sciendo

Civil and Environmental Engineering
Vol. 20, Issue 1, 377-386, DOI: 10.2478/cee-2024-0029

CREEP COEFFICIENT AND SPECIFIC CREEP OF ENGINEERED CEMENTITIOUS COMPOSITE - BENDABLE CONCRETE

Ikram Faraoun AL-MULLA[1,*], Abbas Salim AL-AMEERI[2], Tareq Salih AL-ATTAR[3]

[1] Civil Engineering Department, University of Baghdad, Baghdad, Iraq.
[2] Civil Engineering Department, University of Babylon, Babylon, Iraq
[3] Civil Engineering Department, University of Technology, Baghdad, Iraq.
[*] corresponding author: ikram.faroun@coeng.uobaghdad.edu.iq

Abstract

Creep is a complex behavior of concrete since it induces different stages of response under loading and unloading with time. It represents the time-dependent strain as a result of a constant sustained load applied with time. In cementitious materials such as engineered cementitious composite concrete, ECC, the loaded cement paste is the principal source of creep strain. Therefore, investigating the overall creep behavior, under the loading and unloading stages, will be beneficial in providing data for the performance of ECC concrete. The test for compressional creep strain is done according to the ASTM C-512 under controlled temperature (21 ºC) and relative humidity (40%). In this research, the loading stage lasted for 9 months, and the unloading stage lasted 3 months. The total creep strain, creep coefficient, and specific creep were recorded for six ECC concrete mixes. The mixes have two strength levels, 30 and 60 MPa at 28 days, and contain polypropylene and polyvinyl alcohol fibers. Results revealed significant enhancement, and lower creep behavior, in mixes including fibers compared to plain mixes. The best promising results for the creep coefficient and specific creep were recorded when using mixes of 60 MPa containing polyvinyl alcohol fibers compared to plain mixes.

Keywords:

Engineered Cementitious Composite Concrete;
Polymeric Fibers;
Scanning electron microscope SEM;
Creep coefficient;
Specific creep.

1 Introduction

Engineered cementitious composite, ECC, concrete behavior depends on the interaction between the fibers and the matrix which is considered an essential factor controlling the ECC concrete behavior; this leads to an enhancement in the interfacial zone and provides an ideal property. Using appropriate mineral admixtures may prevent the fiber pull-out from the matrix [1]. Creep is the gradual increase in strain or deformation with time under constant applied stress, thus creep can be calculated from the initial elastic strain attained by the secant modulus of elasticity at the loading age [2]. Cementitious materials are recognized to creep, i.e., display a growth in strain when exposed to sustained stress with time. The most commonly known mechanism is the bond breaking and reformation in the calcium silicate hydrate gel structure at the nanoscale and the slow movement of physically adsorbed water [3]. The creep effect may also be observed from another standpoint, if a concrete specimen is exposed to a loaded restraint, therefor it will be exposed to constant strain, and creep will clear itself as stress decreases with time, this is named relaxation [4]. Experimental data [5], demonstrate that within an inclusive concrete strength range, the creep is inversely proportional to the concrete strength at the time of load application. Moreover, micro-cracking arises due to a local increase in stress, producing nonlinearity behavior of the creep. Consequently, the cementitious materials' creep deformation under sustained loading is produced by the associated changes in the microstructure of the cementitious matrix and the movement of water [6]. ECC paste is the primary source of the creep. On the other hand, fine aggregate provides higher dimensional stability, since it has a larger stiffness than the cement paste, hence the fiber/matrix bond improvement could be an active method to control creep in microcracked ECC [7]. Al-Rihimy et al [2], used self-compacting concrete mixes with strength levels of 40 and 60 MPa

