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Construction of Green Concrete Incorporating Fabricated Plastic Aggregate from Waste Processing

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Abstract: The recent industrial revolution has improved the quality of human life with technological advancement; adversely, it has also doubled waste generation, including plastic waste, in the last two decades. The concrete industry is under strict scrutiny to deliver tangible sustainable solutions to lessen its carbon footprint; the use of plastic waste in concrete can deliver a potential solution to these global environmental issues. In the current study, the fresh, mechanical and durability properties, including water absorption and chloride ion permeability of green concrete containing a plastic, fabricated aggregate were examined. The compressive and flexural strength gain with time was also examined and compared to reference concrete. All the mechanical parameters including compressive strength, flexural strength, splitting tensile strength and modulus of elasticity were found to decrease with the addition of fabricated plastic aggregates as compared to the reference concrete. The increase in the compressive strength and flexural strength at 100% replacement, with an increase in the curing period from 28 to 90 days, was 13% and 11%, respectively. The flexural deformation of green fabricated plastic aggregate concrete signposted the ductile behavior compared to the reference concrete. The concrete with 100% fabricated plastic aggregates showed an increase of 16.4% and a decrease of 68% in the water absorption and chloride ion permeability in comparison to the reference concrete, respectively. This study presents an effectual method for the utilization of plastic waste with promising results, especially for non-structural applications.

Keywords: sustainable structural lightweight concrete; green concrete; fabricated plastic aggregates; physical, mechanical and durability properties

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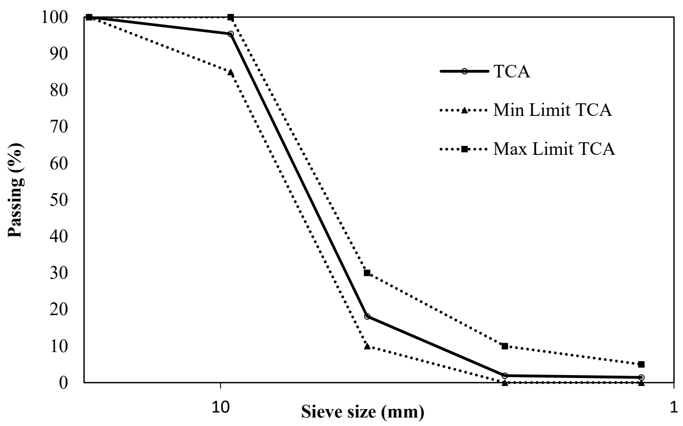
1. Introduction

The fifth industrial revolution has made the world identical to a global village. The habits, cultures, dynamics of life and basic needs have been revitalized with the technological aspect being the focal point. Likewise, the construction industry has also adopted new construction methods and materials to cope with the challenges being imposed. While all the technological advancements are trying to improve the quality of life, adversely, these aforementioned changes have also tremendously increased the production of waste [1]. Among the types of waste, plastic waste is one of the key concerns for environmentalists, as its percentage has doubled within the last two decades [2]. It was claimed that the yearly per individual production of plastic waste varied between 221 kg and 69 kg for countries like the United States and Japan, respectively [2]. However, the more alarming situation is not the generation of plastic waste; rather, it is the recycling percentage, which is on the lower side [3–5]. Therefore, serious efforts are needed from all the sectors, including the construction industry, to contribute to sustainable solutions for plastic recycling. Additionally, the construction industry is under strict scrutiny for its CO_2 emission levels and use of natural resources, while concrete experts are trying to opt for sustainable substitutes [6]. Therefore, in light of the above, the incorporation of recycled plastic in concrete can potentially offer the solution to both the aforementioned problems (plastic waste utilization and the carbon footprint of the concrete industry). It should be noted that attempts have been made in the past to incorporate plastic, and researchers have studied the behavior of concrete with the addition of different recycled plastics [7–17].

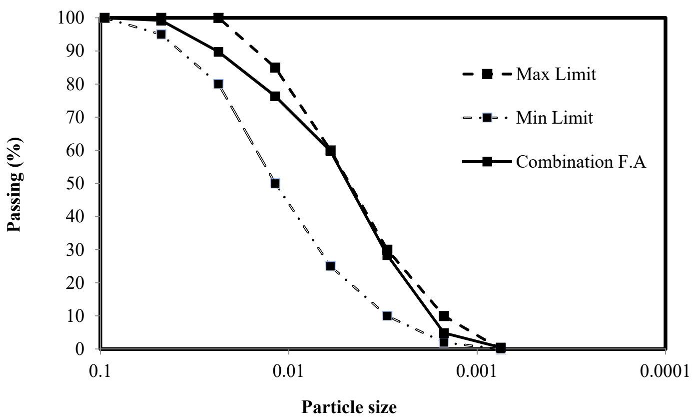
It was noticed that the addition of plastic particles has resulted in lowering the fresh density along with other significant mechanical properties. A cost-benefit analysis was conducted to recommend 10% of plastic (polypropylene) be used as a replacement for natural aggregate in a concrete matrix [18]. Another recent study used three different types of plastics (polypropylene, polyethylene terephthalate and high-density polyethylene) to evaluate the possibility of using them as a coarse aggregate for manufacturing curbs [19]. The test results of compressive strength compared with the minimum design strength suggested 20% as the extreme limit for all three plastic types [19]. A grade 20 concrete was designed by using polyethylene terephthalate plastic as a replacement for fine aggregates [20]. A workability, mechanical and cost analysis was carried out to determine the optimum percentage replacement, which came out at 40% [20]. Another study targeted producing a grade 20 concrete by using a plastic-based manufactured aggregate [21]. Belmokaddem et al. evaluated the morphology, physical and mechanical properties of concrete containing three different types of plastic wastes (high-density polyethylene, polypropylene and polyvinylchloride). The effort was made to maximize the utilization of plastic waste and up to 75% was replaced to get the desired concrete [22]. Tayeh et al. used 40% polyethylene terephthalate and polyethylene plastic waste for the replacement of fine particles in the concrete matrix and then evaluated their mechanical properties. [23]. However, the durability aspects of these concretes produced by the addition of plastic aggregates were limited. In one study, the abrasion resistance of concrete containing plastic with a total aggregate replacement of 7.5% and coarse aggregate replacement of 15% was determined, and an increase of 37% and 33%, respectively, was noted [6,10]. The increase may be attributed to the rough and brittle plastic particles. The performance of concrete containing plastic pieces with regard to water absorption was evaluated by replacing either the fine aggregate or coarse aggregate from the ordinary concrete matrix at the replacement ratios fluctuating from 15% to 50% [7,17,24,25]. It was noticed that for the aforementioned replacement percentage, the water absorption values improved by 17% to 55% [7,17,24,25]. The non-compatibility of the different aggregates within one mix resulting in a weak interfacial zone and increased permeability was attributed by the authors to the increased water absorption values. The drying shrinkage behavior was also examined at various replacement levels of plastic particles for either fine aggregate or coarse aggregate, and the produced concrete indicated higher shrinkage values because of the cement paste experiencing a weaker bond with the plastic particles [25–27]. In addition, the chloride ion permeability has also been investigated for concrete containing crinkled fragments of polyvinylchloride pipes and expanded polystyrene [28,29]. It was noticed that in the concrete produced with 45% crinkled fragments of polyvinylchloride pipes replacing the fine aggregates, the chloride ion permeability increased by 36% [28]. The chloride ion permeability also improved tremendously with the addition of 20 to 35% of expanded polystyrene as a replacement for the overall aggregate content in the concrete matrix [29]. Furthermore, another attempt was made to examine the mechanical properties of plastic aggregate concrete exposed to higher temperature ranges [30]. It was noticed that in the majority of the conducted studies, the recycled plastic particles were added by replacing either the fine aggregates or coarse aggregates from the concrete matrix; however, the studies presenting the durability investigations of concrete integrating fabricated plastic aggregates were inadequate. Therefore, the current study was designed to examine the change in the fresh, mechanical and durability properties of concrete containing fabricated plastic aggregates at different replacement ratios of 25%, 50%, 75% and 100%, with an aim to effectually utilize the plastic waste and lessen the carbon burden on the construction industry. All the concrete mixes were produced by means of a consistent water-cement ratio. The compressive and flexural strengths were also monitored over time. The flexural behavior was also studied using flexural deformation analysis for the newly produced concrete. The inspected durability properties included: water absorption, chloride ion permeability and fire resistance.

