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Research Article

Long-Term Drying Shrinkage Strain of Engineered Cementitious Composite Concrete Contains Polymeric Fibers

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The lack of concrete tensile stress endurance led to the invention of engineered cementitious composite. However, the absence of gravel from the mixture in addition to the high binder content may lead to high shrinkage strain. Therefore, a radical solution to this problem is worth to be anticipated. The importance of this research lies in investigating the long-term drying shrinkage strain of the engineered cementitious composite since there is a lack of information regarding this behavior. Mixes of 30 and 60 MPa strengths were produced with polyvinyl alcohol fibers PVA-ECC and polypropylene fibers PP-ECC. The drying shrinkage strain of PVA-ECC mixes has been compared to PP-ECC mixes for both short term (0–28 days) and long term (0–360 days). Results indicated that all PVA-ECC mixes exhibited lower drying shrinkage strains than PP-ECC mixes. The ultimate drying shrinkage strain was recorded to be 1200 microstrain at 28 days. The increment in drying shrinkage strain after 28 days was 5.6% in PVA-ECC mixes when compared to that in PP-ECC mixes which was 6.77%. For high strength levels, the drying shrinkage strain at the age of 360 days declared a reduction of 3.5% for PVA-ECC compared to PP-ECC mixes. Also, it was lower for mixes with 60 MPa (6.3%) than for mixes with 30 MPa (7.6%). Therefore, despite the higher cement content for mixes with 60 MPa strength, the higher fiber volume fraction and the higher PVA solution percentage restricted the drying shrinkage strain increment. The research also addresses some mechanical tests of engineered cementitious composite concrete such as compressive strength, flexural strength, and strain capacity that may provide a strong relation to the drying shrinkage behavior of the different mixes. The scanning electron microscope images were involved in this research to declare the impact of fiber types on the microstructure of the ECC mixes.

1. Introduction

Polymers used in cement composite modification are widespread due to their contribution in enhancing the materials' properties. Topica et al. [1] declared that adding polyvinyl alcohol solution PVA into a cement paste can adjust the Silicon-Oxygen chains morphology and diminish the porosity. Under several weather conditions, the hydrothermal weather properties of the cementitious composite material containing polyvinyl alcohol fibers were studied by Li et [2]. The study exhibited that fibers are not markedly degraded when exposed to natural weathering, and the products of PVA fiber-cement may considered durable. The reason behind the engineered cementitious composite ECC drying shrinkage is the absenteeism of the coarse aggregates, which acts as a restraining factor for cement internal shrinkage. This fact was intensely investigated by Al-Attar et al. [3], by examining the effect of coarse aggregate characteristics (shape, type, moisture content, and surface texture) on unrestrained shrinkage of concrete especially in hot climates. Large differences in relative shrinkage for different mixes at early ages, less than 28 days, were revealed by Al-Attar [4]. Al-Rihimy et al. [5] declared that the Iraqi ambient temperature displays a large variation between day and night reaching 20°C depending on the season, whether it is winter or summer. For this purpose, they studied the effect of these conditions on the drying shrinkage. The drying shrinkage is measured for