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and produced from Portland limestone cement to study the development of creep strain. Specimens were exposed to sustained compressive loading under controlled conditions in a creep chamber. Test results exhibited that normal-strength Portland limestone cement mixes developed lower ultimate creep, while high-strength concrete showed relatively similar creep behavior to the ordinary Portland cement SCC but with 50% lower specific creep [8]. ECC is reinforced with small, disconnected, micromechanical polymer fibers, it usually uses a 2 percent fibers volume fraction. Thus, ECC concrete deforms but without breaking, this behavior conforms with the results conducted by Sara et al [9]. Two types of Portland Limestone Cement were used. Results revealed that the short-term creep (three months loading), under controlled temperature and relative humidity, has a low strain in mixes containing polymer fibers and limestone cement due to the restriction of the fibers to the matrix strain under creep loading effect and also due to the lower clinker percent in the Portland limestone cement compared with ordinary cement [8]. According to the ACI 209R-92 [10], creep is defined in terms of creep coefficient, which is the creep strain divided by instantaneous (elastic) strain. The specific creep is defined as the creep strain per unit load. Its value depends vastly on the value of the initial strain estimated as part of the testing procedure. In a compressive creep test, the applied load causes deformation over time. The deformation is a result of the combined effect of strain, time, and temperature. The creep strain rate, or the rate at which the material deforms under load, typically decreases over time due to a phenomenon called strain hardening, this behavior is a distinct character of the engineered cementitious composites (ECC). The micro-cracking happens due to a local increase in stress, producing nonlinearity in the behavior of creep. Consequently, cementitious materials' creep deformation under sustained load is caused due to the movement of water and related changes in the cementitious matrix microstructure [6]. The superior behavior of the polyvinyl alcohol (PVA) fibers is related to their high modulus of elasticity and their ionic coating which provides a good chemical bonding with the cement matrix, leading to a rise in the toughness and the elasticity behavior of the engineered cementitious composite concrete mixes. scanning electronic microscopy (SEM) revealed the bond behavior between the polymeric fibers and the engineered cementitious composite concrete matrix. from the SEM test, the microcracks below 50μm were arrested by using polymeric fibers and the sequence of developing microcracks led to enhanced strain capacity of the ECC mixes. [11]. On the other hand, PVA fibers introduce an increase to the bendable concrete strain capacity as concluded by AL-Mulla et al [12] whose 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 present research intends to explore the creep behavior of Six engineered cementitious composite concrete mixes (ECC), produced with polypropylene fibers (PP) and polyvinyl alcohol fibers (PVA) both with polyvinyl alcohol solution and silica fume. The impact of the ECC microstructural behavior on the Creep strain results was also investigated. The creep under compressive sustained loading was carried out for a loading stage to the age of 270 days, then the load was released and the readings were recorded for 90 days. The novelty of this research lies in applying the long-term creep behavior for a newly innovated concrete type (bendable concrete, ECC) and making a comparison between the behavior of the two polymer fiber types (PP and PVA) under two strength levels (30 and 60 MPa). The best results were obtained from ECC mixes containing PVA fibers in high strength levels, and the Scanning Electron Microscope (SEM) approved this conclusion.

2 Materials and Standards

Engineered cementitious composite (Bendable) Concrete used in this research with two cement contents: 275 kg/m^3, and 450 kg/m^3, to achieve a 28-day compressive strength of 30 and 60 MPa, respectively. Type I cement was used, and its chemical and physical properties conform to the ASTM C-150 [13]. The used fine aggregate was tested and its properties confirm the ASTM C33-08 [14]. Silica fume with a strength activity index SAI of 120% was used and conformed to ASTM C-1240 [15]. It was used as a partial cement replacement 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, its replacement with the cement may reduce the creep strain [16]. Polypropylene fibers PP and polyvinyl alcohol fibers PVA, characteristics are shown in Table 1.

Table 1: Polymeric Fibers Characteristics.

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

To enhance the density and reduce the porosity of the engineered cementitious composite, a Polyvinyl alcohol (PVA) solution was used, and mix proportions were introduced in Table 2. These percentages were adopted to achieve the required behavior of fresh and hardened ECC concrete mixes. 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. The absence of coarse aggregate causes the engineered cementitious composite concrete to suffer from high creep.

Table 2: The mix proportions by Weight of cement.

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

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

Six mixes (Table 3) were used in this research, to implement its aim which includes making three comparison stages for the creep strain behavior, the first is between the PVA fibers and PP fibers ECC concrete mixes, whereas the second is between the two strength levels of the ECC mixes (30 and 60) MPa and the third is between plain and fibrous mixes. Since mixes of 30 MPa have lower cement content than that of 60 MPa, the typical fiber volume fractions were adopted as mentioned in Table 3, to ensure better bonding between fibers and matrix, enhance the bendability of the samples, and achieve the ECC fresh mixes workability.

Table 3: The details of the used mixes.

Mixes	28 days Compressive strength [MPa]	Fiber type	Volume fraction [%]
30V	30	Polyvinyl alcohol	1
30P	30	Polypropylene	1
60V	60	Polyvinyl alcohol	2
60P	60	Polypropylene	2
30 Plain	30	-	-
60 Plain	60	-	-

The creep strain test was performed on a cylinder of (100x200 mm) which was arranged according to ASTM C192/192M -15 [17], fives samples for each mix were arranged in a specific creep test rig (loading frame), Fig. 1, and the test was conducted according to ASTM C 512-15 [18].