2. Materials Used and Experimental Details

Type-1, ordinary Portland cement was used to formulate all the concrete mixes. The specific gravity, initial and final setting times were found to be 3.15, 45 min and 135 min, respectively. In order to increase the eco-friendly value of the targeted concrete, the fine aggregates used were a mix of two: local dune sand and quarry waste. They were mixed in different percentages until the criteria [31] were satisfied, as shown in Figure 1a. The major parameter in the concrete constituents in this study was coarse aggregates. Three coarse aggregates were utilized: normal coarse aggregate (NCA); commercially produced lightweight aggregate, Lytag (CPA); and the plastic-based aggregates fabricated (PFA) by using the method registered under Alqahtani et al. [32]. The sieve analysis result of the natural coarse aggregates (crushed stone) and fabricated coarse aggregates, along with their standard limits is shown in Figures 1b and 2a, respectively. The sample PFA particle is shown in Figure 2b. It was observed that the particle sizes of coarse aggregates are almost within the limits specified by [33]. The PFA had shape and texture similar to the NCA aggregates. The fineness moduli of PFA and NCA were 5.743 and 5.83, respectively. The impact value (%) of NCA, CPA and PFA was found to be 9.65, 21.5 and 19.84, while 1554, 889, 1132 kg/m^3 were the unit weights for the NCA, CPA and PFA, respectively. The oven dry density was 2.59, 1.44, 1.81 for NCA, CPA and PFA, respectively. Finally, 1.48%, 16.82% and 0.95% were the water absorption rates for NCA, CPA and PFA, respectively. Normal drinking water was used for the preparation of the concrete mixes.

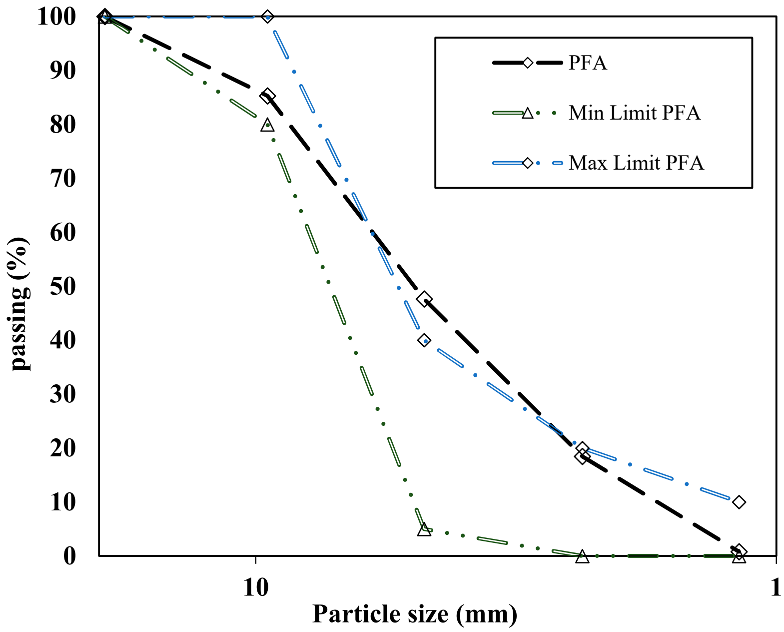


(a)



(b)

Figure 1. Sieve analysis of the normal coarse (**a**) and fine (**b**) aggregates for this study.



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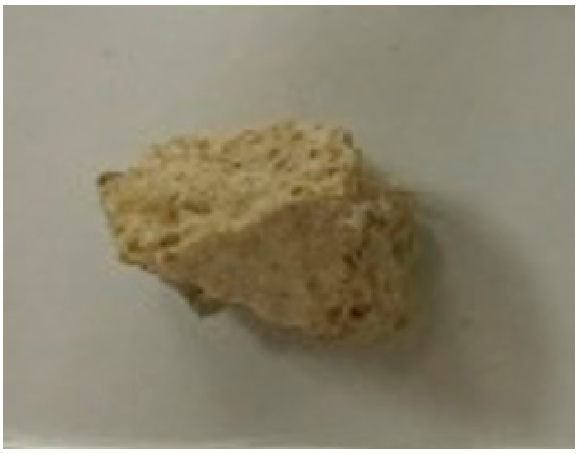


(**b**)

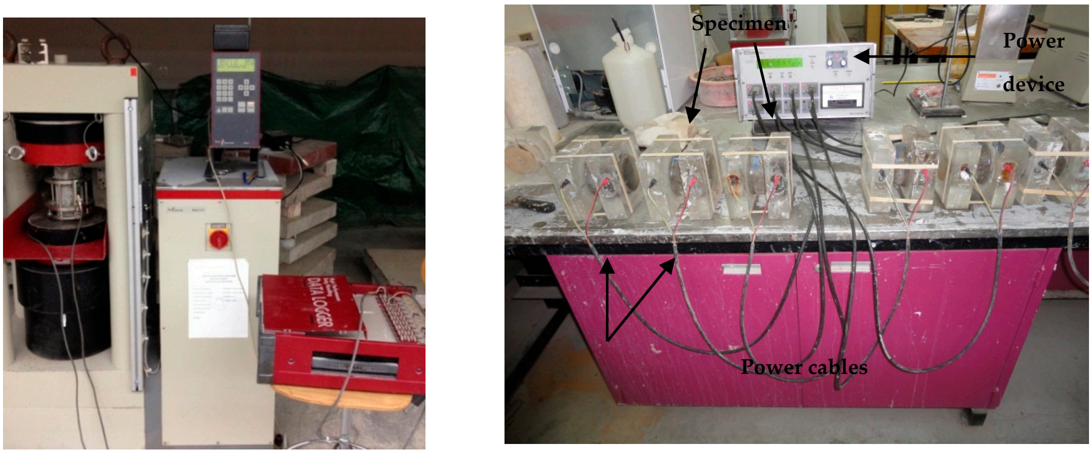
Figure 2. Sieve analysis (**a**) and typical shape of plastic fabricated coarse aggregates (**b**) used for this study.

The complete mix design quantities for the concrete mixes are shown in Table 1. A water to cement ratio of 0.5 was used for all the concrete mixes. The targeted design strength was 30 MPa. Three different types of concretes were prepared. Two were the control mixes, i.e., one made with NCA (CLC2) and the second with CPA (CLC1) for comparing the properties of the tested concrete with normal as well as lightweight concrete. The third concrete series was produced by replacing the NCA with four different replacement ratios of PFA (FALCXX) as shown in Table 1. The last two numbers in the designation of the specimens show the percentage of NCA being replaced with PFA.

To ensure the compatibility of the newly produced concrete with PFA, the fresh, mechanical and durability properties for all the concrete mixes were determined. The slump values were determined by using the traditional cone method following [34], while the fresh density was assessed by using [35]. The dry density, compressive strength, splitting tensile strength and modulus of elasticity were measured by using the procedures listed in [36–39], respectively. Figure 3a shows the test set-up for determining the modulus of elasticity for the concrete specimen.

Table 1. The concretes' mixing proportions for this study.

