes (60 MPa) have shown an enhancement in flexural strength of about 33% and 50% for mixes 60P and 60 V compared to mixes 30P and 30V, respectively. This behavior is due to the higher percentages of fibers (2%) in the mixes of high strength compared to 1% fibers for normal strength concrete (these fiber fractions were adopted to achieve the best workability and flowability for each mix). Whereas mixes with polyvinyl alcohol fibers (PVA) show better behavior in flexural strength with time compared with mixes produced with polypropylene fibers (PP). This behavior can be explained due to the chemical bonding between PVA fibers and cement matrix. Additional bonding is provided by the ionic coating of the PVA fibers, which gives additional bonding to the matrix, enhancing the flexural behavior of the bendable concrete. The flexural behavior represented in Figure 2 may also be due to the effect of the fiber's tensile strength, 1620 MPa for PVA fibers, compared to 600 MPa for PP fibers. This characteristic is considered a determining factor to enhance the flexural strength behavior of the bendable concrete mixes.

The error bars of the standard deviation of flexural strength for different fiber contents with different levels of strength are presented in Figure 3, the bar charts represent the average flexural strength for each mix at 28 days. From this Figure, it can be noticed that there is an overlap between error bars in the mixes of the same strengths and fiber type, which means there are no huge differences between them when changing fiber contents. Also, it can be noticed that there is no overlap in error bars of standard deviation between different mixes, which means there are differences between them when using different fiber contents and types. Mixes of 60 MPa with polyvinyl fibers PVA show the highest flexural strength due to their high density, good fiber distribution, high tensile strength of PVA fibers, and adequate chemical and mechanical bond between PVA fibers and matrix. The potential sources of the errors in the data may result from the differences in the mix strength and the differences in the fiber types and fractions.

Table 5: Flexural strength results of bendable concrete with ages of curing

	Flexural strength, MPa, at age:		
Mix	28 (days)	60 (days)	90 (days)
30P	9.36	10.78	11.90
30V	9.54	11.20	12.70
45P	10.34	11.85	12.00
45V	11.70	13.40	14.67
60P	12.48	13.20	13.37
60V	14.37	15.00	15.62

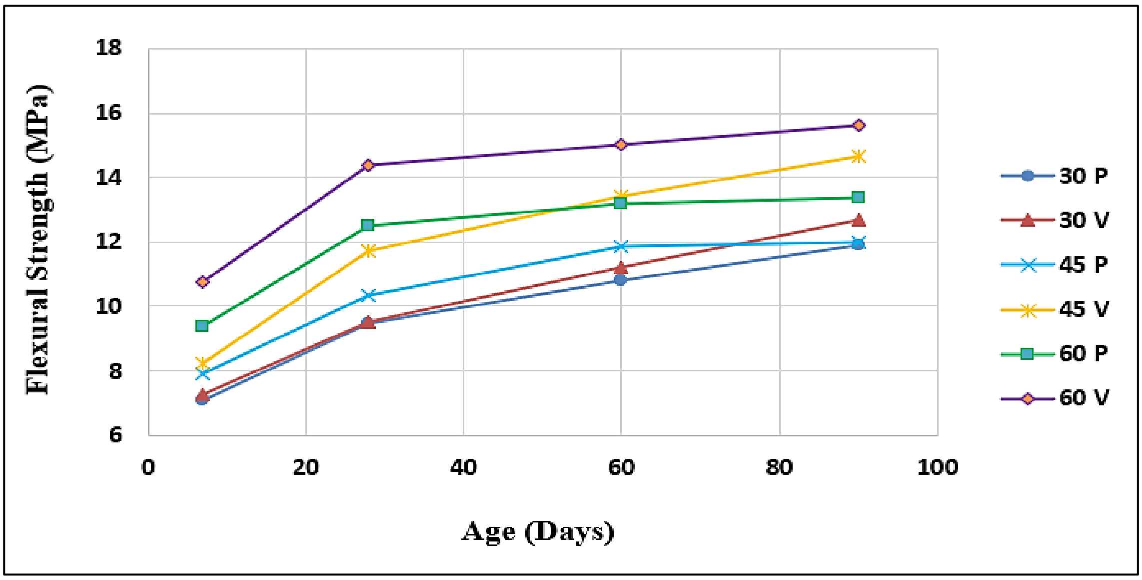

Figure 2: The relationship between the flexural strength of bendable concrete and the age of curing