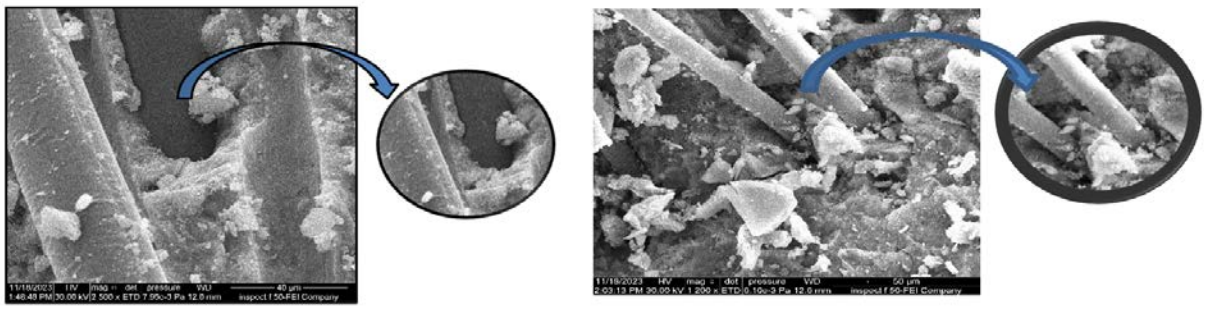


Fig. 1: Creep strain test for engineered cementitious composite concrete mixes.

3 Results and discussion

3.1 ECC microstructural behavior when using polymer fibers

Based on Li's conclusions, bendable concrete has a great tendency to creep due to its high cement content and there is no coarse aggregate involved [6]. From this research, results revealed that mixes containing polyvinyl alcohol fibers (PVA) recorded lower creep strain than those with polypropylene (PP) fibers. The reason behind this behavior is related to the properties of PVA fibers which have a higher modulus of elasticity compared to that of PP fibers which leads to a reduction in the creep strain. This behavior conforms with the results of Donatas et al [19], who stated that PVA fibers own a high modulus of elasticity and may reduce the crack width, hence reducing the creep strain of the mix. 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, Fig. 2. Consequently, the composite creep was physically limited due to the adhesion between the matrix and PVA fibers. Since fibers increase the tensile strength of the composite, hence it will reduce the potential cracking and creep. Polypropylene fibers (PP) have high ductility and fine distribution with a lower elastic modulus comparatively, hence enabling the concrete matrix to resist the enlargement of the microcracks at the early age of loading [20].

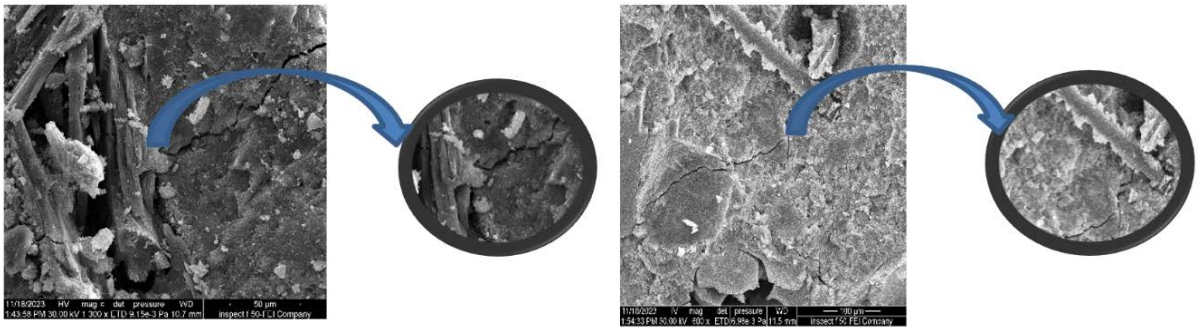


a) ECC mixes with PVA fibers. b) ECC mixes with PP fibers.

Fig. 2: Scanning Electron Microscope with 2500X magnification (40-50 μm): a) bond between PVA polymer fibers and ECC matrix, b) bond between PVA polymer fibers and ECC matrix.

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. The previous explanation declared that the bonding strength and microstructure of the engineered cementitious composite concrete were improved.

