

Evaluating the creep behaviour of plastic-processed aggregate-based concrete

Research Article

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Abstract: In this study, the mechanical and creep characteristics of concrete integrating the plastic-processed aggregates (PPAs) were evaluated. A constant water-to-cement ratio was used with PPAs that were incorporated at 25, 50, 75 and 100% to formulate the concrete mixes. The mixing of PPAs in concrete has resulted in a decrease in mainstream mechanical properties, including dry density, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity by 18.6, 27.8, 37.2, 26.4, and 63.6%, respectively, at 100% aggregate replacement. The instantaneous creep strain, ultimate shrinkage strain, and ultimate creep strain of the PPA concrete mixes were significantly higher than that of the reference concrete especially at total replacement of PPA in the concrete mix. The increase in instantaneous creep strain, ultimate shrinkage strain, and ultimate creep strain at 100% replacement was found to be 100, 119, and 69%, respectively. The increase in creep strains of the PPA concrete mixes can be attributed to the reduction in the mechanical properties of subsequent concrete. Even with the reduction in the mechanical and creep properties of PPA concrete, the use of plastic-based aggregates in non-structural concrete applications is encouraged.

Keywords: *Processed aggregates • Instantaneous creep strain • Ultimate shrinkage strain • Ultimate creep strain • Non-structural concrete*

1. Introduction

Concrete can broadly be divided into two main components: aggregates, mainly responsible for the concrete overall strength, and the cement mortar that forms the lubrication in the fresh state and provides binding ability between the aggregate particles at the hardened state. Concrete due to its wide spectrum of mechanical and durability properties has tremendously increased its application and production all around the globe [1]. Utilization of concrete for the complete structure or only a few structural parts has become an integral part of almost every mega project. The structures nowadays require strong endurance against different types of loadings throughout their service life with increasing demands of skyscrapers, large-span bridges, and other large-scale infrastructure facilities [2]. The design life of such structures is generally around a century, which, along with other loading parameters, brings attention to the

evaluation of the creep behaviour of the material used [3]. Creep technically refers to the increase in the strain of the material under the application of constant load over a period of time. The increase in strain because of the time-dependent stress will eventually lead to concrete cracking [4]. The shortening of the column is also reported to be one of the probable causes occurring as a result of time-dependent strain, which ultimately can cause uneven settlement [5]. The cracking and uneven settlement caused by creep can affect the overall safety of the structure. Therefore, the concrete characteristics affecting the creep behaviour of concrete have been studied in the last few decades [6]. The studies have shown that the loading period, concrete loading age, the concrete's material properties, water-to-cement ratio, temperature, relative humidity, and specimen's size are among a few of the significant factors influencing the concrete's creep behaviour [7]. The earlier the concrete is loaded, the higher the creep, compared to the aged concrete specimens. A direct relation was reported between the water to cement ratio and creep; the higher the water-to-cement

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ratio, the higher the creep [8]. The increase in temperature is generally associated with an increase in the creep strains of concrete [9]. Another recent study has highlighted the temperature and stress level at which the concrete is exposed, concrete's age at the loading time, and aggregate type to be the major influencing factor for concrete's creep resistance [10].

The environmental concerns raised against the concrete industry have called for various mitigation techniques to lower the emission bar. Among various other methods involving the concepts of off-site construction, green design, and sustainable structures, concrete engineers have also tried substituting the three components of concrete, i.e. fine aggregates (limestone sand [11] and bottom coal ash [12]), coarse aggregates (shredded plastic [13], waste plastic [14], and different types of plastics [15]), and cement [1]. Although cement is the main contributor to concrete's overall emissions, the replacement of coarse aggregates that represent the major volume in concrete composition was offered as a potential solution for not only reducing the environmental burdens but also for resulting in concrete with modified mechanical and durability properties depending on the type of waste/material being replaced [16]. Recycled plastic has been among the common materials replacing natural aggregates either as plastic pieces [17] or plastic being used as the main material to produce synthetic lightweight aggregates [18]. Recent studies have shown the possibility of plastic aggregates being used as a suitable alternative for producing lightweight structural/non-structural concrete [19]. However, recent studies have focused massively on the fresh, mechanical, and durability properties and less attention has been paid to exploring the creep behaviour of concrete containing plastic aggregates. The synthetic aggregates manufactured by using plastic are generally spongy with higher void content compared to natural coarse aggregates [19], which can benefit in lowering the total weight of the structure; however, the porous structure can reduce the mechanical strength and also the creep resistance [20]. Few researchers have evaluated the creep resistance of lightweight concrete incorporating apricot shell [21], shale [2], processed clay [22], and synthetic polymer [23] and found that the resulting concretes had lesser creep resistance than normal concrete. Another recent study has evaluated the creep resistance of lightweight concrete and normal concrete having the same compressive strengths [24] and shown the former to have reduced creep resistance at even the same level of compressive strength. In light of the above, it was observed that the creep resistance of lightweight concrete has been studied in the last few years; however, not much focus has been laid on lightweight concrete containing processed plastic-based

aggregates. In addition, as shown in the above literature review, the other mechanical properties of recycled plastic concrete have been examined in various recent studies; however, the creep characteristics data were limited. Therefore, the current study was designed to study the creep behaviour of lightweight concrete containing processed plastic-based aggregates with different replacement ratios. The processed plastic-based aggregate was replaced at 25, 50, 75, and 100% with the normal coarse aggregates. The tests were conducted on all the specimens to determine the mechanical properties and evaluate the creep resistance of the concrete for a period of 1 year. The evaluation of different mechanical properties in relation to the creep resistance of the processed plastic-based aggregate concrete was also carried out.

2. Materials and methodology

Ordinary Portland cement with a specific gravity of 3,500 cm²/g, a fineness of 3.15, an initial setting time of 45 min, and a final setting time of 135 min was used for all the concrete specimens as binding agents. The chemical composition of the cement showed the sum of the three major parts (C₃S, C₂S, and C₃A) to be around 82.05% and C₄AF to be 11%. Two types of coarse aggregates were used: the first one was the natural, normal coarse aggregate (CNA), while the second was the processed plastic aggregate (PPA) synthesized following the methodology stated originally by Alqahtani [25]. Table 1 shows the physical properties, tests, and the respective standards followed to characterize the aggregates. The physical appearance and optical microscopic image of the PPAs used in this study are shown in Figure 1.

Test	Experimental values		Standard used
	CNA	PPA	
Fineness modulus	5.83	5.67	ASTM C136/C136M-14 [26]
Unit weight (kg/m ³)	1,554	1,132	ASTM C29/C29M-16 [27]
Voids (%)	37.79	37.44	ASTM C29/C29M-16 [27]
Specific gravity	2.59	1.81	ASTM C127-15 [28]
Water absorption (%)	1.48	0.95	ASTM C127-15 [28]

Table 1. Aggregate properties used in the current study.