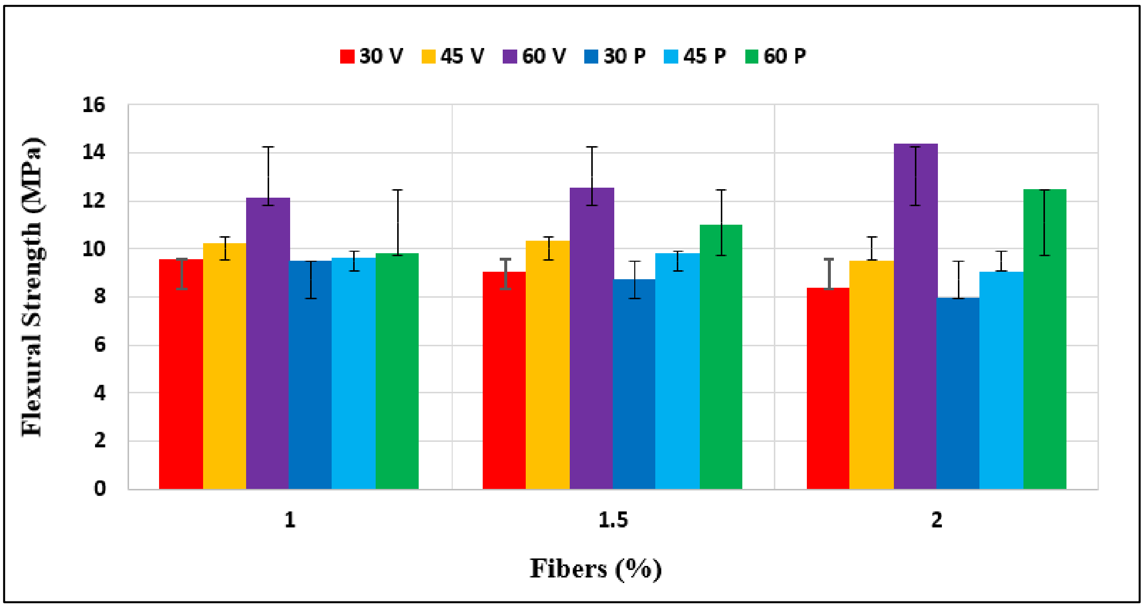

Figure 3: Error bars of Standard deviation of flexural strength for different fiber contents in bendable concrete mixes

3.2 Strain capacity of bendable concrete

The relation between the strain capacity of bendable concrete and polypropylene fiber percentages for each strength level is illustrated in Figure 4, it shows a reduction in the strain capacity for the mix of 30 MPa with the increase in fiber volume fraction. In contrast, the mixes of 45 MPa strength gained their maximum strain when using 1.5% of fibers. Mixes with 60 MPa strength give maximum strain capacity when using 2% fiber. This strain behavior of the three mixes (30, 45, and 60) MPa with fiber percentages is attributed to the cement content in these mixes, which affects the homogeneity and viscosity of the mixes. Mixing 30 MPa with 2% fiber reduces strain capacity due to its lower cement content, which may lead to substantial heterogeneity, poor dispersion, and inadequate bond strength between fibers and matrix. For mix 60 MPa, the higher cement content extends to the appropriate homogeneity, increasing strain capacity as the fiber increases and giving better bond strength between fibers and matrix. This qualification confirms Yang et al.'s [31] conclusion that the fiber distribution in the specimen's cross-section shows a strong correlation between increasing tensile strain capacity and enhancement of fiber dispersion. They also revealed that the fibrous matrix needs enough paste content to achieve a good covering and better bond on interfaces.