The importance of using polymer fibers relies on their role in arresting the microcracks (at the level of 50 μm and below), Fig. 3, which means that multiple cracking will propagate instead of one wide crack width and fibers will bear the stress until it slips or fractured depending on its bonding type with the ECC matrix as mentioned previously, Fig. 2. This behavior is considered a distinctive feature of engineered cementitious composite-bendable concrete.



a) Cracks arrested by PP fibers. b) Cracks arrested by PVA fibers.

Fig. 3: microcracks at 50 μm and below: a) cracks arrested by polypropylene fibers, b) cracks arrested by polyvinyl alcohol fibers.

3.2 Loading stage

This stage lasts about (270 days), and samples are subjected to sustained loading within their elastic limits. The results obtained showed that high-strength concrete (60 MPa) records (20%) lower creep strain than normal-strength concrete (30 MPa) as illustrated in Figs. 4 and 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. Also, the higher modulus of elasticity for the high-strength concrete may lead to lower creep strain.

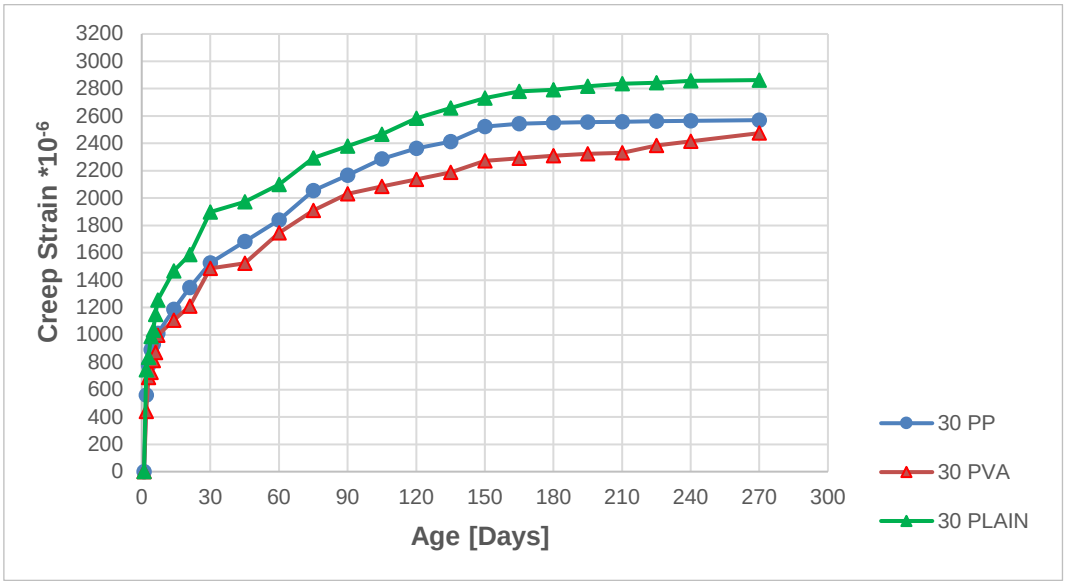


Fig. 4: Creep strain results for 30 MPa mixes.

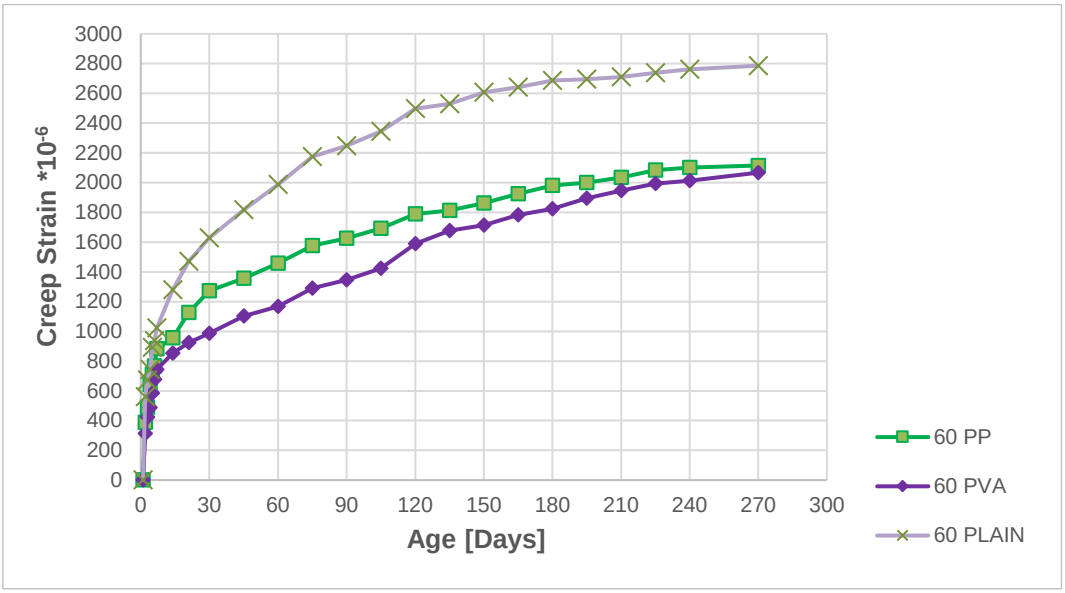


Fig. 5: Creep strain results for 60 MPa mixes.