ASTM C136/C136M-14 was used to examine the particle size distribution of both the aggregate series, and the results are shown in Figure 1(c) and (d) [26]. The PPA can be classified as a lightweight aggregate as its particle size distribution is contained inside the ASTM standard limits [26]. A percentage of 65% dune sand and 35% crushed sand obtained after several tests in order to meet the ASTM C136/C136M-14 criteria (as shown in Figure 2) was used as a fine aggregate [26].

The total water quantity shown in Table 2 was estimated based on the moisture and absorption content of the respective aggregates [29,30]. The dry density, compressive strength, splitting tensile strength, Poisson's ratio, and abrasion resistance for all the concrete specimens were determined by following BS EN 12390-7:2009 [31], ASTM C39/C39M-16 [32], ASTM C496/C496M-11 [33], ASTM C469/C469M-14 [34], and ASTM C944/C944M-12 [35], respectively. The dry density test of the concrete was conducted

in line with BS EN12390-7:2009. Therefore, on the day of testing (i.e. the 28th day), cube specimens of $50 \text{ mm} \times 50 \text{ mm} \times 50 \text{ mm}$ in dimension were taken from the curing tank and dried in the oven for 24 h at $105 \pm 10^\circ\text{C}$. The next day, the specimens were taken from the oven and cooled in an airtight vessel to room temperature. Subsequently, the dry weight and the actual measurements (i.e. length, width, and height) of each specimen were measured. Then, the actual volume of each specimen was computed using the actual measurements. Finally, the dry density was calculated using the dry weight and the actual volume of each cube specimen. The steps outlined in ASTM C39/C39M-16b were followed to determine the compressive strength of all the concrete series. To carry out the compressive strength test, a cylindrical specimen, with a diameter of 100 and a height of 200 mm was used. A Toni Tech Compressive Machine was used to maintain a constant rate of loading of 0.2 MPa/s . Splitting tensile strength was

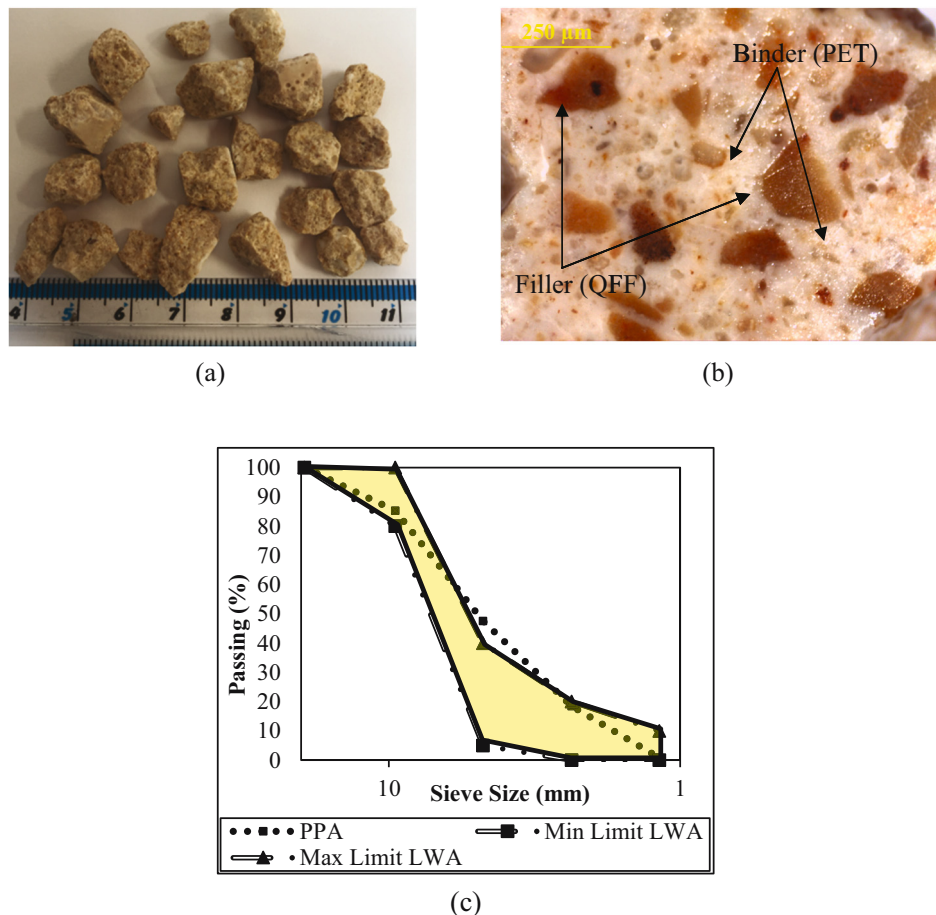


Figure 1. PPAs used in this study: (a) texture and physical appearance, (b) optical microscopic image, and (c) grading curve in comparison with the ASTM maximum and minimum limits of LWA [26].

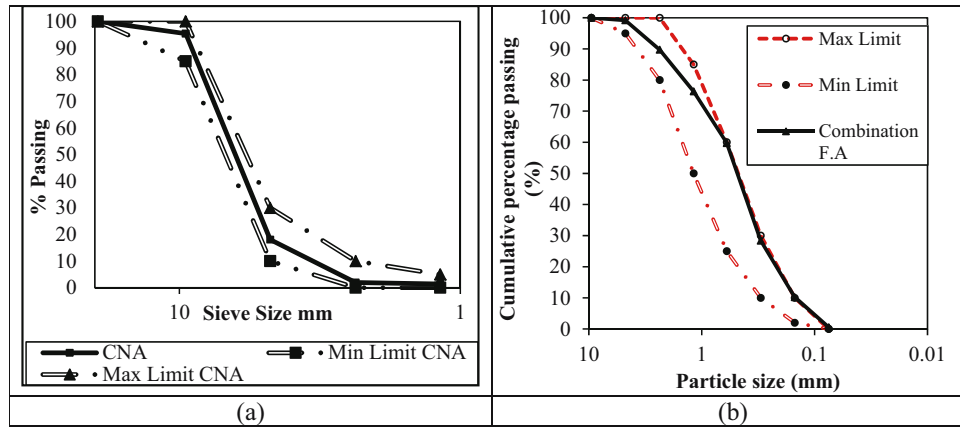


Figure 2. Grading curve of the (a) natural coarse and (b) fine aggregates in comparison with the ASTM limits [26].

Concrete series	W/C	Total water	Free water	Cement	Fine aggregate	Coarse aggregate	
						PPA	CNA
	kg/m ³						
CN	0.50	240.3	225	450	880	—	688
PPAC25		239			847	141	516
PPAC50		237.6			815	282	344
PPAC75		236.2			782	423	172
PPAC100		234.8			750	565	—

Table 2. Mix proportions for concrete mixes used in the current study.

determined by following the steps outlined in ASTM C496/C496M-11 on a concrete cylindrical specimen with a diameter of 50 and a height of 100 mm. A constant rate of loading of 1 MPa/min was used for the test.