6 months after 7 days in water curing, for outdoor ambient temperature varies from −4 to +39°C and the relative humidity ranges from 15 to 60%; results were compared to those of specimens kept in the shrinkage chamber, under controlled temperature of 21°C and relative humidity of 35%. It was concluded that, due to the irreversible nature of shrinkage strain, the drop in ambient temperature and the rise of atmosphere moisture or relative humidity would not reverse the shrinkage strain [5]. Moreover, higher cement content in ECC results in a higher shrinkage magnitude. Experimental studies showed a high value of ECC drying shrinkage that may exceed that of normal concrete by two to three times [2]. Numerous techniques may be implemented to overcome the shrinkage tendency. Zhang et al. [6] presented that replacing Portland Cement (Type 1) with low-shrinkage cement makes it probable to reduce the ECC drying shrinkage to a limit lower than that of normal concrete. Likewise, Yang et al. [7] described ECCs with a shrinkage near the normal concrete upper range, achieved by using a large fly ash amount. Sahmaran et al. [8] recommended the use of an internal curing agent to overcome early age drying shrinkage and autogenous shrinkage. Ikram et al. [9] reported that using bendable concrete produced from Portland limestone cement is conceivable and introduces sensible compressive and flexural strength results, in addition to a lower drying shrinkage strain when compared to Ordinary Portland cement. It is possible to use locally manufactured Portland limestone cement (IL) in making engineered cementitious composite concrete with adequate mechanical properties [10]. Sara et al. [11] discovered a reduction in drying shrinkage strain when using Portland limestone cement (IL), in addition to the availability of PVA acetate, which improves the bonding strength. Also, the presence of PP fibers acts as a bridge between matrix, fiber, and matrix/fiber interface, making the concrete more durable and stronger. According to the previous clarification, the bonding strength and the microstructure of the concrete were enhanced leading to a reduction in the drying shrinkage compared to reference mixes. Adeyemi et al. [12] determined that the 2% PVA fiber content is adequate to prevent any cracks resulting from shrinkage in ECC mixtures. Donatas et al. [13] revealed that PVA fibers that have high modulus of elasticity may decrease the crack width and consequently reduce the drying shrinkage. Sara Saed et al. [14] displayed that the use of two types of Portland limestone cement, Karasta (CK) and Tasluja (CT) PLC, leads to a reduction in drying shrinkage and creep due to the chemical composition of the two types of the cement and the calcium carbonate percent added to the clinker; therefore, less clinker/cement ratio gives lower creep and shrinkage. The high cementitious material content in engineered cementitious composite concrete makes it suffer from drying shrinkage strains intensively. Many drying shrinkage types of research focus on the short-term drying shrinkage test while exploring the long-term drying shrinkage strain is still enigmatic. This research aims to investigate the long-term drying shrinkage strain in a controlled chamber under 21°C temperature and 40% relative humidity. Six engineered cementitious composite concrete mixes with two 28-day-strength levels, 30 and 60 MPa, and with two types of polymeric fibers, polypropylene PP and polyvinyl alcohol PVA fibers, were tested for drying shrinkage till the age of 365 days.

2. Significance of the Study

The significance and novelty of this research lie in the exploration of the long-term drying shrinkage behavior of engineered cementitious composite concrete (Bendable concrete) from one side and the role of the two different types of polymeric fibers, PP which is a hydrophobic fiber and PVA which is a hydrophilic fiber, in controlling the progress of the drying shrinkage with time from another side. The results submitted in this paper are worth contemplating since they will provide new data of study for a recently invented concrete type (Bendable Concrete).

3. Materials and Methods

Engineered cementitious composite (Bendable) Concrete used in this research is composed of Type I cement (ordinary Portland cement OPC), ASTM C150 [15], with two cement contents: 275, and 450 kg/m^3, for 28-day compressive strength of 30 MPa and 60 MPa, respectively. Polyvinyl alcohol (PVA) solution was used to reduce the porosity and enhance the engineered cementitious composite density [16]. Fine aggregate (sand) with fineness modulus (2.7) conformed to the ASTM C33-08 [17]. Silica fume with an activity index of 120% was adopted; it is prepared according to ASTM C-1240 [18]. It was used as a partial replacement of cement by about 10% of cement weight. The role of silica fume in the mix appears as it affects the arrangement of the cement paste microstructure and its interfacial transition zone [11, 19]; its replacement with the cement may reduce the drying shrinkage strain. The characteristics of polypropylene fibers PP and polyvinyl alcohol fibers PVA are shown in Table 1. No coarse aggregate was used in the production of engineered cementitious composite concrete because coarse aggregates tend to increase the crack width, which contradicts the property of bendable concrete [2]. The absence of coarse aggregate causes the engineered cementitious composite concrete to suffer from high drying shrinkage strain because the coarse aggregate is the element that restricts the drying shrinkage of concrete [20]. Polyvinyl alcohol, PVA, solution was added to a cement matrix to enhance its performance since it can affect water retention and its workability in the fresh mixing state. Fibers are used in engineered cementitious composite concrete to restrict the propagation of microcracks and reduce the drying shrinkage strains. Therefore, making a comparison of the behavior of engineered cementitious composite concrete with two types of polymeric fibers (polypropylene fibers and polyvinyl alcohol fibers) is worth contemplating. Polypropylene fibers are hydrophobic materials, while polyvinyl alcohol fibers are hydrophilic materials; therefore, they are coated with an ionic chemical film; this film may react chemically with the cement matrix and provide additional bonding. A drying shrinkage test was performed on a prism

Table 1: Characteristics of polymeric fibers.