Creep strain under loading results were recorded for nine months as graphed in Figs. 4 and 5. Results were introduced on the behavior of creep for the mixes of 30 MPa and 60 MPa with age, and a comparison between the creep behavior of the mixes was elucidated. It specifies low creep strain by using polymeric fibers. For high-strength concrete mixes, it is obvious that creep strain is lower than normal-strength concrete, due to the presence of silica fume which has both chemical and physical effects, the low w/c ratio, and the high modulus of elasticity. Commonly, mixes without fibers (PLAIN mixes) show higher creep strain than with fibers.

3.3 Creep coefficient

The creep coefficient was calculated according to ACI 209 [10] and represented in Figs. 6 and 7, ECC fiber concrete mixes and plain ECC concrete mixes have divergent creep coefficient results (4.6, 4.3, and 5.1), for 30 PP, 30 PVA, and 30 PLAIN, respectively. On the other hand, high-strength ECC concrete mixes and plain ECC concrete mixes have divergent creep coefficient results (2.55, 2.4, and 3.3), for 60 PP, 60 PVA, and 60 PLAIN, respectively. High-strength ECC concrete mixes have a lower creep coefficient than normal-strength concrete by about (44%). Generally, the creep coefficient of the tested bendable concrete samples was in range between (2-4.7), which conforms ACI-209 which limits the creep coefficient between (1-6).

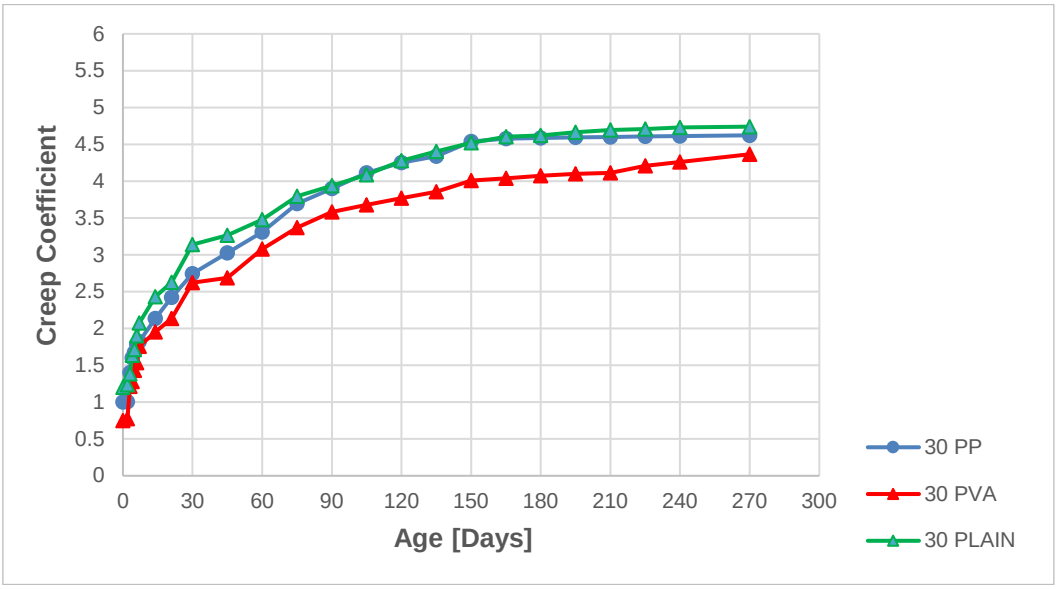


Fig. 6: Creep coefficient for 30 MPa mixes.