The creep test was conducted for concrete 100 mm × 200 mm cylinders in line with ASTM C512/C512M-10 [36]. Figure 3 shows the creep test set-up, where the specimens were prepared and tested as follows. Initially, samples used for the time-dependent strain (i.e. samples subjected to load) were prepared with sulphate capping, while those used for shrinkage strain measurements (i.e. unloaded sample) were not capped. Then, electrical strain gauges having 60 and 1 mm length and width, respectively, were fixed vertically in the middle of each specimen's sides, as shown in Figures 3 and 4. After that, samples used for time-dependent strain were placed in a series in the loading frame, as shown in Figure 4(a), where these frames, together with unloaded samples (i.e. shrinkage samples) (Figure 4(b)) were placed in a controlled chamber with relative humidity and temperature of $38 \pm 4\%$ and $23 \pm 2^\circ\text{C}$, respectively. Subsequently, the electrical strain gauges for

both loaded and unloaded samples were connected to the data acquisition instrument to record the strain readings.

At loading, specimens were loaded at a pressure equivalent to 40% of the ultimate compressive strength using a hydraulic jack that was placed on each frame (Figures 3 and 4). This pressure was frequently maintained as it should not exceed 2% lower than that of the initial reading. The reading of the initial strain (instantaneous strain) was noted immediately after the loading and was continuously recorded for over 1 year. The data reading intervals were automatically programmed to be taken every 15 min, which is more than those specified in ASTM C 512 [36].

Consequently, the strain induced by shrinkage was calculated at any time as the average of the strain readings of the unloaded samples. However, the time-dependent strain induced by creep and shrinkage was calculated at any time as the average of the strain readings of the loaded samples.

Moreover, the strain induced by creep was only calculated at any time as the difference between the time-dependent strain (i.e. for loaded samples) and shrinkage

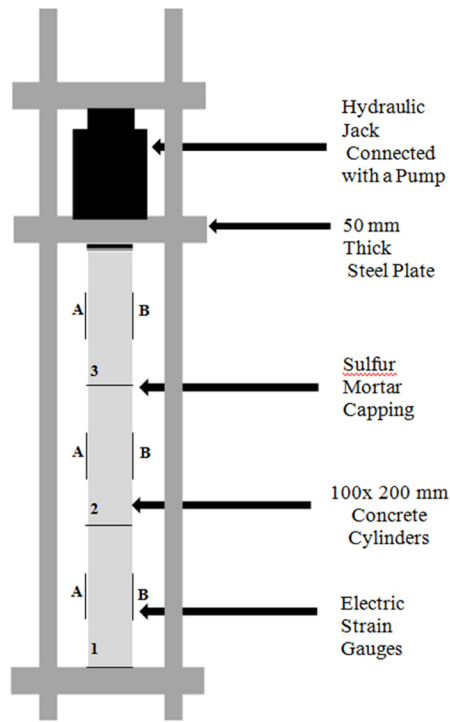


Figure 3. Creep test setup.

strain (i.e. for unloaded samples). Finally, the creep coefficient was computed at any time as follows:

$$\text{Creep coefficient} = \frac{\text{Creep strain} - \text{Instantaneous strain}}{\text{Instantaneous strain}}.$$

3. Results and discussions

Table 3 outlines the mechanical properties of all the concrete series. It was noticed that all the mechanical properties had shown a decreasing trend with an increase in the replacement volume of the PPA, including the dry density, compressive strength, tensile strength, flexural strength, and modulus of elasticity, while the abrasion and Poisson's ratio increased. Although the mechanical properties of PPA concretes are lower compared to control concrete, it displayed the minimum levels to satisfy the requirements listed in ASTM C330/C330M-14 criteria to be used in lightweight structural applications [37].

3.1 Creep

The effect of PPA on the creep performance was conducted on all the concrete series. The effect of manufactured aggregate on the time-dependent strain is shown in Figures 5–7.

Figures 5–7 depict a rapid increase in the strain immediately after applying load, while the rate was gradually reduced as the loading age increased. Figure 7 shows that the instantaneous strain of the PPAC mixes was significantly higher (i.e. 7–100%, 53–734 μstrain) than that of the CN, except for PPAC25, which was marginally lower by 9%. Similarly, the increase in the ultimate shrinkage strain of the PPAC mixes compared with that of the CN ranged from 28 to 119% (146.7–627.3 μstrain) as the replacement level was increased from 25 to 100%, as shown in Figure 6.

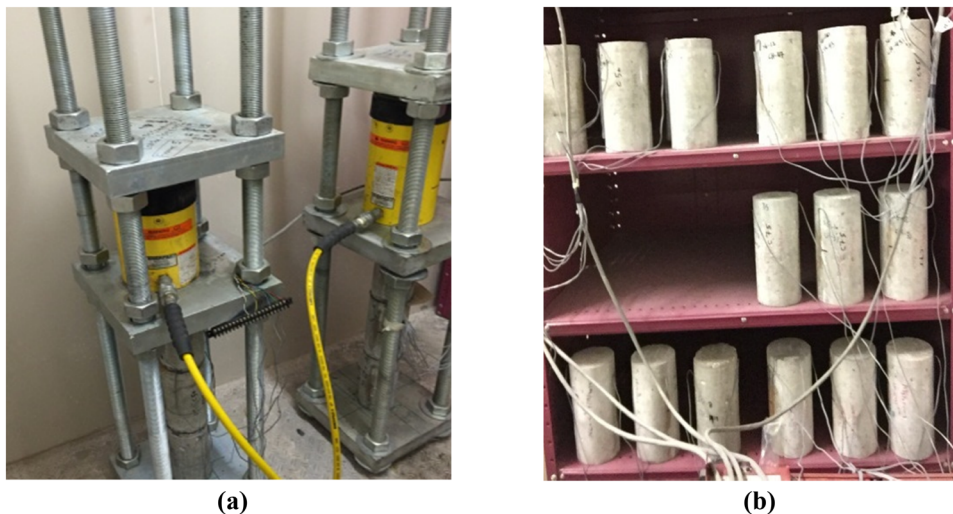


Figure 4. Creep setup with (a) loaded sample and (b) unloaded samples.

Sample	Dry density (kg/m ³)	Compressive strength (MPa)	Tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)	Poisson ratio	Abrasion-weight loss (g)
CN	2,183	41.8	3.58	5.42	27.82	0.25	0.40
PPAC25	2,086	35.3	3.32	5.24	20.58	0.28	0.60
PPAC50	1,995	31.7	2.42	5.04	15.06	0.38	0.61
PPAC75	1,896	30.4	2.36	4.47	10.66	0.39	0.63
PPAC100	1,777	30.2	2.25	3.99	10.14	0.39	0.66

Table 3. Major mechanical properties for all the concrete series

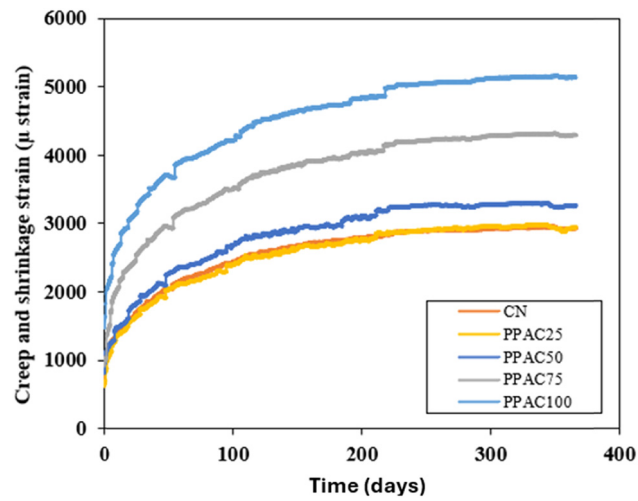


Figure 5. Results of time-dependent strain for loaded specimens of PPACs and CN.