Characteristics	PVA	PP
Elongation (%)	6	10
Length (mm)	12	12
Diameter (μm)	39	32
Aspect ratio (L/d)	30.8	100.0
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

of 78 × 78 × 380 mm which was arranged according to ASTM C192/192M [21], and an average of three specimens for each mix was taken. For the long-term drying shrinkage (age of 360 days), the behavior of concrete was tested according to ASTM C 157/C157M [22].

4. Mix Proportions

Four ECC concrete mixes were used in this research, their proportions (by cement weight) are presented in Table 2, and the specifications of the used chemical admixtures conformed to the ASTM C-494 [23]. The practice for making and curing concrete test specimens in the laboratory conformed to the ASTM C-192 [21]. Table 3 reveals the symbols of the used mixes.

Table 2: ECC concrete mix proportions.

Materials	28-d compressive strength (MPa)	
	30 MPa	60 MPa
Cement content (kg/m^3)	275	450
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 3: Details of the used mixes.

Mixes	Target compressive strength (MPa)	Fiber type	Fiber (%)
30 PLAIN	30	—	—
60 PLAIN	60	—	—
30P	30	Polypropylene	1
30V	30	Polyvinyl alcohol	1
60P	60	Polypropylene	2
60V	60	Polyvinyl alcohol	2

5. Results and Discussion

5.1. Effect of Fiber Type on Drying Shrinkage Behavior. The drying shrinkage strain of the ECC concrete mixes was measured under controlled temperature (21°C) and relative humidity (32%). The short-term drying shrinkage was recorded till 28 days, from which the mixes containing PVA fibers had lower drying shrinkage strains compared to the mixes containing PP fibers; both mixes showed lower drying shrinkage than their related reference mixes. The reason behind this behavior is related to the properties of PVA fibers, which are a hydrophilic material that tends to retain the mixing water of the mix for a longer period than polypropylene fibers which are hydrophobic materials. Also, the ionic coating of the PVA fibers provided a good chemical bonding with the matrix compared to PP fibers; the scanning electron microscopy (SEM), Figures 1 and 2, support this conclusion. Another explanation for this behavior is that a higher PVA fiber modulus of elasticity than that of PP fibers reduces the drying shrinkage strain. This behavior conforms with the results of Donatas et al. [13], who reported that PVA fibers with a high modulus of elasticity might reduce the crack width and reduce the drying shrinkage. Results displayed that a denser layer of hydration products was formed around the PVA fibers and the amount of the formed portlandite and C-S-H gel was higher around the PVA fibers, as shown in Figure 1. The composite shrinkage is physically limited due to the adhesion between the matrix and PVA fibers. Fibers increase the composite's tensile strength, reducing the potential for cracking and shrinkage.

5.2. Short- and Long-Term Drying Shrinkage Results. The normal concrete drying shrinkage strain ranges between (200–600) $* 10^{-6}$ [2]. The short-term strain for ECC concrete mixes till the age of 28 days of testing is two to three times that of normal concrete. The results of this research are represented in Table 4 and Figure 3. The long-term drying shrinkage behavior till one year of results reading is introduced in Figure 4, from which it can be noticed that the rate of drying shrinkage strain after 28 days of testing becomes lower till the end of the testing period (360 days).

Generally, after 28 days of testing, high-strength concrete (60 MPa) records a lower percent increment in drying shrinkage readings than normal-strength concrete (30 MPa) (Table 5); this behavior may be attributed to many reasons such as the higher density, the lower w/b ratio, and the higher PVA solution which increases the viscosity and reduces the porosity of the high strength mixes and also due to the higher fibers volume fraction in the high strength mixes.

The error bars of the standard deviation of the drying shrinkage results with time are presented in Figure 5, from which it can be noticed that there is an overlap between the same mixes with time which means there are no huge differences between them. When comparing different mixes, no overlaps can be noticed; this means that there is a difference in the results between the different mixes with time. Many researchers [2, 6, 13, 14] studied the drying shrinkage behavior for up to 28 days; since the long-term drying shrinkage is worth contemplating, this research studied the drying shrinkage behavior after 28 days to 360 days, Figure 4. The percentage of increment in drying shrinkage strain