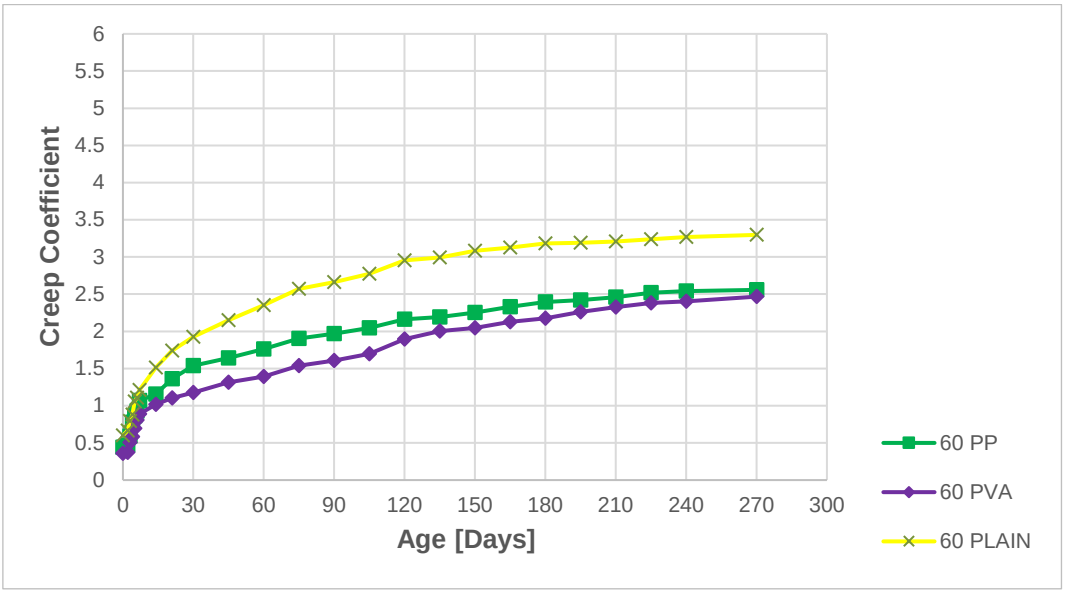


Fig. 7: Creep coefficient for 60 MPa mixes.

3.4 Specific creep

The specific creep of six engineered cementitious composite mixes is presented in Figs. 8 and 9. Results were calculated according to ACI 209 [10], normal strength concrete mixes give higher specific creep than high-strength ECC concrete. High-strength concrete mixes give approximately half the specific creep of normal-strength concrete.

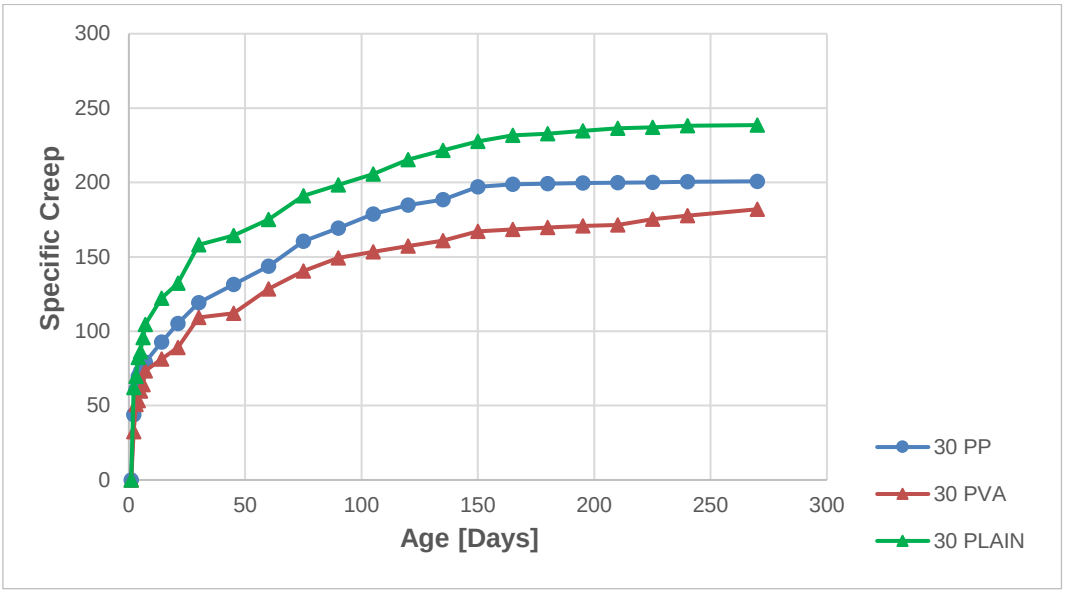


Fig. 8: Specific creep for 30 MPa mixes.