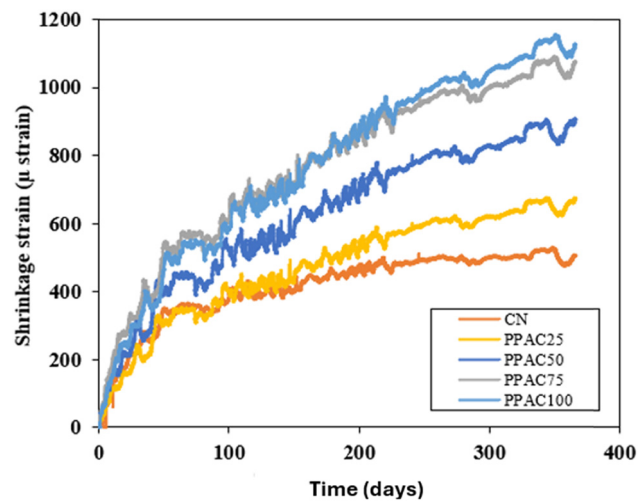


Figure 6. Results of shrinkage strain for unloaded specimens of PPACs and CN.

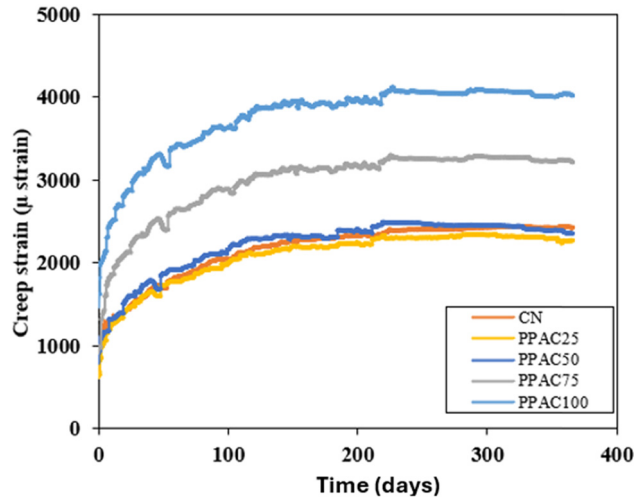


Figure 7. Results of creep strain of PPACs and CN.

Additionally, there was an increase in the ultimate creep strain (Figure 7) of PPAC mixes compared with that of the CN, ranging from 3 to 69% (55.2–1681.7 μ strain) as the replacement level was increased from 50 to 100%. However, the PPAC mixes made at a replacement level of 25% and CN had ultimate creep strain results that differed marginally by less than 4%.

Generally, the creep of concrete behaviour is influenced by the type of aggregate, cement paste, modulus of elasticity, and the ITZ between the aggregate and the cement paste [4]. Thus, the increase in the creep of the PPAC mixes can be attributed to the reduction in the mechanical properties of both the aggregate and subsequent concrete. This ultimately would decrease the resistance of the entire composite towards the creep tendency [38].

3.2 Correlation between the creep and different parameters

3.2.1 Creep coefficient and time

The creep models of AASHTO (2007) [39] and ACI 209.2R-08 [40] were used to predicate the creep coefficient of the RP3F3C mixes. These models estimate the creep coefficient (ϕ) at time (t, t_0) using equation (1). This equation consists of mainly two parts: the former is called the time function for the development of the creep over time, while the latter is the ultimate creep coefficient. The parameters of this equation used in each model are represented in Table 4.

$$\phi(t, t_0) = \underbrace{\frac{(t - t_0)^d}{B + (t - t_0)^d}}_{\text{time function}} \underbrace{C_u}_{\text{ultimate creep coefficient}}, \text{ where } C_u = \lambda \gamma_c. \quad (1)$$

Figure 8 compares the predictions of the ACI 209.2R-08 and AASHTO (2007) models with the experimental results of the creep coefficient of the PPAC mixes. As shown in Figure 8, the predictions of the ACI 209.2R-08 and AASHTO (2007) empirical model underestimate the creep coefficient results of the PPAC mixes, except for PPAC100, which was in agreement with AASHTO (2007). This is not surprising because these models were not developed specifically for

Type of model	
AASHTO LRFD (2007) [39]	ACI 209.2R-08 [40]
$B = (61 - 0.58 f_c')$	$B = 10$
$d = 1$	$d = 0.6$
$\lambda = 1.9$	$\lambda = 2.35$
$\gamma_c = k_{vs} k_h k_f t_0^{-0.118}$	$\gamma_c = \gamma_{ia} \gamma_H \gamma_{vs} \gamma_s \gamma_\rho \gamma_a$
$K_{vs} = 1.45 - 0.0051(v/s) \geq 1.0$	$\gamma_{ia} = 1.25(t_0)^{-0.118}$
$K_h = 1.56 - 0.008RH$	$\gamma_H = 1.27 - 0.0067RH$
$k_f = \frac{35}{7 + f_c'}$	$\gamma_{vs} = 2/3 \left[1 + 1.13 \cdot e^{-0.0213 \left(\frac{v}{s} \right)} \right]$
	$\gamma_s = 0.82 + 0.00264(S_i)$
	$\gamma_\rho = 0.88 + 0.0024(\rho_a)$
	$\gamma_a = 0.46 + 0.09\alpha$

Table 4. Parameters of the creep coefficient in different models.

lightweight concrete containing manufactured plastic aggregate.

Therefore, the results presented in Figure 8 reflect that the equations proposed by ACI209.2R and AASHTO (2007) need to be calibrated based on the existing data. Accordingly, a non-linear regression analysis of the experimental results was performed to calibrate these models for the PPAC mixes using equation (1), based on the methodology proposed by Shuraim et al., which includes the following assumptions [41]:

- In order to get the best-fit regression, it was assumed that the parameters B , d , and C_u were unknown.
- In order to calibrate the ACI 209.2R-08 model, it was assumed that the parameter C_u was unknown; while B

and d follow ACI 209.1R-05 as B and d both are constant, as shown in Table 4.

- In order to calibrate the AASHTO (2007) model, it was assumed that the parameter C_u was unknown, while B and d follow AASHTO (2007) (Table 4), where B was computed while d was constant.

Figure 9 shows the regression analysis curves (i.e. best fit, ACI 209.2R-08, AASHTO, 2007) of the creep coefficient of the PPACs mixes in comparison with the experimental results. The summary of the results of these curves is presented in Table 5.