The tensile strain capacity increases when using 2% polymeric fibers for 60 MPa and 45 MPa strength grades, as shown in Figure 5. This behavior may be ascribed to the cement content, which provides an adequate coating to the fibers and increases the bonding force with the fibers. Results revealed an enhancement in the mechanical properties when using polyvinyl alcohol (PVA) fibers since they make a robust and convenient bond with the cementitious matrix due to their geometric characteristics and hydrophilic nature. Furthermore, the distribution of PVA fibers in the matrix was remarkably homogeneous due to their excellent dispersion. The surface coating of PVA fibers allows them to slip when overloaded so they are not fractured. It prevents the fiber from rupturing, which would lead to extensive cracking. Thus, bendable concrete deforms much more than normal concrete but without fracturing [18].

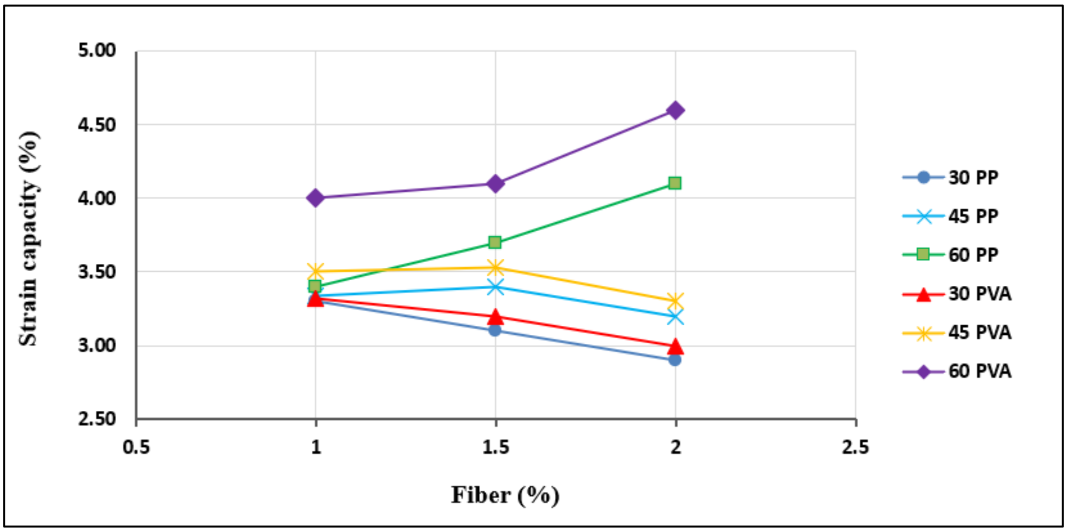

Figure 4: Strain capacity with different fiber contents and types

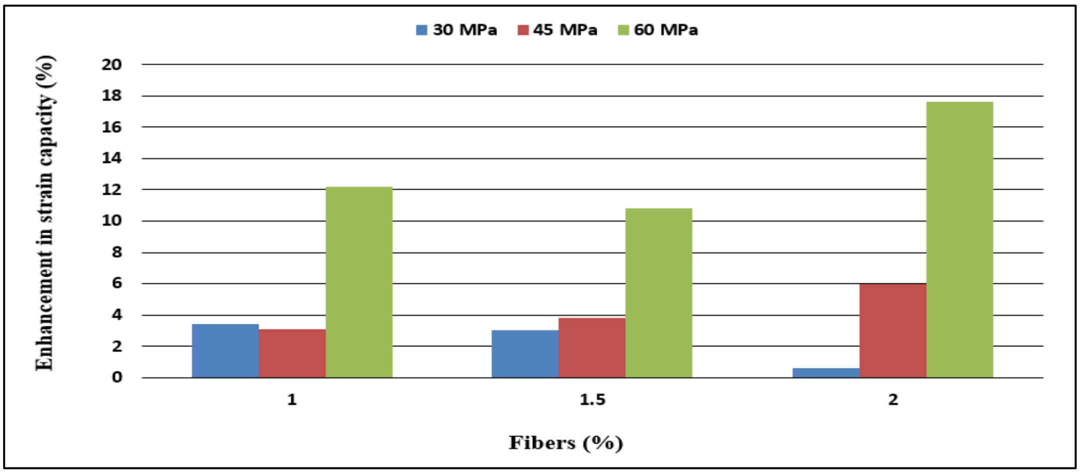

Figure 5: Enhancement, percentage of strain capacity of bendable concrete mixes with PVA fiber compared to bendable concrete mixes with PP fibers