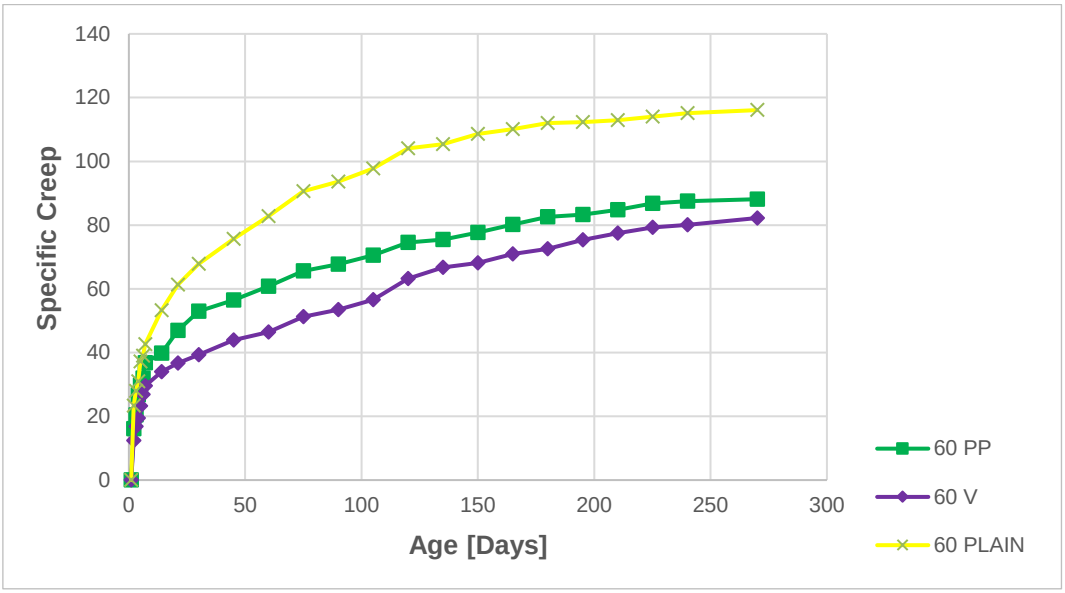


Fig. 9: Specific creep for 60 MPa mixes.

3.5 Unloading stage

After 270 days of loading exposure, the load was released and the results were recorded for another (90 days). Thus, specimens experiment elongation behavior after they deal with shortening behavior in the loading stage (creep under uniaxial compression). Recovery strain (the elongation of the specimen with time after removing the compressive stress) with age for all mixes was presented in Figs. 10 and 11. It could be concluded that when using ECC with fibers, low recovery strain was adopted. A lower recovery strain in high-strength concrete mixes than normal-strength concrete was recorded, this behavior could be due to the low w/c ratio, the presence of silica fume which has chemical and physical effects, higher fiber volume fraction, and the high modulus of elasticity. Mixes with PP fibers give a higher recovery strain than the mixes with PVA fibers, due to their lower modulus of elasticity and the better bond between PVA fibers and the matrix compared to PP fibers with the matrix.