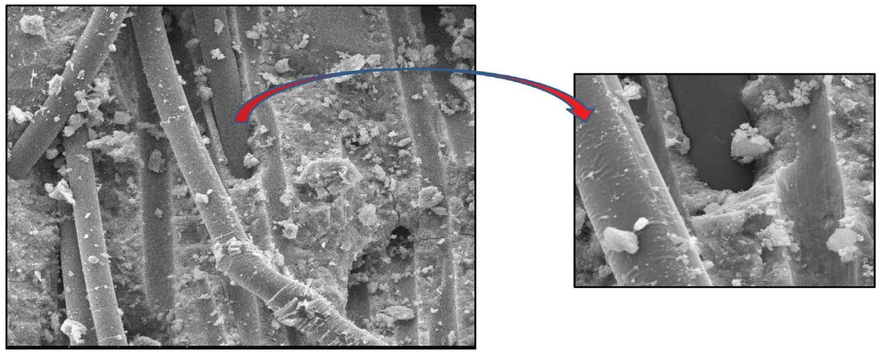

Figure 1: SEM for 30 V mix, an interface between PVA fibers and cement matrix at 1200x magnification.

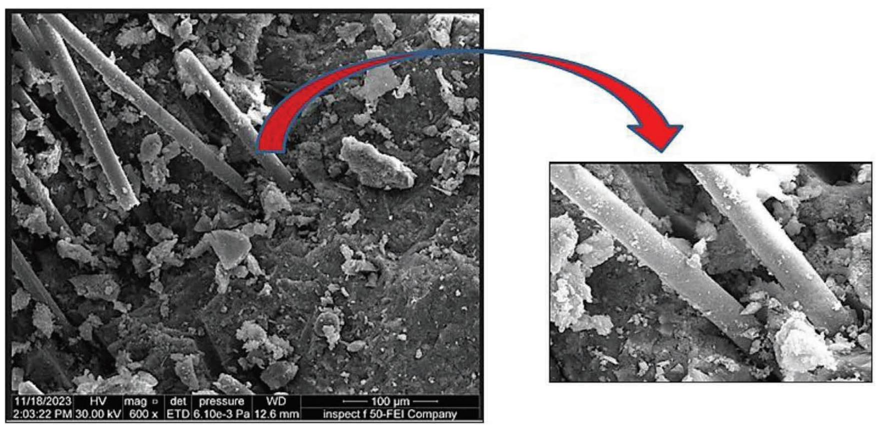

Figure 2: SEM for 30 P mix, an interface between PP fibers and cement matrix at 1200x magnification.

Table 4: Drying shrinkage strain for ECC concrete mixes.

Age days	Drying shrinkage strain $\times 10^{-6}$					
	30 PLAIN	30 PP	30 PVA	60 PLAIN	60 PP	60 PVA
0	0	0	0	0	0	0
1	150	123	138	139	109	97
2	464	389	377	412	245	176
3	557	523	531	539	470	212
4	689	674	774	680	576	424
5	897	886	879	891	641	653
6	991	952	947	973	773	798
7	1078	1000	1000	1054	946	991
14	1162	1148	1135	1156	1068	1087
28	1233	1211	1201	1227	1174	1146
32	1243	1224	1209	1235	1193	1158
39	1265	1245	1215	1251	1208	1160
45	1278	1251	1223	1264	1210	1168
60	1288	1258	1230	1267	1216	1171
75	1300	1262	1235	1284	1220	1176
90	1310	1265	1241	1298	1228	1181
105	1318	1269	1249	1304	1231	1189
120	1327	1270	1256	1311	1239	1193
150	1346	1275	1263	1324	1245	1206
180	1359	1277	1270	1335	1249	1214
240	1378	1281	1278	1342	1252	1224
360	1384	1288	1278	1350	1255	1230

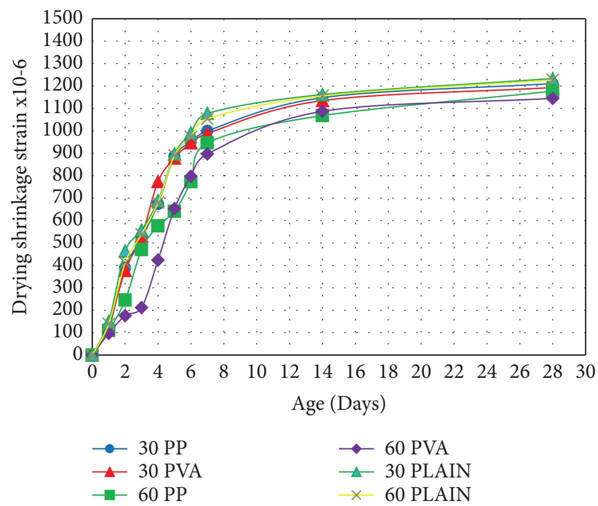

Figure 3: Drying shrinkage strain at the age of 28 days for ECC mixes.