<table>
<tr><th rowspan="2">Concrete Series</th><th rowspan="2">Total Water</th><th rowspan="2">Free Water</th><th rowspan="2">Cement</th><th rowspan="2">Fine Aggregate</th><th colspan="3">Coarse Aggregate</th></tr>
<tr><th>NCA</th><th>PFA</th><th>CPA</th></tr>
<tr><th></th><th colspan="7">kg/m³</th></tr>
<tr><td>CLC1</td><td>302.4</td><td rowspan="6">225</td><td rowspan="6">450</td><td>759</td><td>-</td><td>-</td><td>452</td></tr>
<tr><td>CLC2</td><td>240.3</td><td>880</td><td>688</td><td>-</td><td>-</td></tr>
<tr><td>FALC25</td><td>239</td><td>847</td><td>516</td><td>141</td><td>-</td></tr>
<tr><td>FALC50</td><td>237.6</td><td>815</td><td>344</td><td>282</td><td>-</td></tr>
<tr><td>FALC75</td><td>236.2</td><td>782</td><td>172</td><td>423</td><td>-</td></tr>
<tr><td>FALC100</td><td>234.8</td><td>750</td><td>-</td><td>565</td><td>-</td></tr>
</table>



(**a**) (**b**)

Figure 3. Test set-up for modulus of elasticity (**a**), and chloride ion penetration (**b**).

Water absorption for all the concrete series was assessed by the techniques listed in [40]. The resistance of concrete to the chloride ion penetration was determined by using a concrete cylindrical specimen of 100 × 50 mm, following the steps indicated in [41]. Thus, the test was conducted in four stages, i.e., preparation, suction, saturation, and testing. The test set-up for chloride penetration resistance is shown in Figure 3b. The drying shrinkage of the concrete specimens was assessed by using the steps explained in [42]. A concrete prism of 75 × 75 × 285 mm was used for the drying shrinkage.

3. Study Results

3.1. Fresh and Mechanical Properties

The major fresh and mechanical properties of all the concrete series are shown in Table 2. All the values have been normalized with respect to the reference lightweight concrete (CLC1). It was observed that, except for slump, all the measured parameters for the reference normal weight concrete were observed to be higher than for CLC1. The values of slump and fresh density were found to be inversely related for all the FALC series as compared to CLC2. The fresh density values were found to reduce with the percentage of PFA increasing in the concrete mix with CLC2 as datum. This decrease may be because of the lightweight PFA particles contributing to the reduction in overall density of the concrete mix. The same trend was found for the dry density values. The increase in the slump values and decrease in the fresh and dry densities are in agreement with the previous findings [13,15,17,18]. As expected, the mechanical parameters including the compressive strength, splitting tensile strength and modulus of elasticity showed a reduction with the addition of PFA. The decrease in modulus of elasticity was more profound at 100%

replacement of PFA as compared to compressive or splitting tensile strength. The decline in the values of the mechanical parameters was found to be in line with existing studies [18,19]. The decrease in the mechanical properties primarily may be because of the weak interfacial bond between the fabricated aggregates and the cement paste, as compared to normal coarse aggregates. The percentage of plastic increases this effect.

Table 2. Normalized major fresh and mechanical properties with respect to control lightweight concrete.

Concrete Mixes	Slump (mm)	Fresh Density (kg/m^3)	Dry Density (kg/m^3)	Compressive Strength (MPa)	Splitting Tensile Strength (MPa)	Modulus of Elasticity (GPa)
CLC1	240	1876	1625	33.4	2.34	17.95
CLC2	95	2327	2183	41.8	3.58	27.82
FALC25	140	2213	2086	35.31	3.32	20.58
FALC50	170	2139	1995	31.72	2.42	15.06
FALC75	175	2016	1896	30.41	2.36	10.66
FALC100	190	1938	1777	30.21	2.25	10.14

3.2. Mechanical Properties and Time

As discussed in the previous section, the fresh and mechanical properties of the FALC concretes were affected as compared to CLC1 and CLC2. Therefore, in order to observe the detailed trend of the major mechanical properties (compressive strength and flexural strength), their variation with different curing periods was observed.

3.2.1. Compressive Strength at Different Curing Periods

The trend of the compressive strength gain at different curing periods for the PFA concrete is shown in Figure 4. As seen in Figure 4, the rate of improvement in compressive strength with age (7 to 28 days) for FAlC made at 25, 50, 75 and 100% replacement of NCA with PFA was 32, 31, 40 and 29%, respectively, as compared to 40% for CLC2 and 49% for CLC1. Similarly, the compressive strength improvement from 28 to 90 days was noted as 21, 16, 12 and 13% at the same replacement levels, respectively, as compared to 38 and 35% attained by CLC2 and CLC1, respectively.

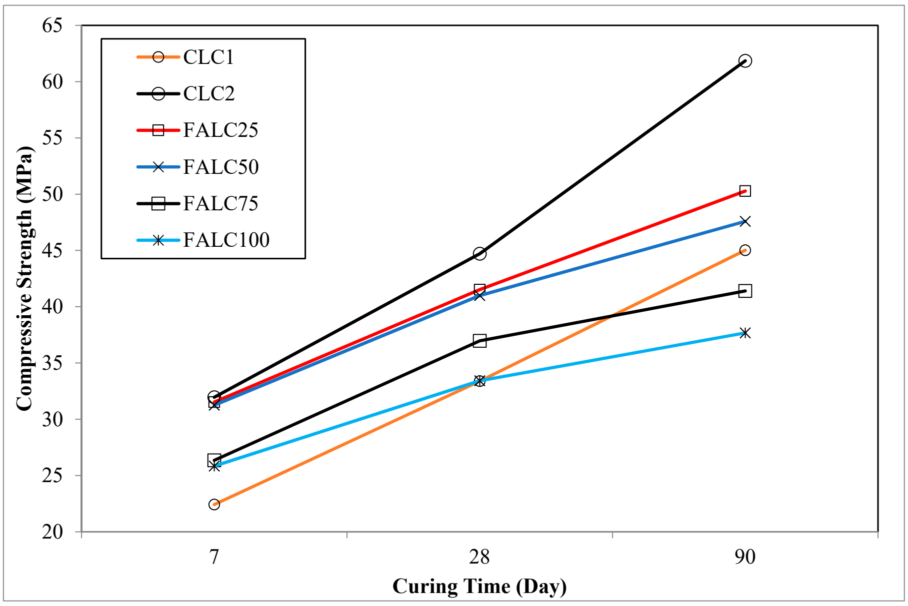


Figure 4. Influence of replacement level on compressive strength of FALC after 7, 28 and 90 days of curing, in comparison with CLC1 and CLC2.

These results show that the improvement in the compressive strength rate with age (up to 90 days) fluctuated with respect to the increase in replacement content. However, in general, the strength gained from 7 to 28 days is much higher than that observed from 28 to 90 days. Therefore, it was observed that, despite the decrease in the compressive strength of FALC concretes in comparison to CLC2, the strength gain trend and mechanism remained the same for both of the concrete types.

3.2.2. Flexural Strength at Different Curing Periods

The influence of the replacement level on flexural strength of FALC after 7, 28 and 90 days of curing in comparison with CLC1 and CLC2 is shown in Figure 5.