As shown in Table 5, the maximum coefficient of determination (R^2) was obtained by the “best fit” representation followed by ACI 209.2R-08 and AASHTO (2007). However,

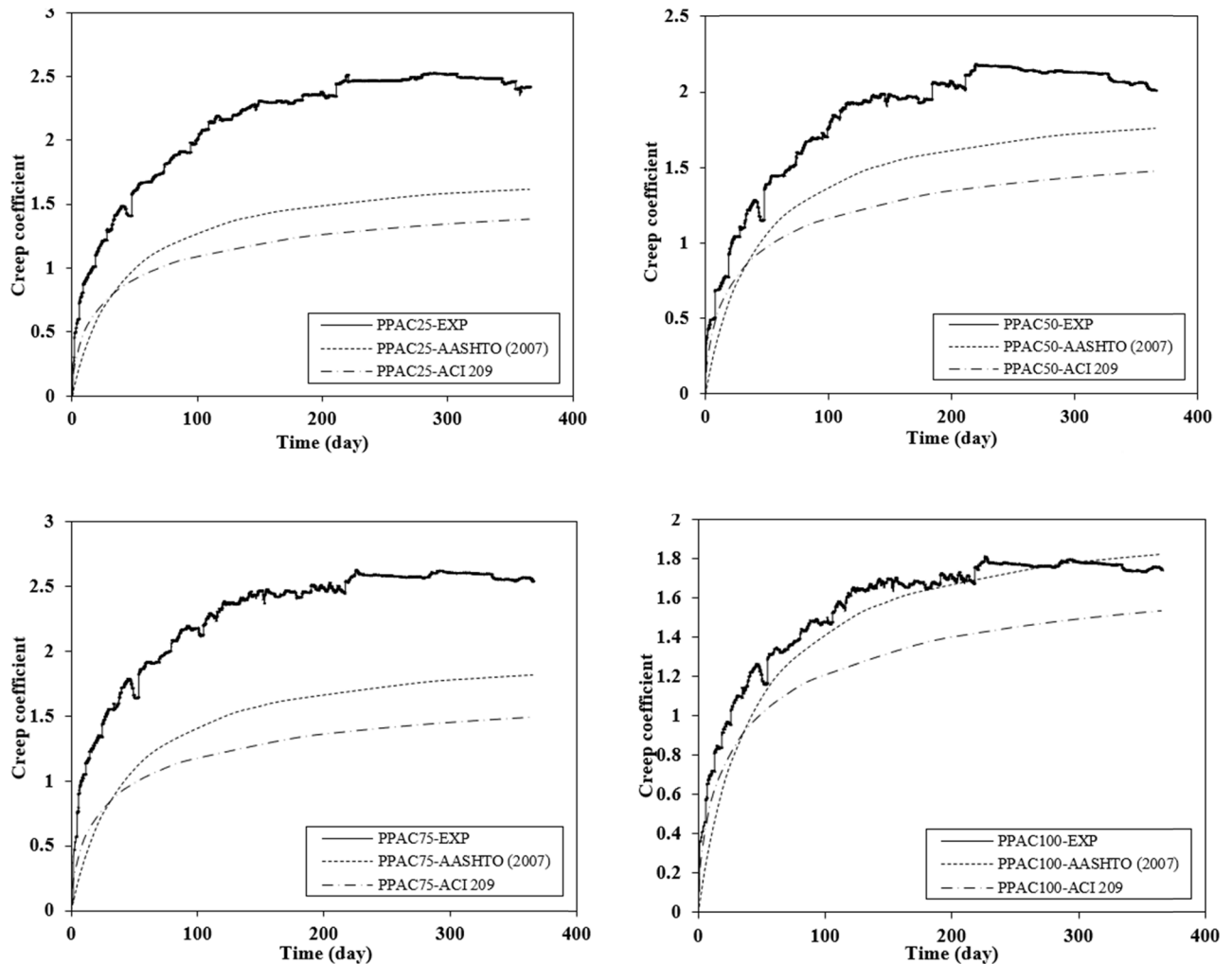


Figure 8. Comparison between the experimental results and the predictions of the analytical models related to the creep coefficient of PPAC mixes.

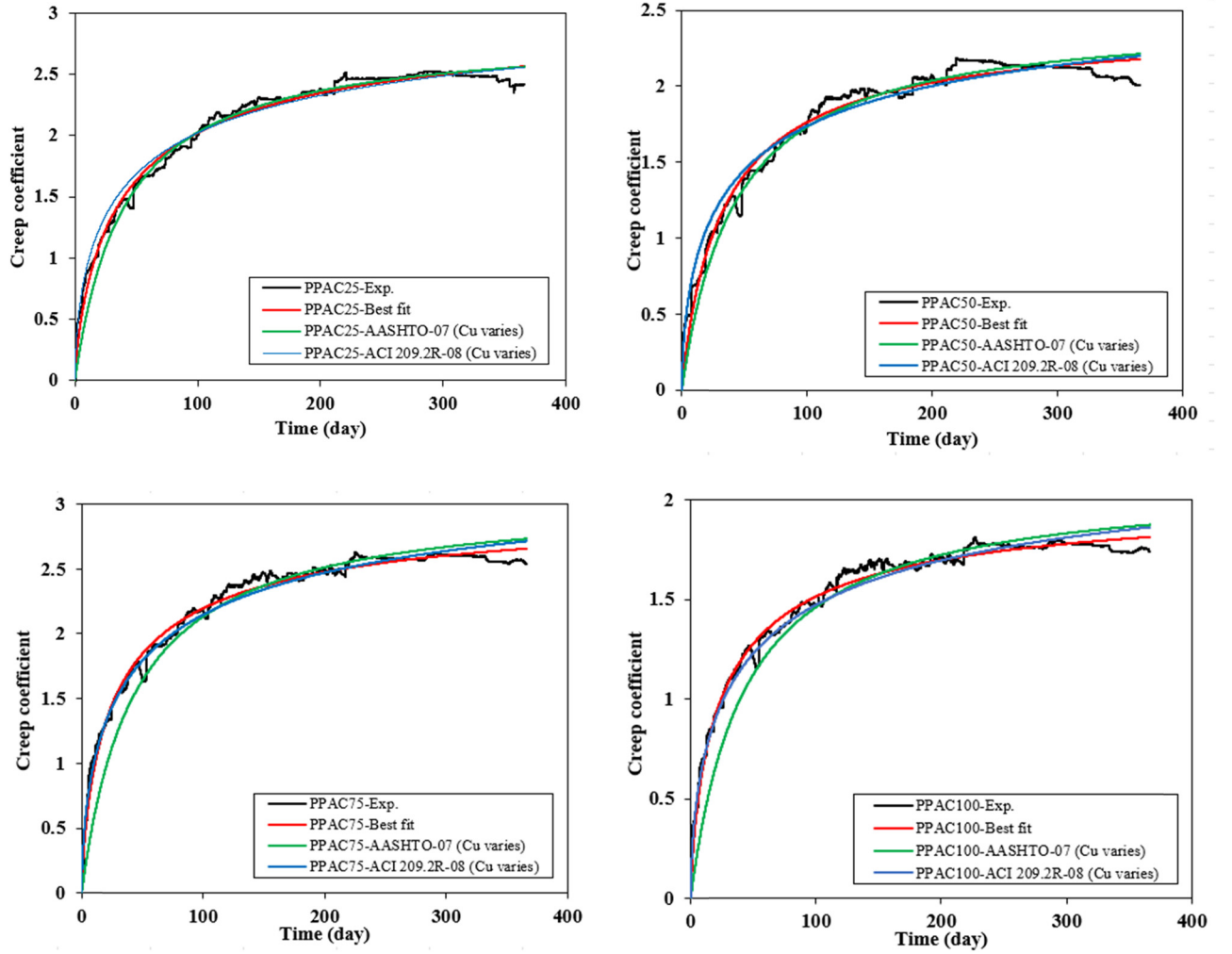


Figure 9. Regression and experimental curves for creep coefficients of PPAC mixes.

there was a significant difference between the parameters of the best-fit regression (i.e., B , d , and C_u) for each mix. This reveals that the best-fit representation is impractical, as it needs variations in B , d , and C_u .