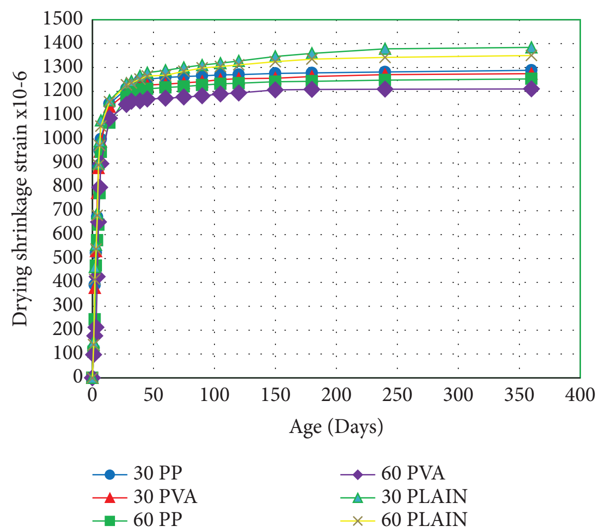

Figure 4: Long-term drying shrinkage for different ECC mixes.

Table 5: Percentage of increment in drying shrinkage strain after 28 days.

Age	30 PP	30 PVA	60 PP	60 PVA	30 PLAIN	60 PLAIN
32	3.067993	1.760268	1.359388	1.135371	0.81103	0.651997
39	3.482587	2.347024	2.633815	1.310044	2.595296	1.95599
45	3.731343	2.766136	2.803738	2.008734	3.649635	3.015485
60	4.311774	3.101425	3.313509	2.270742	4.460665	3.259984
75	4.643449	3.520536	3.653356	2.707424	5.433901	4.645477
90	4.892206	4.02347	4.163127	3.144105	6.244931	5.786471
105	5.223881	4.694049	4.587935	3.842795	6.893755	6.275469
120	5.472637	5.029338	4.842821	4.19214	7.623682	6.845966
150	5.721393	5.196982	5.352591	5.327511	9.164639	7.90546
180	6.55058	5.783738	5.522515	5.502183	10.21898	8.801956
240	7.048093	6.454317	5.947324	5.58952	11.75994	9.372453
360	7.628524	6.789606	6.372133	5.676856	12.24655	10.02445

compared to 28 days strain is reviewed in Figure 6. It can be noticed that the high-strength mixes gave a lower percentage increment in drying shrinkage (5.67%) than normal-strength mixes (6.879%). Furthermore, using PVA fibers in the engineered cementitious composites reduces the percentage of increment in drying shrinkage strain.

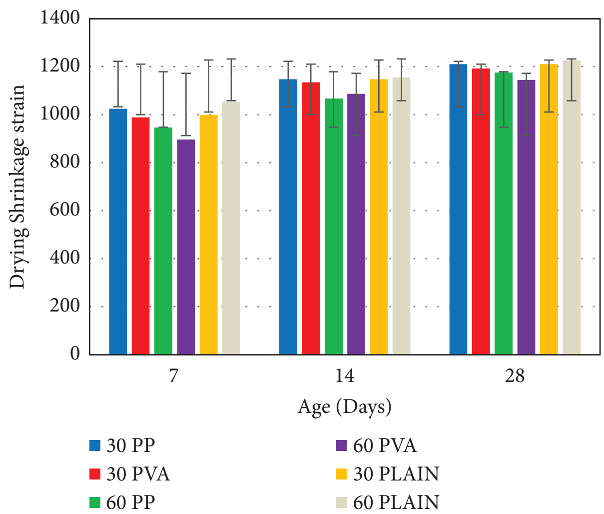

Figure 5: Error bars of the standard deviation of drying shrinkage strain with time.