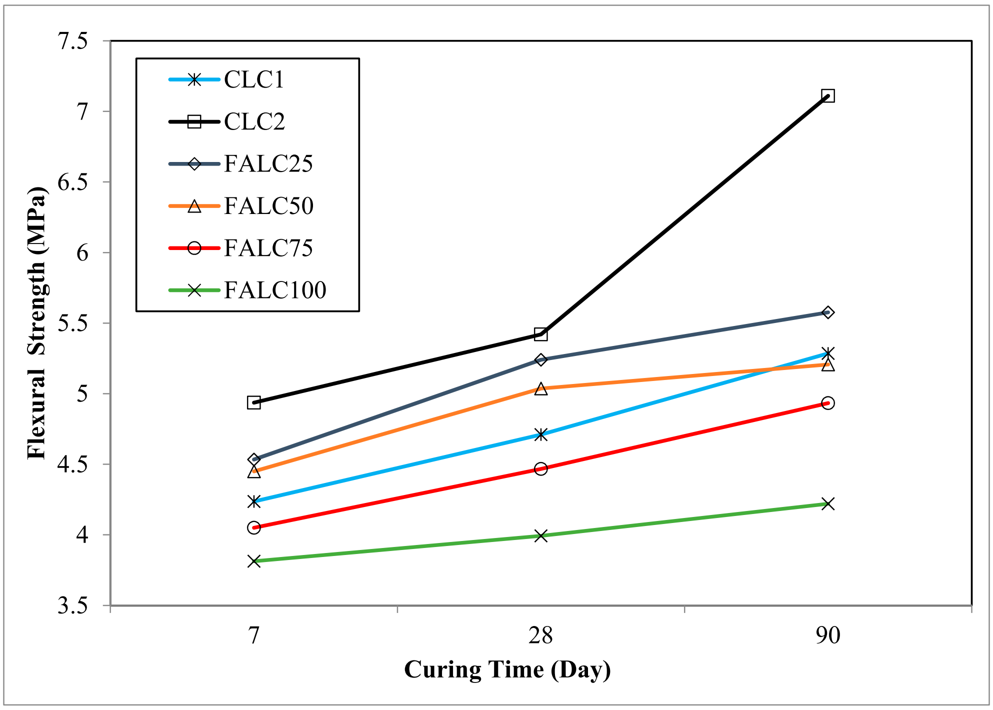


Figure 5. Influence of replacement level on flexural strength of RP3F3Cs after 7, 28 and 90 days of curing, in comparison with NC and LAC.

It was observed that FALC prepared at various substitutions (25 to 100%) of PFA showed the enhancement in the flexural strength values with age. The improvement in flexural strength with age (from 7 to 28 days) varied from 5 to 16% as compared to 10% for CLC2 and 11% for CLC2. In the same way, the increase in the curing period of FALC from 28 to 90 days resulted in a similar improvement, varying between 3 and 11%, as compared to 31 and 12% achieved by CLC2 and CLC1, respectively.

3.2.3. Flexural Deformation

The behavior of the FALC under flexural loading was also observed, as the incorporation of fabricated plastic aggregates might enhance the ductility of the concrete mix. The experimental load-deformation curves for concretes having different fabricated aggregate proportions are shown in Figure 6. It was observed that FALC achieved sudden failures, similar to conventional concrete, i.e., CLC2. However, the deformation corresponding to the peak load at failure was proportionally increased with the increase in the replacement content of PFA.

It is clear from this figure that the peak load was reduced by 6, 10, 21 and 22%; concurrently, the deformation corresponding to the peak load was 2, 20, 22 and 22% higher than CLC2, due to replacing the PFA by 25, 50, 75 and 100%, respectively. These results are consistent with the findings of [14] in which a 9% improvement in flexural deflection was found for concrete made directly with a 20% plastic replacement for FA. Therefore, it is clear that the increase of the NCA replacement with PFA prolonged the failure, showing more ductile behavior of the resulting concrete.