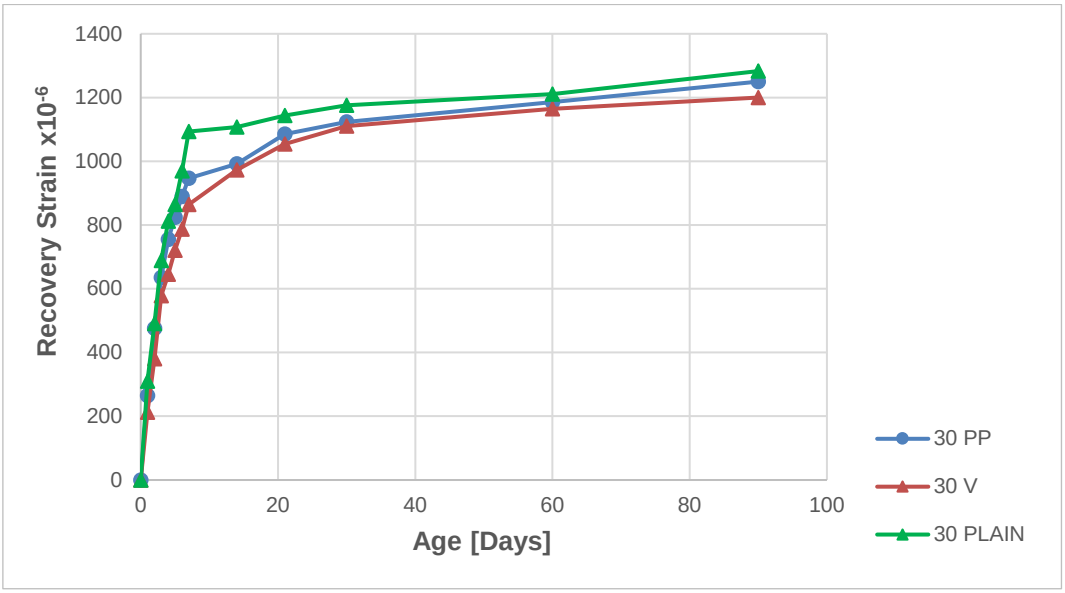


Fig. 10: Recovery strain under load release for 30 MPa mixes.

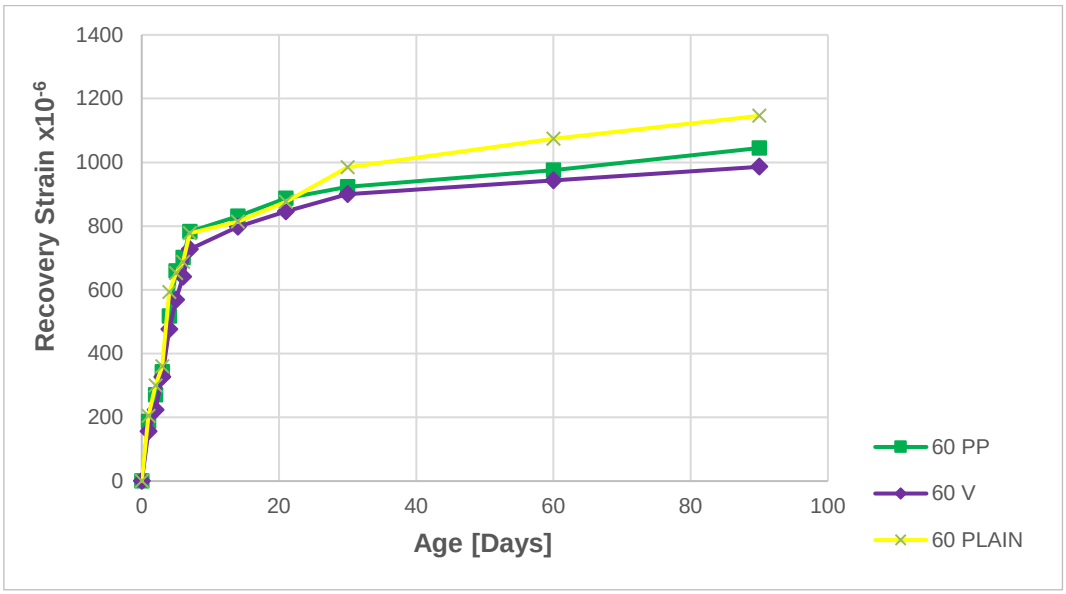


Fig. 11: Recovery strain under load release for 60 MPa mixes.

4 Conclusions

1) Exploring the overall creep behavior of bendable concrete is worth contemplating since there is a lack of data for this long-lasting test, and that makes the adopted results in this paper remarkably interesting.

2) The creep coefficient of High-strength ECC concrete was noticeably lower than that of normal-strength ECC concrete by about (44%).

3) The range of creep coefficient for the bendable concrete samples was (2-4.7) and that confirms the ACI-209.

4) High-strength concrete mixes give approximately half the specific creep of normal-strength concrete.

5) Lower recovery strain was recorded in high strength due to the low w/c ratio, the presence of silica fume which has chemical and physical effects, higher fiber volume fraction, and the high modulus of elasticity.

6) ECC concrete Mixes with PP fibers give a higher recovery strain than those with PVA fibers, due to their lower modulus of elasticity and the weaker bond of PP fibers with the matrix compared to that of PVA fibers with the matrix. This behavior has been supported through the SEM images.

7) Creep overall behavior was recorded for 360 days (270 days under loading and 90 days after load release), this behavior is worth anticipating especially since it is conducted for engineered cementitious composite which is a new inventory in the concrete industry.

Acknowledgment

The authors gratefully appreciate the cooperation of the civil engineering laboratories at the University of Baghdad and the staff of the civil engineering department at the University of Technology for their help in implementing this research. A special thanks are dedicated to Dr. Ammar Sabah Al-Rihimy and the staff of Al-Khoura company for their help in performing the scanning electron microscope (SEM) for the mixes.

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