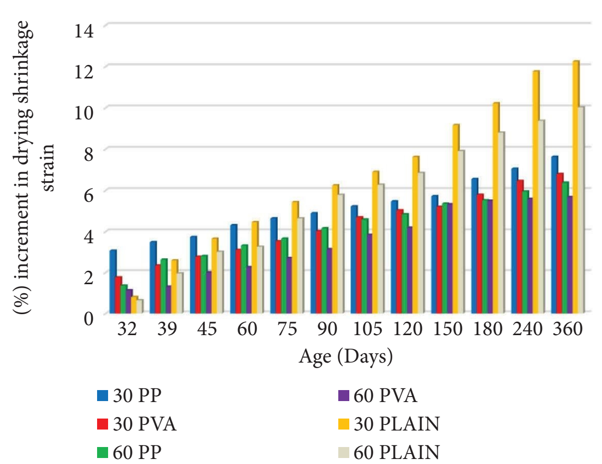

Figure 6: Percentage of increment in drying shrinkage strain after 28 days of testing for all mixes.

The reduction percentage in drying shrinkage strains, as introduced in Figure 7, was 1.5% for 30 MPa mixes and 2.7% for 60 MPa mixes at 28 days age of testing and reached 1.85% for 30 MPa mixes and 3.4% for 60 MPa mixes after 360 days of testing. This behavior is related to the PVA properties and the high-strength characteristics of the engineered cementitious composite. The presence of PVA solution helps to increase the bond strength, and the existence of the polymeric fibers acts as a bridge between the matrix, fiber, and matrix/fiber interface, which results in stronger and more durable concrete [2]. The earlier explanation acknowledged that the microstructure and the bonding strength of the engineered cementitious composite concrete were enhanced when using PVA solution and polymeric fiber.

5.3. Reduction in Drying Shrinkage Strain Using Polymer Fibers. The fear of drying shrinkage in ECC comes from the fact that ECC does not contain coarse aggregates which perform as internal restraints on cement shrinkage. In addition, a higher shrinkage magnitude may be expected for ECCs with higher cement content. Free drying shrinkage measurements are a function of drying time and relative humidity [2]. The use of polymeric fibers restrains the microcracks and reduces the tendency of ECC to suffer drying shrinkage strains.

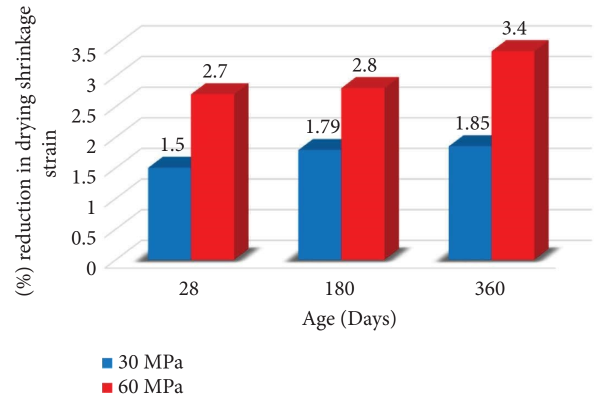

Figure 7: Percentage reduction in drying shrinkage strain when using PVA fibers compared to PP fibers.

The maximum % reduction in drying shrinkage when using polymeric fibers compared to the reference mixes was about 18.75 and 16.16% for PVA and PP fibers, respectively, in normal-strength mixes (30 MPa), Figure 8 and Table 6. It was about 57 and 40.5% for PVA and PP fibers, respectively, in the high-strength mixes (60 MPa), Table 7 and Figure 9. This behavior is due to the high density, high fiber volume fraction, high modulus of elasticity of the PVA fibers, high percentage of PVA solution, higher silica fume ratio, and the higher ability of PVA fibers to retain the water since they are a hydrophilic polymer.

5.4. Mechanical Tests and Results. The recent research conducted a flexural strength (center point loads) test, it was adopted on a prism of (100 × 10 × 400 mm), and the test was implemented according to ASTM C293/2002 [24]. Tensile strain capacity for a prism of (100 × 10 × 400 mm) was also implemented in this research [25]. When the tensile strain of the concrete exceeds its tensile strain capacity, cracking occurs. From Figure 10, tensile strain capacity increases by using 2% polymeric fibers; this performance may be related to the cement content, which delivers satisfactory coating to the fibers, hence increasing the bond with the fibers. Results discovered an enhancement in the mechanical properties when using polyvinyl alcohol (PVA) fibers since they make a robust and suitable bond with the cementitious matrix; this behavior could be due to their characteristics and hydrophilic nature. Moreover, the distribution of PVA fibers in the matrix was homogeneous due to their admirable dispersion. Thin film surface coating of PVA fibers permits them to slip when loaded so they are not fractured, and that will prevent the rupturing of fiber, which would cause widespread cracking, Figure 1. Consequently, bendable concrete deforms much more than normal concrete but without fracturing [26].