3.3 Field emission of scanning electron microscope (FE-SEM)

The previous results revealed that the use of PVA fibers in bendable concrete enhances its flexural strength and its strain capacity due to the virtuous chemical bond between PVA fibers and the bendable concrete matrix since it is coated with an ionic coating, compared to the polypropylene fibers bonding with bendable concrete mix. Figure 6 and Figure 7 introduce a microscopic image of the bond of the PVA fibers with the matrix and the bond between PP fibers and the matrix.

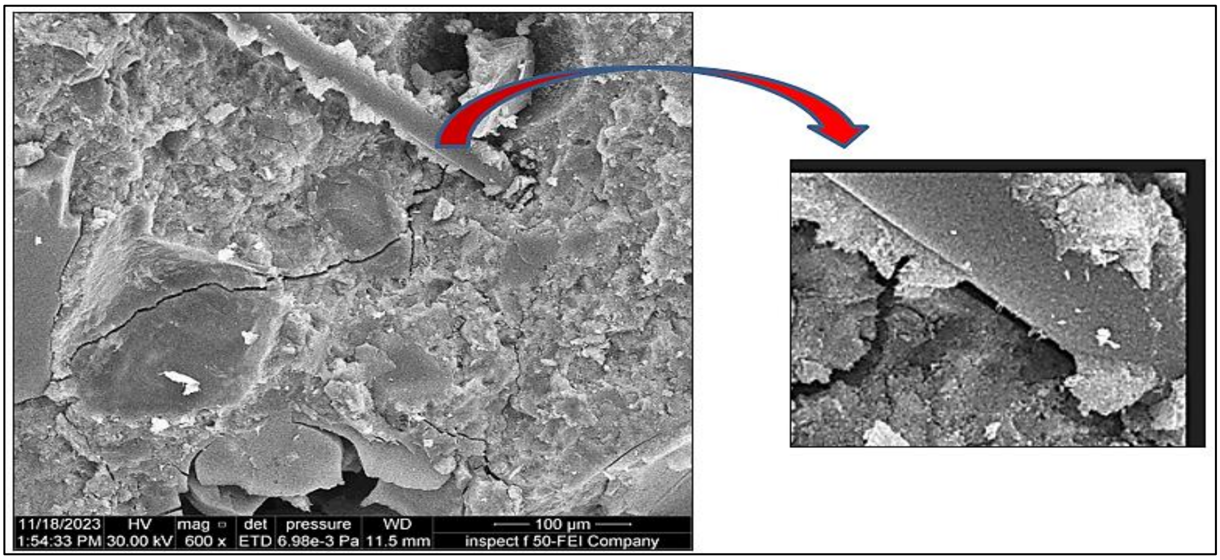

Figure 6: SEM for polyvinyl alcohol (PVA) fiber combined with the cement matrix, right image magnified 1200 x