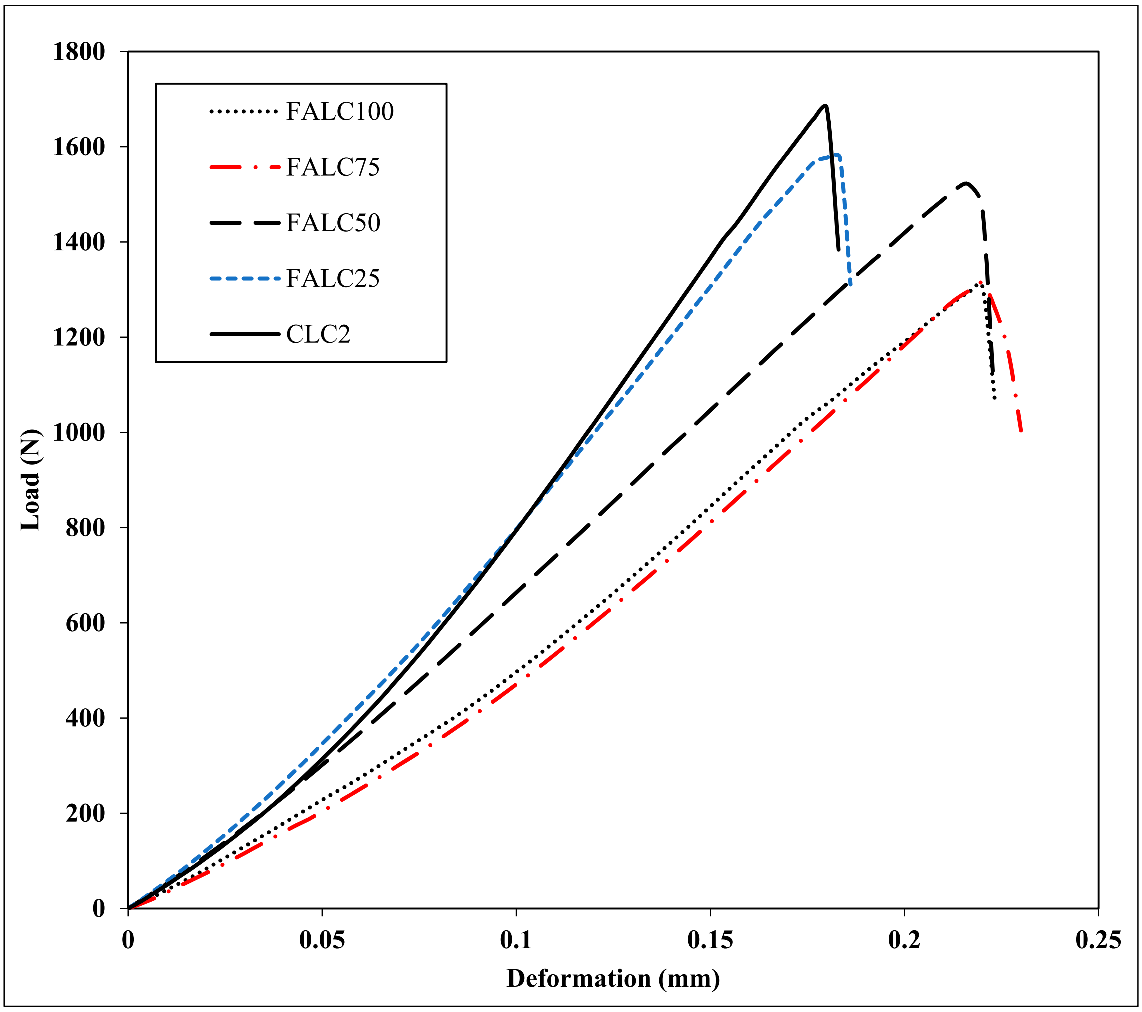


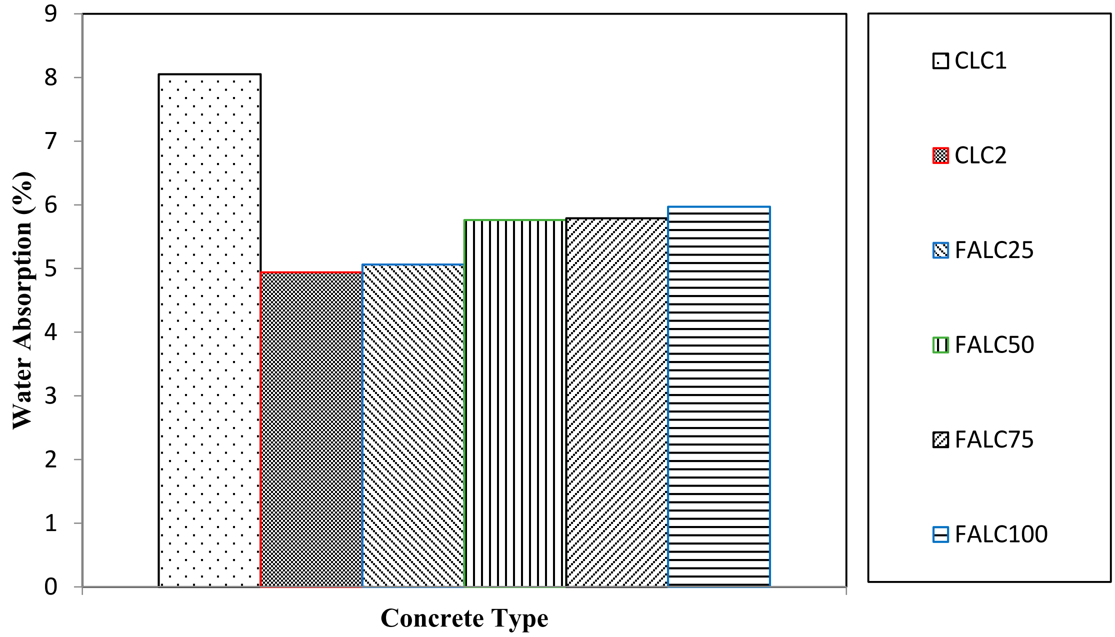
Figure 6. Trend of failure deformation for FALC mixes.

3.3. Durability Related Properties

3.3.1. Water Absorption

The water absorption values for FALC mixes at different fabricated aggregate proportions are shown in Figure 7a.

It was observed that there was a marginal difference of less than 3% between the water absorption of CLC2 and FALC25; however, CLC2 had 16 to 21% lower water absorption than the remaining FALC mixes, as shown in Figure 7a. Nonetheless, the increase in the water absorption of the FALC mixes is still lower than that reported in previous studies [17,19,43] where replacing 15% and 50 to 80% of CA and both aggregates (CA and FA) with plastic particles increased water absorption by 33% and 55 to 98%, respectively. This increase in the water absorption of FALCC is most likely related to the decrease in the packing level of the mix due to the poorer grading of PFA compared with that of NCA. Furthermore, it was also noticed that CLC1 showed higher water absorption values compared to all FALC mixes, mainly because of the higher water absorption of CPA compared to PFA. In addition, the water absorption values for the current study were plotted against the existing studies and are shown in Figure 7b.



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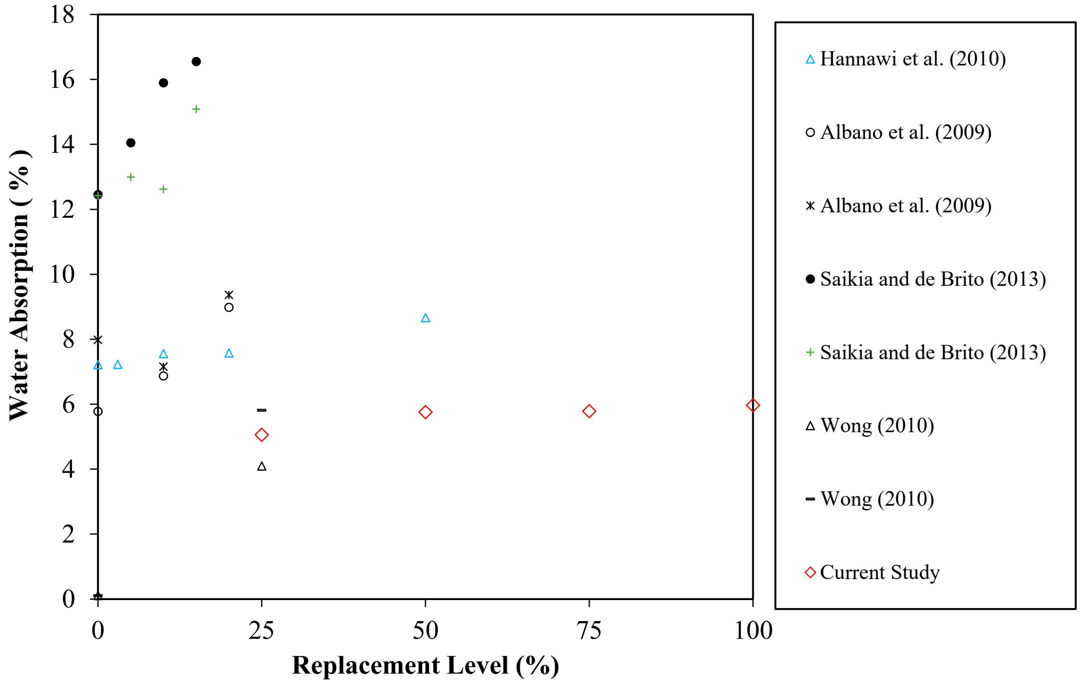


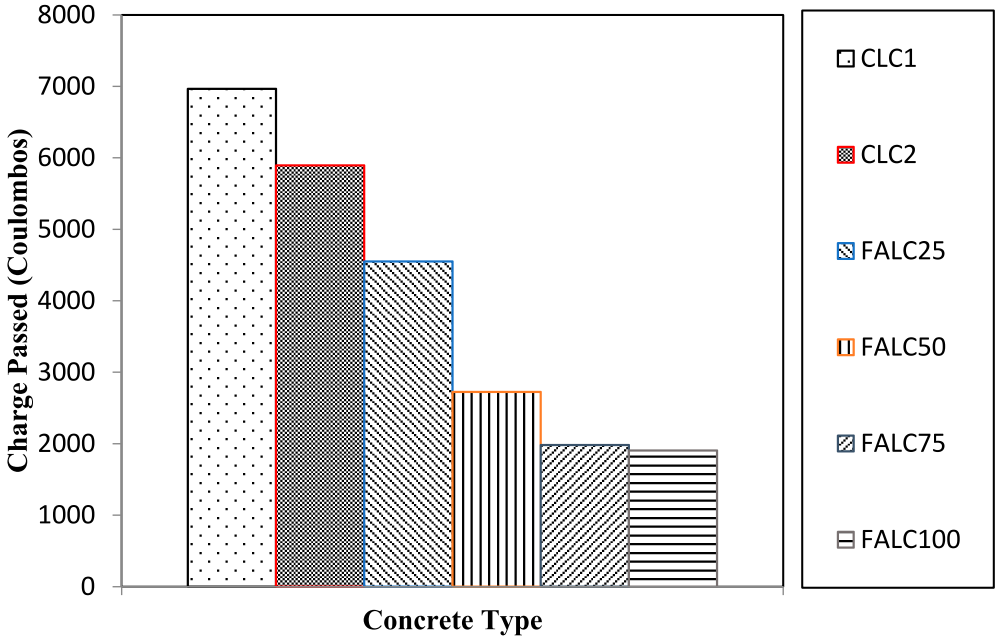
(**b**)

Figure 7. (**a**). Water absorption of all concrete series in this study. (**b**). Water absorption of current study compared with existing studies [7,10,24,25,43].

It was observed that overall, the percentage aggregate replacement for the existing studies which estimated the water absorption values was on the lower side as compared to the current study [7,18,19,43]. However, for the same replacement ratio, the water absorption values were found to be less as compared to previous studies as shown in Figure 7b.

3.3.2. Chloride Permeability

The chloride permeability values for FALC mixes at different fabricated aggregate proportions were assessed by the amount of charge passed and are shown in Figure 8a.