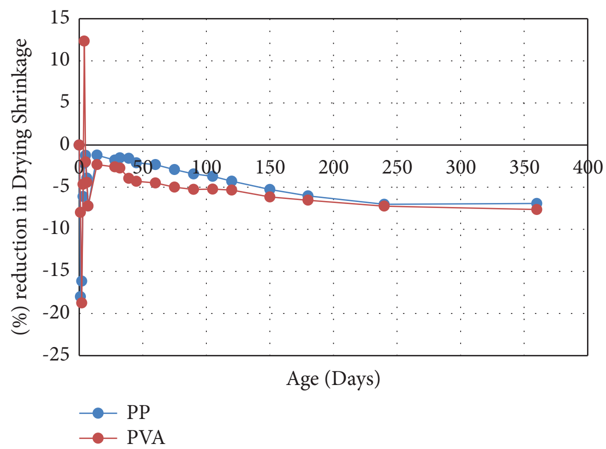

Figure 8: Percentage of reduction in drying shrinkage for 30 MPa mixes compared to the reference mix.

Table 6: Reduction percentage in drying shrinkage compared to the reference mix for 30 MPa.

Age	PP	PVA
0	0	0
1	−18	−8
2	−16.1638	−18.75
3	−6.10413	−4.66786
4	−2.17707	12.33672
5	−1.22631	−2.00669
6	−3.93542	−4.43996
7	−7.23562	−7.23562
14	−1.20482	−2.32358
28	−1.78427	−2.5953
32	−1.52856	−2.73532
39	−1.58103	−3.95257
45	−2.11268	−4.3036
60	−2.32919	−4.50311
75	−2.92308	−5
90	−3.43511	−5.26718
105	−3.71775	−5.2352
120	−4.2954	−5.35041
150	−5.27489	−6.16642
180	−6.03385	−6.54893
240	−7.03919	−7.25689
360	−6.93642	−7.65896

From Figure 11, it can be observed that high-strength mixes showed an enhancement in flexural strength of about 33% and 50% for mixes 60 PP and 60 PVA in comparison to mixes 30 PP and 30 PVA, respectively. This performance may be due to the higher fiber percentage (2%) compared to 1% fibers for normal-strength concrete (fiber fractions were implemented to attain the best workability and flowability for the mixes). On the other hand, mixes with polyvinyl alcohol fibers (PVA) show better behavior in flexural strength with time compared with mixes produced with polypropylene fibers (PP), due to 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 11 may be due to the effect of the fiber's tensile strength, 600 MPa for PP fibers compared to 1620 MPa for PVA fibers. The mechanical behavior of the ECC concrete mixes conformed with Al-Mulla et al. [27]. It introduces a broad explanation for the drying shrinkage behavior of the mixes, as it can be seen that the mixes contain PVA fibers show lower drying shrinkage, due to their higher flexural strength and higher strain capacity.

Table 7: Reduction percentage in drying shrinkage compared to the reference mix for 60 MPa.

Age	PP	PVA
0	0	0
1	−21.5827	−30.2158
2	−40.534	−57.2816
3	−12.8015	−60.6679
4	−15.2941	−37.6471
5	−28.0584	−26.7116
6	−20.555	−17.9856
7	−10.2467	−5.97723
14	−7.61246	−5.96886
28	−4.31948	−6.60147
32	−3.40081	−6.23482
39	−3.43725	−7.27418
45	−4.27215	−7.59494
60	−4.02526	−7.57695
75	−4.98442	−8.41121
90	−5.39291	−9.01387
105	−5.59816	−8.81902
120	−5.49199	−9.00076
150	−5.96677	−8.91239
180	−6.44195	−9.06367
240	−6.70641	−8.79285
360	−7.03704	−8.88889