Considering the second-best representation in the sense of the R^2 value, the time function of ACI 209.2R-08 has a better capability to represent the experimental results than AASHTO (2007). Therefore, this study proposed a modification of the current ACI 209.2R-08 model by modifying the ultimate creep coefficient factor (λ_{PA}), as shown in equation (2):

$$\varphi(t, t_0) = \frac{(t - t_0)^{0.6}}{10 + (t - t_0)^{0.6}} \lambda_{PA} \gamma_c \quad (2)$$

The proposed value of λ_{PA} takes the value of 3.7, which represents the average values of λ_{PA} , resulting from the

calibration of the ACI 209.2R-08 model for the PPAC mixes, as shown in Table 6.

Figure 10 compares the creep coefficient curves plotted using the proposed model with those observed experimentally, where the proposed model yielded a good capability of representing the experimental results of the PPAC mixes. Additionally, the proposed equation was found to correlate well with the experimental data, with a coefficient of correlation ranging from 0.96 to 0.98, as shown in Table 7.

3.2.2 Density of concrete

Figure 11 shows the relation between the dry density and creep coefficient for all the concrete series integrating certain percentages of recycled plastic aggregates. It was

Model type	Parameter	Concrete type			
		PPAC25	PPAC50	PPAC75	PPAC100
Best fit	B	17.72	26.45	12.71	12.46
	D	0.77	0.92	0.76	0.77
	C_u	3.04	2.42	3.03	2.05
	R^2	0.98	0.96	0.98	0.98
AASHTO (2007)	B	40.52	42.60	43.36	43.47
	D			1	
	C_u	2.84	2.47	3.06	2.09
	R^2	0.97	0.96	0.93	0.92
ACI 209.2R-08	B			10	
	D			0.6	
	C_u	3.30	2.83	3.50	2.40
	R^2	0.97	0.94	0.96	0.96

Table 5. Regression analysis results of the PPAC mixes.

Model type	Parameter	Concrete type			
		PPAC25	PPAC50	PPAC75	PPAC100
ACI 209.2R-08	γ_{la}	0.844	0.844	0.844	0.844
	γ_H	1.015	1.015	1.015	1.015
	γ_{vs}	1.158	1.158	1.158	1.158
	γ_s	1.189	1.268	1.282	1.321
	γ_p	0.88	0.88	0.88	0.88
	γ_a	0.73	0.73	0.73	0.73
	γ_c	0.759	0.810	0.819	0.844
	C_u	3.30	2.83	3.50	2.40
	$\lambda_{PA} = C_u/\gamma_c$	4.35	3.49	4.27	2.84

Table 6. Calculations for calibrating the ACI models for PPAC mixes.

noticed that the replacement of recycled plastic aggregates resulted in reducing the density of produced concrete. The creep coefficient has also shown a similar trend of decreasing values with an increase in the replacement proportions of recycled plastic aggregates, except for the concrete containing 75% replacement of aggregates. However, the overall trend represented by the linear trend line has shown a gradual decrease in the slope of creep coefficients with an increase in the replacement ratio of PPAs compared to the reference mix.

It was observed that the density of concrete was mainly influenced by the density of coarse aggregates, and, as shown in Table 1, the recycled plastic aggregates

have a lower density than that of normal coarse aggregates, which resulted in a decrease in the total density of concrete. In a recent study, the authors investigated the effect of the incorporation of different materials on the creep characteristics of concrete and found that the higher-density concretes displayed an increase in the creep strains [42]. The increase in the creep strains was attributed to the decrease in porosity. In this study, the opposite was true, where the increase in PPAs caused a decrease in the density and creep coefficients of the resulting concrete.

3.2.3 Compressive strength

Figure 12 shows the relation between the 28-day compressive strength and creep coefficient for all the concrete series integrating certain percentages of recycled plastic aggregates. The maximum decrease of approx. 30% in the compressive strength was observed for the concrete incorporating 100% PPAs, whereas a decrease of approx. 23% in the creep coefficient was observed for the concrete incorporating 100% PPAs compared to the reference concrete mix.

The reduced strength of the PPA and a possible weak PPA–cement transition zone can be considered as one of the main sources of strength decrease of recycled concrete compared to reference concrete. It was also observed that the creep was found to be directly influenced by the compressive strength values of recycled concrete, except at a 75% replacement ratio. However, the overall trend represented by the linear trend line has shown a direct