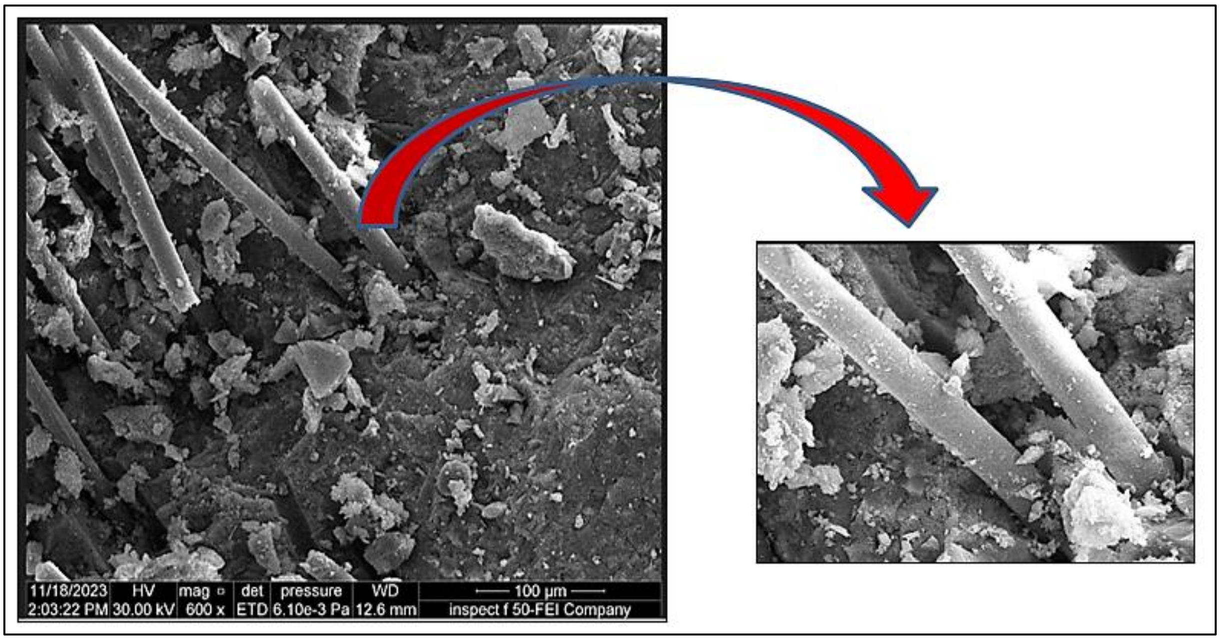

Figure 7: SEM for polypropylene (PP) fibers with the cement matrix, there is no chemical combined between them, right image magnified 1200 x

4. Conclusion

The current study supports the following conclusions:

1) Higher cement content in the high-strength mixes leads to appropriate homogeneity, which increases strain capacity as the fiber increases and gives better bond strength between fibers and matrix; this behavior is evident in mixtures of 60 MPa with 450 kg/m^3 cement content.
2) Due to chemical reactions, additional bonding between the fibers and matrix could be provided by the ionic coating of the PVA fibers, which enhances the flexural behavior of the bendable concrete. The SEM test results support this behavior.
3) The higher tensile strength of PVA fibers (1620 MPa) enhanced flexural behavior and compressive strength, especially in high-strength mixes, which give (14.37 MPa) in flexural strength compared to (8.33 MPa) for normal-strength concrete.
4) The best behavior in both flexural and strain capacity was gained when using polyvinyl alcohol (PVA) fibers in a mix of 60MPa strength due to their high density, a good bond between fibers, and matrix lower porosity due to the lower W/C ratio.
5) The enhancement percentages in tensile strain capacity were 4.6%, 6%, and 17.6% for mixes 30 MPa, 45 MPa, and 60 MPa, respectively, when using PVA fibers compared to PP fibers.

6) In bendable concrete mixes containing polyvinyl alcohol (PVA) fibers, the best fiber content to achieve higher strain capacity and flexural strength was 2%.
7) The Field emission SEM images support the acquired results and the fiber's behavior within the matrix.

Author contributions

Conceptualization: I. Ahmed, T. al-attar and A. Al-Ameeri, methodology: I. Ahmed, validation: T. Al-attar and I. Ahmed, investigation: I. Ahmed, resources: I. Ahmed, writing-original draft preparation: I. Ahmed and T. al-attar, writing- review and editing: T. Al-Attar, visualization: T. Al-Attar, supervision: T. Al-Attar, and A. Al-Ameeri. All authors have read and agreed to the published version of the manuscript.

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Data availability statement:

the data supporting this study’s findings are available on request from the corresponding author.

Conflicts of interest

The authors of the current work do not have conflicts of interest

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