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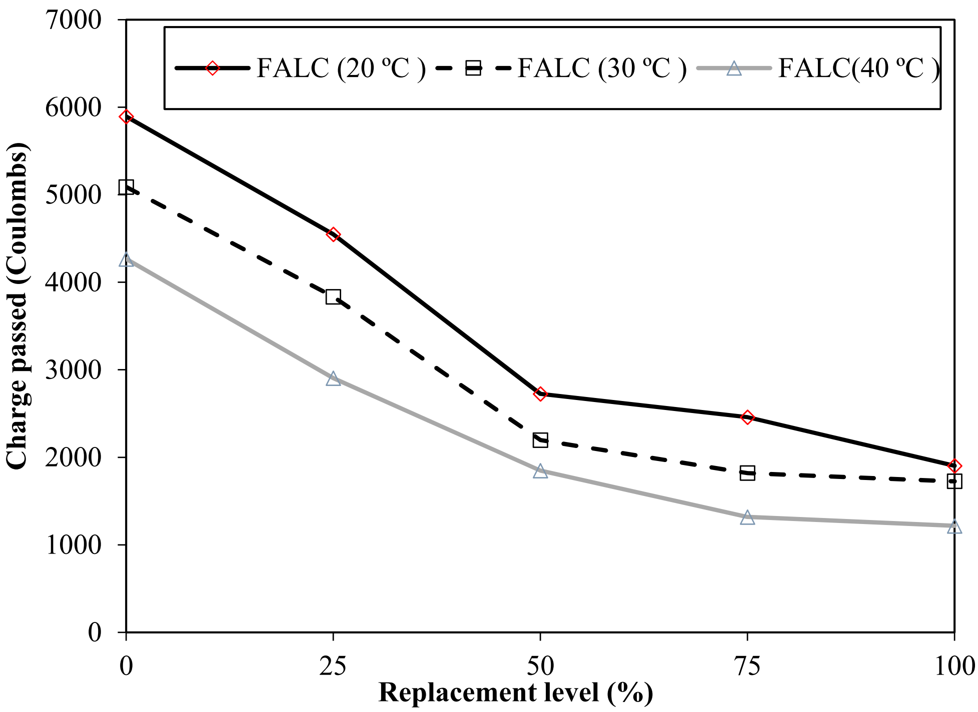

(**b**)

Figure 8. (**a**) Chloride permeability of all concrete series in this study. (**b**) Effect of curing temperature on chloride permeability.

From the results, it was shown that the decrease in the chloride permeability of the FALC mixes compared with that of CLC2 ranged from 23 to 68% (1346–3991 coulombs), as the substitution percentage PFA was increased from 25 to 100%. The explanation for these reductions is in agreement with [12], which is related to the lowered ion conductivity and impervious nature of the plastic that exists in the PFA matrix. Consequently, the passage for ion transfer is disrupted and thereby, chloride ion penetration is reduced. Furthermore, it was also noticed that CLC1 had shown higher chloride permeability values compared to all FALC mixes, mainly because of the higher water absorption of CLC1 compared to FALC mixes, which provides easy access for the ions to flow. In addition, the effect of the curing temperature on the chloride permeability was also studied. The concrete specimens produced by using the fabricated plastic aggregates were cured at three different temperatures, i.e., 20 °C, 30 °C and 40 °C, and the chloride penetration resistance was measured for each replaced percentage at each temperature; the results are shown in Figure 8b.

It was observed that the increase in the curing temperature resulted in a decrease in the chloride penetration resistance for all types of concrete. The percentage decrease from the CLC2 was found to be 13.7% and 27.6% as compared to the specimens cured at ordinary temperature (20 °C), at 30 °C and 40 °C, respectively. In addition, the increase in the percentage of fabricated aggregates further lessened the chloride permeability of the concretes, i.e., at 25% replacement the decrease was found to be 15.7% and 36.1% as compared to the specimens cured at ordinary temperature (20 °C), at 30 °C and 40 °C, respectively. Concurrently, for 100% replacement of fabricated aggregates, the reduction percentages were 9.3% and 36.1% as compared to the specimens cured at ordinary temperature (20 °C), at 30°C and 40°C, respectively.

3.3.3. Drying Shrinkage

The drying shrinkage values for FALC mixes at different fabricated aggregate proportions (50% and 100%) were assessed by the amount of charge passed and are shown in Figure 9. The drying shrinkage values have generally increased as compared to both the reference concrete mixes.

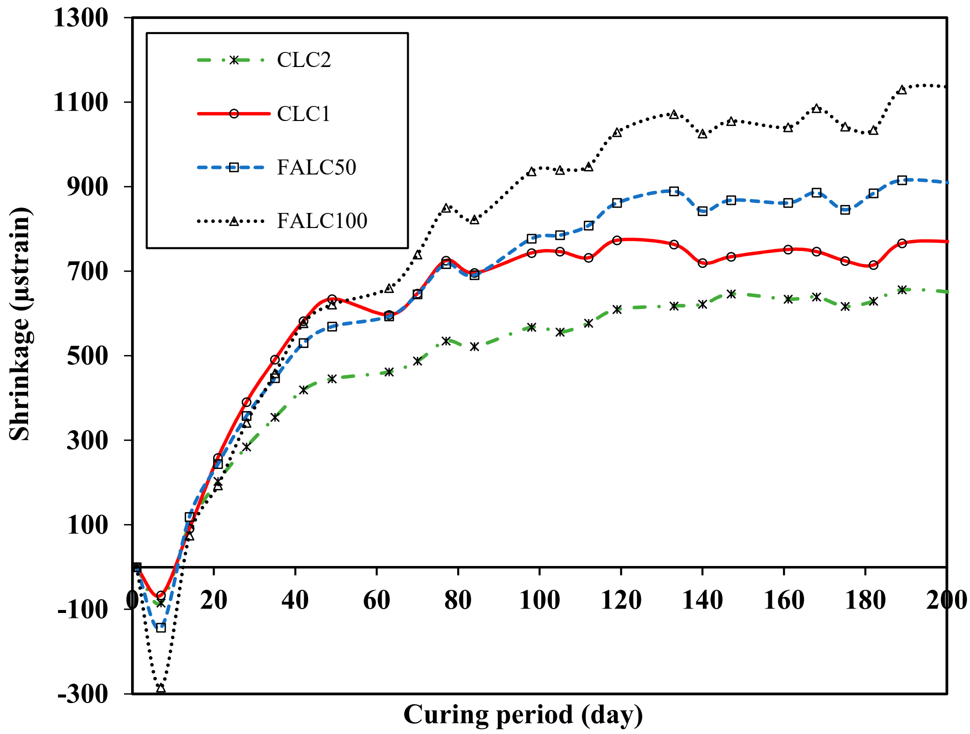

Figure 9. Drying shrinkage of concrete mixes (FALC50, FALC100, CLC1 and CLC2).

The increase in the drying shrinkage of the FALC mixes compared with that of the CLC2 ranged from 26 to 29% (93–104 μstrain), from 37 to 65% (210–369 μstrain) and from 39 to 72% (259–474 μstrain) at 28, 91 and 182 days of air curing, respectively, as the replacement level was increased from 50 to 100%. However, FALC100 and LAC had drying shrinkage results that differed by –7 to 47% (–33 to 364 μstrain) at the same period of curing. The increase in the drying shrinkage values is mainly attributed to the lower modulus of elasticity of FALC mixes and the lower water absorption of PFA. The previous studies have reported higher drying shrinkage values with the addition of plastic aggregates [21,22] which indicated the acceptable behavior of the prepared FALC series in this study. In addition, it was noted that Sojobi et al. (2021) had recommended the percentages for ternary blends, to produce the hollow sandcrete blocks with zero shrinkage, which can be considered to reduce the shrinkage for the concretes in the current study [44].