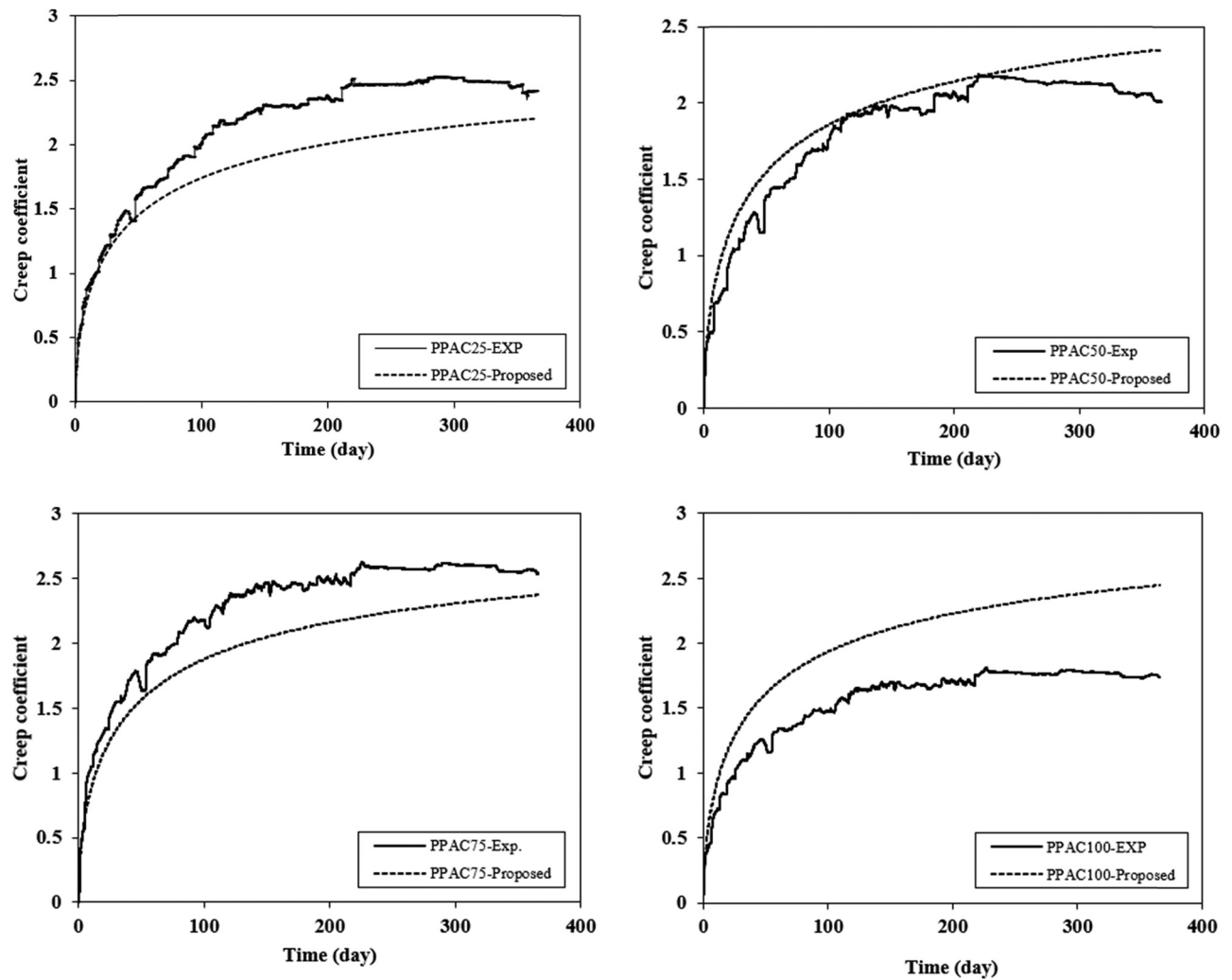


Figure 10. Comparison between the proposed model and the experimental results for the creep coefficient of PPAC mixes.

Concrete type	Coefficient of correlation (equation (2))
PPAC25	0.98
PPAC50	0.96
PPAC75	0.97
PPAC100	0.97

Table 7. Coefficient of correlation of the proposed model for the creep coefficient of PPAC mixes.

relationship represented by the gradual decrease in the slope of creep coefficients with an increase in the replacement ratio of PPAs compared to the reference mix. The results found in the current study are in agreement with the previous literature [43,44] where the increase in

strength has shown an increase in the creep resistance. Recently, the effect of increasing the porosity was investigated, and the creep coefficient was found to increase with increasing porosity of the concrete matrix [8]. In another study, the coarse aggregates were replaced by polystyrene lightweight aggregates, and it was observed that the creep strain increased by 66–80% replacement ratio compared to the reference mix, whereas the 20% replacement showed an increase in the creep strain by 19% [23]. The authors attributed the increase in the creep strain to the inadequate resistance of lightweight aggregate. In another study, the apricot shell was used as lightweight aggregates to formulate the recycled lightweight concrete and the incorporation of apricot shells caused a decrease in the creep resistance of the resulting concrete

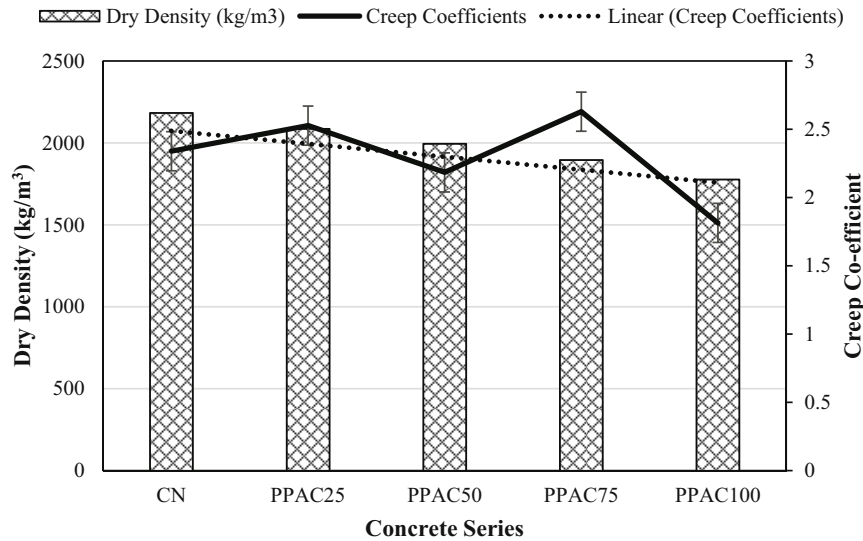


Figure 11. Relationship between the dry density and creep coefficient for all the concrete series.

[21]. The highest creep strains were exhibited by the concrete containing the total replacement of coarse aggregates by apricot shells, which was ascribed to the weaker bond at the interfacial transition zone, leading to decreased compressive strength and ultimately increasing the creep strains [21]. In the current study, 100% replacement of PPAs has also shown the highest creep strains compared to the reference mix, as shown in Figure 7. The authors attribute this increase mainly to the decrease in compressive strength. Another recent study has shown comparable trends in the creep resistance when lightweight aggregates were incorporated into the concrete matrix [45].

3.2.4 Splitting tensile strength

The relation between splitting tensile strength, compressive strength, and creep coefficient of recycled concretes is shown in Figure 13. The splitting tensile strength showed an identical tendency as that of compressive strength with the different replacement ratios of PPAs incorporated into concrete mixes. The decrease of approx. 37% was observed in total replacement of PPAs in concrete mixes. The relation between the coefficient of creep and splitting tensile strength was also similar to that of the compressive strength and splitting tensile strength; however, the

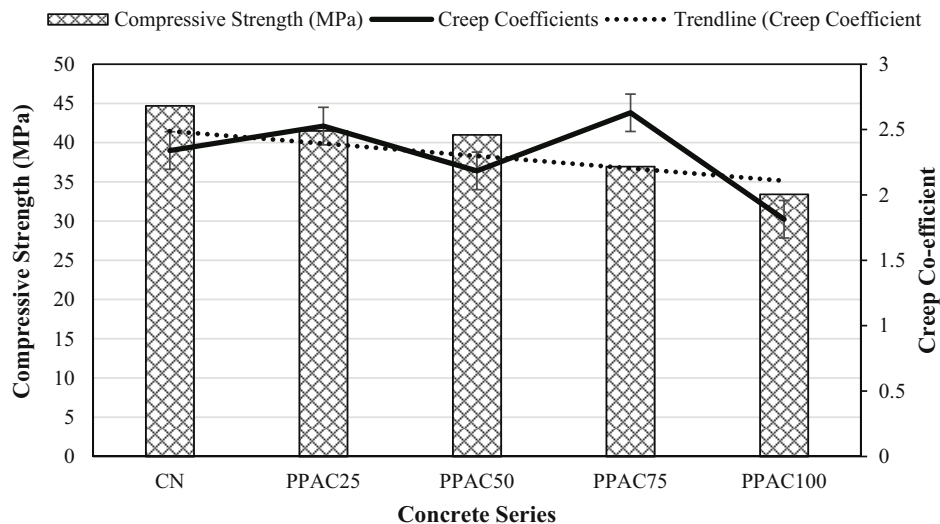


Figure 12. Relationship between the compressive strength (28 days) and creep coefficient for all the concrete series.