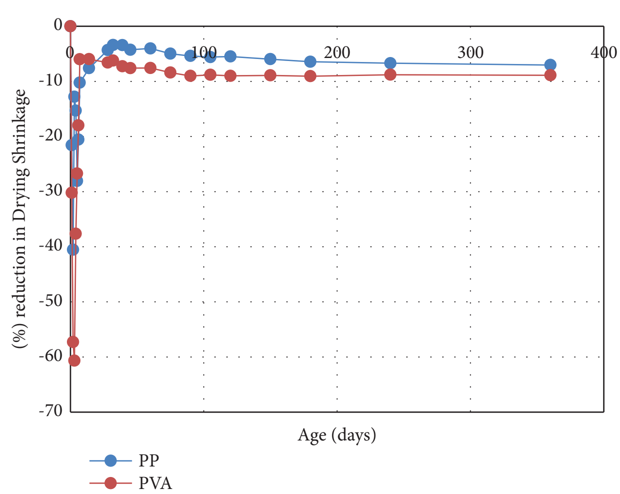

Figure 9: Percentage of reduction in drying shrinkage for 60 MPa mixes compared to the reference mix.

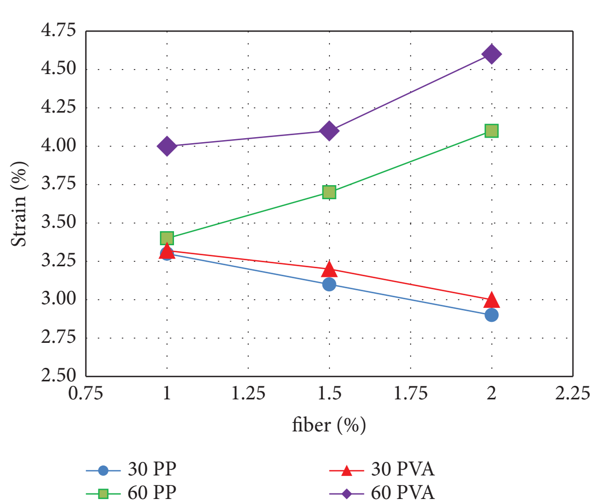

Figure 10: Strain capacity with different fiber contents and types.

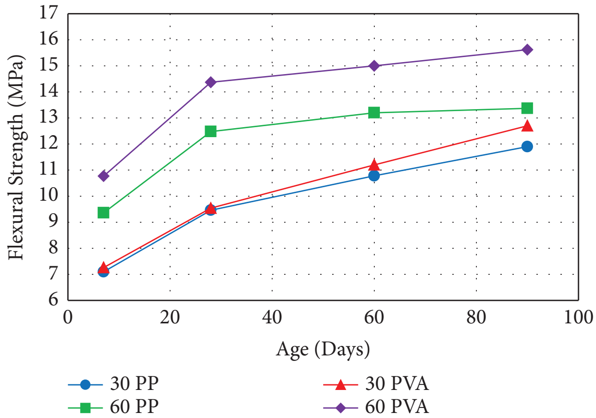

Figure 11: Flexural strength of bendable concrete and the curing age.

6. Conclusions

By studying the drying shrinkage behavior of different engineered cementitious composite concrete mixes, the following conclusions can be deduced:

(1) Mixes with PVA fibers show lower drying shrinkage strain than those containing PP fibers, and the use of polyvinyl alcohol solution enhances the mix viscosity and reduces its porosity, thus reducing the drying shrinkage strain. This behavior was supported through the SEM images.

(2) Studying the long-term drying shrinkage behavior to 360 days of testing revealed that high-strength engineered cementitious composite shows a lower increase in drying shrinkage behavior.

(3) The maximum percentage of reduction in drying shrinkage behavior was 3.4% when using mixes of 60 MPa with PVA fibers compared to mixes with PP fibers and 1.85% when using mixes of 30 MPa with PVA fibers compared to mixes with PP fibers.

(4) The high PVA fiber's tensile strength provides a high ECC concrete flexural strength and strain capacity and a reduction in the drying shrinkage strain, compared to that of mixes with PP fibers.

Data Availability

The data used to support the findings of this study are included within the article.

Ethical Approval

This work did not report on or involve the use of any animal or human data or tissue.

Disclosure

The funder was involved in the manuscript writing and publishing.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Authors' Contributions

Ikram Faraoun Al-Mulla conceived the study and curated the data. Ikram Faraoun Al-Mulla and Dr. Tareq Al-Attar contributed to the formal analysis, investigated the study, wrote the original draft of the manuscript, and reviewed and edited the manuscript. Ikram Faraoun Al-Mulla, Dr. Abbas Al-Ameeri, and Dr. Tareq Al-Attar helped with methodology and validated the study. Dr. Abbas Al-Ameeri and Dr. Tareq Al-Attar supervised the study.

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