4. Discussion

4.1. Correlation between Dry Density and Compressive Strength

From the results of the mechanical properties, it was found that the dry density as well as the compressive strength were affected by the replacement with fabricated aggregates; however, to explore in detail the relationship between the changes, the 28-day compressive strength and dry density for the newly produced concretes in comparison with the results of existing studies was studied and is shown in Figure 10.

The overview of the results obtained in Figure 10 shows an increasing trend between density and compressive strength. However, in reality, there is no generalized relationship between density and compressive strength for different types of lightweight concrete [8,11,13,18,20,45–51]. The correlation suggested in this study has a correlation coefficient (R^2 = 0.74) and this can be expressed (Equation (1)) as:

$$F_c = 0.043x - 49.411 \tag{1}$$

where:

y is the 28-day cylinder compressive strength (MPa)

x is the 28-day dry density (kg/m^3)

The difference between the experimental and the predicted compressive strength values using Equation (1) is shown in Table 3. It was observed that the proposed equation has overestimated the results for the predicted compressive strength values at 25, 50 and 75% replacement levels by a range varying from 6.6 to 14.8%. However, at full replacement level (100%), the proposed equation has underestimated the result for the predicted compressive strength by 10.6%. These findings confirm that the concrete made with shredded or plastic particles behaves differently than that made with aggregate manufactured from plastic aggregate used in the current study.

Table 3. Comparison between experiment and predicted compressive strength.

Concrete Type	Experimental Results		Predicted Results (MPa)	Percentages Difference between Predicted and Experimental Results
	X (kg/m^3)	Y (MPa)	Equation (1)	(%)
FALC25	2086	35.3	40.3	14.2
FALC50	1995	31.7	36.4	14.8
FALC75	1896	30.4	32.1	6.6
FALC100	1777	30.2	27	−10.6

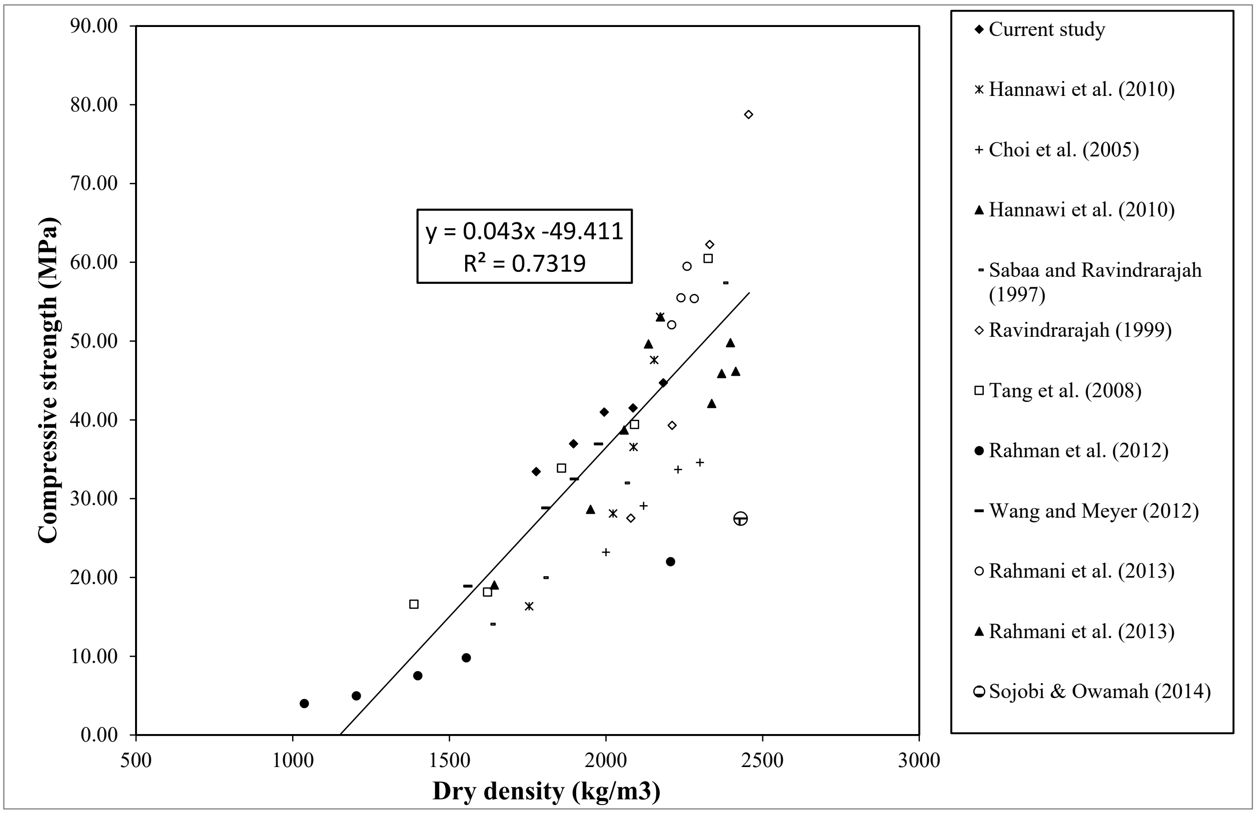

Figure 10. Correlation between 28-day dry compressive strength and dry density for FALC in comparison with existing studies [8,11,24,26,45,49–51].

4.2. Correlation between Chloride Permeability and Compressive Strength

As one of the primary indicators of the concrete matrix, permeability varied with the addition of fabricated aggregates into the concrete mix; therefore, the relationship between the altered permeability and compressive strength in light of an existing study conducted by Kou et al. [12] was investigated, and is shown in Figure 11. The following equations were derived by regression analysis for the plotted data of FALC (Equation (2)) and the existing study (Equation (3)), respectively:

$$y = 333.03\,(f_c) - 7780.7 \quad (2)$$

$$y = 111.94\,(f_c) + 1327.3 \quad (3)$$

It was observed that regardless of the concrete type, the decrease in the strength resulted in decreased chloride permeability values. Thus, the increase in the percentage of the fabricated aggregate addition resulted in reduced strength and correspondingly, permeability values.

Table 4 presents the percentage difference in the values predicted by Equations (2) and (3) and the experimental values. It was noticed that Equation (2) yielded a good prediction of the chloride permeability of the FALC mixes with an error ranging from 12.6 to 1.9 % for f_c values ranging from 31.7 to 35.3 MPa, respectively, while the same equation overestimates the chloride permeability for FALC at 75 and 100%. On the other hand, Equation (3) had shown a higher difference with the predicted values being overestimated by 16.04 to 147.3%, respectively. The percentage difference increased with the increase in the replacement of the fabricated aggregates. This is due to the differences in the type of aggregates used in Kou's study compared to the plastic aggregate manufactured in the current study and its resulting concrete. The chloride penetration resistance of concrete prepared with other waste or by-products (fly ash and crushed sand as a replacement for cement and river sand) has also been examined, and it was found that the incorporation of these materials has resulted in higher chloride ion resistance as compared to the concrete prepared using recycled plastic aggregates, as shown in the current study [52,53].