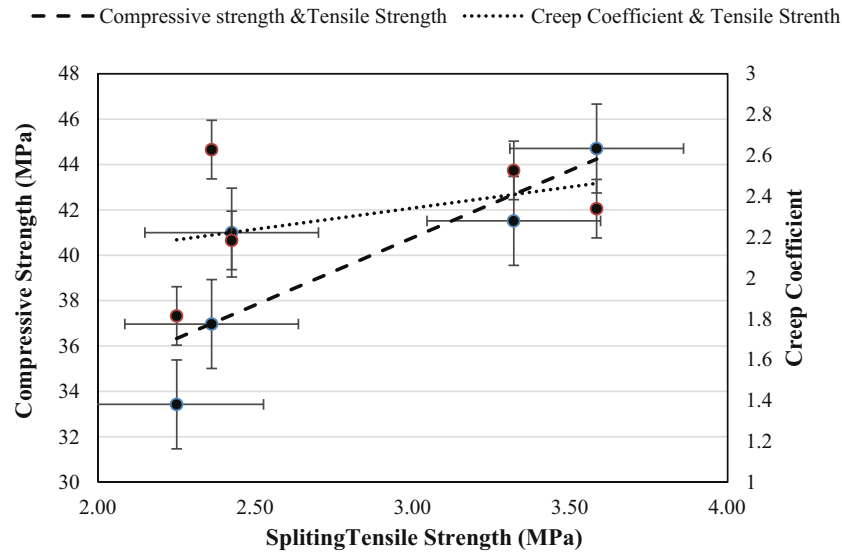


Figure 13. Relationship among the compressive strength, splitting tensile strength, and creep coefficient for all the concrete series.

decrease of creep coefficients with respect to splitting tensile strength was more gradual.

In another study, it was reported that total replacement of coarse aggregates by synthetic lightweight aggregates resulted in a decrease of approx. 40% [46]. In addition, other researchers reported a decrease ranging from approx. 50% [47] to 70% [48], owing to the total replacement of coarse aggregates by synthetic lightweight aggregates. The vertical and horizontal lines represent the error percentage with regard to the experimental data. It was observed that the increase in the plastic content caused an increase in the

elasticity of the total concrete matrix, causing an increase in the Poisson ratio, while the compressive strength and creep were found to decrease mainly because of the possible weak plastic-processed aggregate–cement interfacial zone.

3.3 Poisson's ratio

The relation among the Poisson ratio, compressive strength, and creep coefficient of recycled concretes is shown in

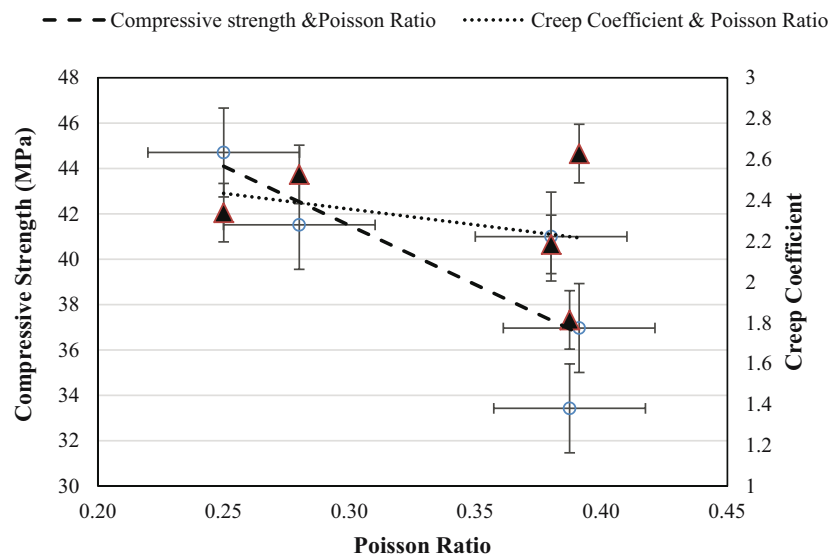


Figure 14. Relationship among the Poisson ratio, compressive strength, and creep coefficient for all the concrete series.

Figure 14. It was observed that the PPA integration in the concrete mixes as a replacement for coarse aggregates increased the Poisson ratio of the new concretes.

The maximum increase in the Poisson ratio at total recycle aggregate replacement was found to be approx. 56% compared to the reference concrete mix. In another study, the authors reported an increase of approx. 30% at total replacement of PPAs in the concrete mix [46]. The relation between the coefficient of creep and the Poisson ratio was also the same as that of the compressive strength and Poisson ratio; however, the decrease of the creep coefficients with respect to the Poisson ratio was steadier.

4. Conclusions

In this experimental study, the mechanical and creep characteristics of concrete integrating the PPAs were evaluated. The following are the main conclusions of this study:

1. The concrete mixes containing the total replacement of PPAs showed a reduction of approx. 18.6, 27.8, and 37.2% in the dry density, compressive strength, and splitting tensile strength compared to the reference concrete mix.
2. The instantaneous creep strain of the PPA concrete mixes was significantly higher than that of the reference concrete mix, with an increase ranging from 7 to 100%. Likewise, the ultimate shrinkage strain of the PPA concrete mixes showed an increase ranging from 28 to 119%, corresponding to the aggregate replacement of 25 and 100%, respectively.
3. The ultimate creep strain of PPA concrete mixes at a 25% replacement ratio showed the same creep characteristics as that of reference concrete mix; however, as the replacement level was increased from 50 to 100%, the ultimate creep strain increased by 3–69%, respectively. The increase of creep strains of the PPA concrete mixes can be attributed to the reduction in the mechanical properties of both the aggregate and subsequent concrete.
4. A model was also proposed to predict the creep coefficients of PPA concrete mixes. The model is a modification to the existing AASHTO (2007) and ACI 209.2R-08 creep equations to normalize it for processed plastic concretes. In addition, quantitative relationships linking the varying percentage of PPAs on the creep performance of recycled plastic concrete in relation to various mechanical properties were also established.

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Author contributions

Conceptualization: F.A.; Methodology: F.A. & I.Z.; Validation: F.A. & I.Z.; Formal Analysis: F.A. & I.Z.; Investigation: F.A. & I.Z.; Resources: F.A.; Data Curation: F.A. & I.Z.; writing–original draft: F.A. & I.Z.; writing–review and editing: F.A. & I.Z.; Funding acquisition: F.A.

Conflict of interest statement

Authors state no conflict of interest.

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