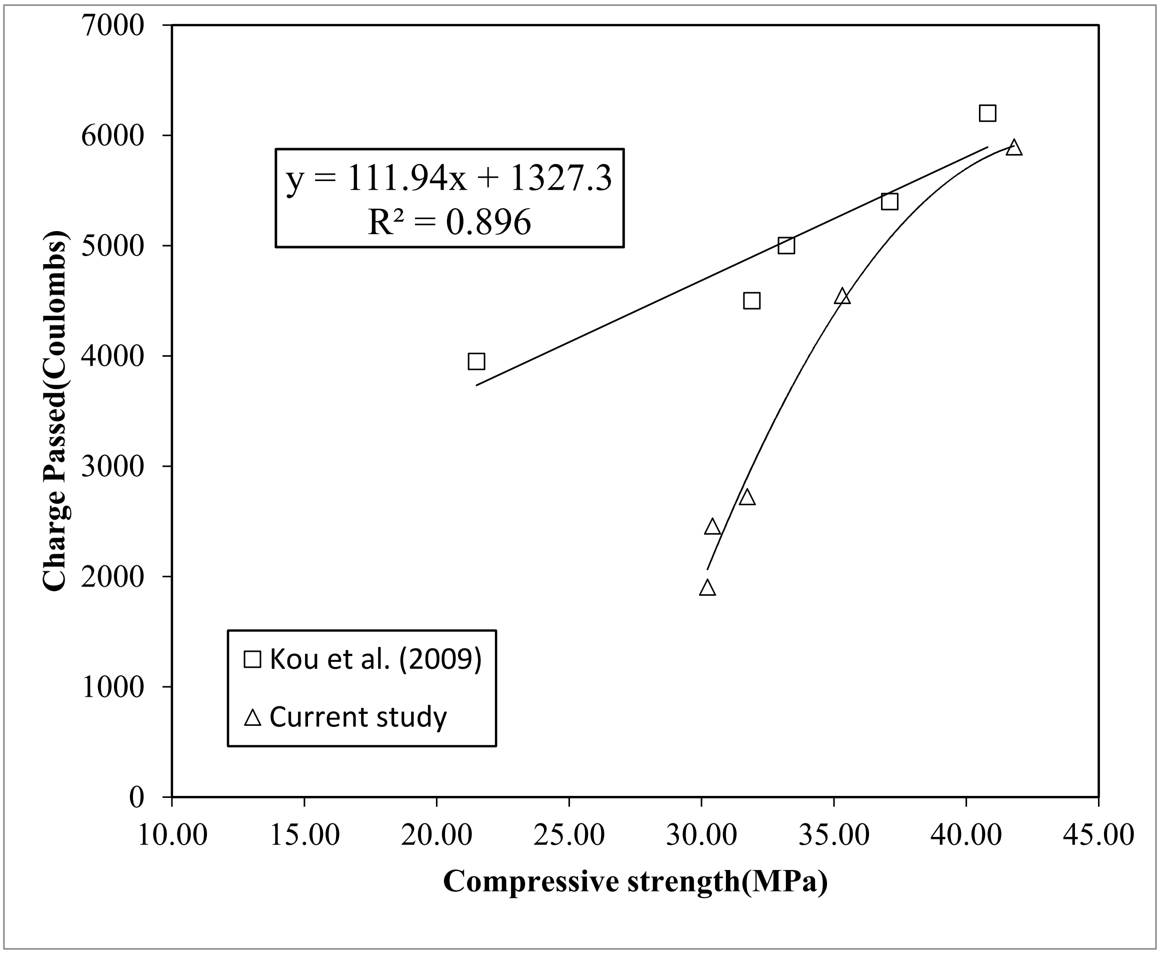

Figure 11. Relationship between compressive strength and chloride permeability [12].

Table 4. Percentage difference in the values predicted by Equations (2) and (3).

Concrete Type	Experimental Results		Predicted Results		Percentage Difference between the Predicted and Experimental Results	
	x	y	Equation (2)	Equation (3)	Equation (2)	Equation (3)
FALC25	35.3	4549	3975.2	5278.8	–12.6	16.04
FALC50	31.7	2725	2776.3	4875.8	1.9	78.9
FALC75	30.4	1981	2343.4	4730.3	18.3	138.7
FALC100	30.2	1904	2276.8	4707.9	19.6	147.3

In addition, the correlation between the chloride permeability and the compressive strength of the fabricated aggregate concrete was also obtained for different curing temperatures, and the results are shown in Figure 12.

It was observed that the increase in curing temperature resulted in a decrease in the compressive strength, and correspondingly, the chloride penetration resistance also decreased. The equations for different curing temperatures are also proposed and shown in Figure 12.

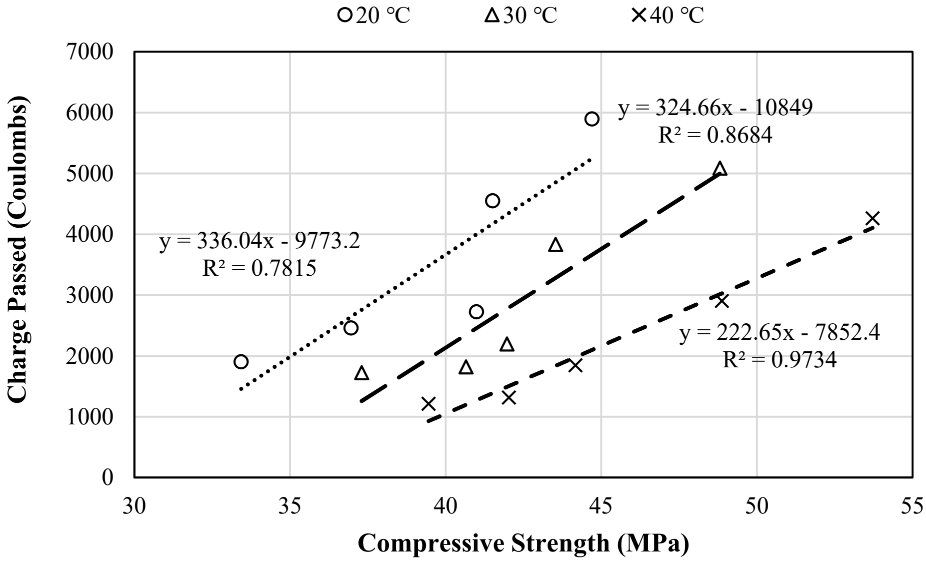

Figure 12. Relationship between compressive strength and chloride permeability at different curing temperatures.

5. Conclusions

The current study was undertaken to investigate the change in the fresh, mechanical and durability properties of green concrete containing fabricated plastic aggregates at different replacement ratios. The compressive and flexural strengths were also monitored over time, along with an insight into the flexural deformation for the newly produced green concrete. The examined durability properties included water absorption and chloride ion permeability. The major conclusions are as follows:

1. Except slump, the fresh as well as the mechanical parameters including dry density, compressive strength, splitting tensile strength and modulus of elasticity have shown a reduction with the addition of fabricated plastic aggregates as compared to typical concrete. The slump increased due to the fluidity created in the mix because of the presence of plastic; concurrently, the decrease in the mechanical properties is mainly related to the weakening of the interfacial bond between the fabricated aggregates and the cement paste, as compared to normal coarse aggregates. The percentage of plastic increases this effect.
2. The compressive strength improvement from 28 to 90 days was noted as 21, 16, 12 and 13% at the 25, 50, 75 and 100% replacement of normal coarse aggregates with fabricated plastic aggregates, respectively. During the same curing period, a slight improvement varying between 3 and 11% was observed for flexural strength. In addition, it was also evident from the flexural deformation test that the increase of the replacement percentage of fabricated plastic aggregates extended the failure, showing the more ductile behavior of the resulting concrete.
3. The increased water absorption and decreased chloride ion-based permeability was observed with the increase in the addition of fabricated plastic aggregates in the normal concrete. The increased water absorption may be linked to the decrease in the mechanical properties because of the weakened bonding between the plastic aggregates and the cement. Concurrently, the decrease in the chloride ion permeability might be related to the presence of plastic particles, which can form hurdles for the flow of the ions.
4. The relations between the dry density, permeability and compressive strength were also examined and equations were proposed for green plastic aggregate concrete. The current study showed an efficient method to utilize plastic waste in large quantities; however, the industrial non-structural applications should be subjected to detailed durability and economic investigations.

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