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Novel Lightweight Concrete Containing Manufactured Plastic Aggregate

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ABSTRACT

Plastic waste and its low recycling rate make a significant contribution towards the pollution of the environment. It is therefore essential that plastic waste is utilised in different applications, such as aggregates in concrete. In this paper, an investigation of a manufactured plastic aggregate as a replacement for pumice lightweight aggregate and Lytag aggregate in concrete is presented. The influence of replacement level on the fresh, hardened and microstructure properties of concrete was investigated. The slump, compressive strength, flexural strength, splitting tensile strength and elastic modulus decreased with the increase in replacement level. Neither the fresh density nor the hardened density was significantly affected by replacement level. The Lytag and conventional lightweight concrete mixes had a brittle failure; whereas the concrete mixes incorporating the manufactured plastic aggregate had a ductile post-peak behaviour. The results suggest that the concrete mix containing the manufactured plastic aggregate at a replacement level of 25% can be used in structural and non-structural applications requiring moderate strength and ductility. Predictive models were proposed and demonstrated to be in good agreement with the experimental results for the mechanical properties of the concrete mixes incorporating the manufactured plastic aggregate.

Keywords: plastic waste; recycled plastic aggregate; lightweight aggregate; lightweight concrete; mechanical properties; SEM; correlations

Abbreviations

CA	Coarse aggregate
E_c	Modulus of elasticity
FA	Fine aggregate
ITZ	Interfacial transition zone
LAC	Concrete made using Lytag aggregate
LWA	Conventional pumice volcanic lightweight aggregate
LWC	Concrete made using conventional lightweight aggregate (LWA)
LYA	Lytag aggregate
RP2F1A	Recycled plastic aggregate made using 30% LLDPE and 70% red or dune sand
RP2F1C	Concrete made using recycled plastic aggregate (RP2F1A)
RP2F1C25	The concrete mix containing RP2F1A at a replacement level of 25%
RP2F1C50	The concrete mix containing RP2F1A at a replacement level of 50%
RP2F1C75	The concrete mix containing RP2F1A at a replacement level of 75%
RP2F1C100	The concrete mix containing RP2F1A at a replacement level of 100%
RPAs	Recycled plastic aggregates
SLA	Synthetic lightweight aggregate
W/C	Water to cement ratio
WPLA	Waste PET lightweight aggregate
f_c	Cylinder compressive strength
f_r	Flexural strength
f_t	Splitting tensile strength
γ_w	Dry density

1.0 Introduction

The use of plastic is consistently growing because of its versatility. The total plastic produced worldwide in 2014 was estimated at 313 million tonnes (Mt) [1]; in 2015 it increased to 322 Mt, which is about 3% rise in two years [2]. According to the Plastic Association, the European consumption of plastic in 2014 was 59 Mt, with almost half of this amount (i.e. 25.8 Mt) being disposed of as waste [2]. Unfortunately, the recycling rate is not encouraging, since only 29.7% of the plastic waste was recycled in Europe in 2014 and only 8.8% in the USA in 2012 [2, 3].

The bulk quantity of waste plastic is usually sent to landfill or dumped into the oceans, which are the terminus in the lifecycle of plastic, causing polluting effects over long periods of time. For instance, it has been reported that around 28.95 Mt of plastic waste was disposed of in the USA in 2012 [2, 3]. Moreover, Jambeck et al. [4] reported that every year, from 4.8 to 12.7 million metric tonnes of plastic waste are disposed of in the oceans. Alternatively, plastic waste is incinerated; however, this generates a significant amount of carbon and other toxic emissions, as well as the generation of residue which also presents toxicity issues [5].

For these reasons, the possibility of using plastic waste in different industries, such as the construction sector was explored. One of the potential applications is implementing plastic as replacement for aggregates in concrete, since the consumption of aggregates reached 48.3 billion metric tonnes in 2015 [6]. Several studies [7-26] were conducted on the effect of replacing coarse (CA) and/or fine aggregate (FA) in concrete with plastic. However, few studies have reported on the influence of manufactured plastic aggregate on the performance of concrete, when it is used as a replacement for aggregate [27-34].

The use of plastic to manufacture plastic aggregate has the potential to mitigate the aforementioned problems and reduce the rapid consumption of non-renewable materials such as natural aggregate. Additionally, it could overcome the drawbacks associated with existing lightweight concrete made from either natural or manufactured lightweight aggregates. For example, concrete containing natural lightweight aggregate (i.e. pumice or scoria) has high mining and hauling costs, excessive drying shrinkage and high water absorption. In the same context, incorporating a manufactured aggregate, such as Lytag, in concrete can adversely affect the durability performance due to its high permeability; along with consuming high levels of energy, supplementary materials and chemical additives during its manufacture [27-28].

The main findings of the research studies [8, 10, 21-22, 24] conducted on concrete containing shredded or plastic aggregate particles indicate that the concrete workability, density and mechanical properties; such as compressive strength, splitting tensile strength, flexural strength and modulus of elasticity; significantly decrease with the increase in plastic content. For example, the density of concrete and cement mortar was reduced by 7 to 50% due to the increase in the ratio of plastic particles from 20 to 100% [7, 9, 16, 18, 20, 22]. Other researchers [11, 19] observed a marginal decrease in density, varying from 6 to 10%, at high replacement levels (from 75 to 100%) of CA or FA with plastic. Furthermore, studies [8, 9, 11, 18, 20, 22, 25] reported a significant reduction, ranging from 34 to 70%, in the 28-day concrete compressive strength when 20 to 100% of the conventional FA was substituted directly with plastic. Similarly, replacing 30 to 80% of the conventional CA directly with plastic resulted in a substantial reduction (ranging from 65 to 78%) in the 28-day concrete compressive strength [14, 16-17, 26].

Other studies [27-34] have showed a similar decreasing trend in the mechanical properties of concrete with an increase in synthetic lightweight aggregate content; while workability increased in some instances and in others it is decreased. For instance, Choi et al. [27, 28] reported that the slump of concrete made with waste PET lightweight aggregate (WPLA), at a 75% replacement level of FA, was 46% higher compared to conventional concrete. This increase was attributed to the spherical shape and smooth surface texture of the WPLA particles. Conversely, a reduction in slump (ranging from 7 to 28%) was also observed by other researchers [30, 31, 33] when lightweight CA was fully replaced with synthetic lightweight aggregate (SLA). However, the plastic-based aggregates developed in these studies [27-34] were of the same shape and size. Additionally, these aggregates were either a composite made from plastic and fly ash, or plastic coated with either river sand or granulated blast furnace slag (GBFS). Moreover, the extrusion process used for the production of these aggregates restricted the scope of their practical utilization.

The extant literature suggests that widely available fillers (e.g. red sand and quarry fines) need to be utilized for the manufacture of well graded plastic-based aggregates. Recently, Alqahtani et al. [34, 35] manufactured recycled plastic aggregates (RPAs) using different types of plastic and fillers by means of a novel technique (compression moulding press). Tests carried out on concrete samples showed that slump, fresh density and 28-day compressive strength results ranging from 40 to 220 mm, 1827 to 2055 kg/m^3 and 14 to 18 MPa, respectively, were achieved with the total replacement of CA in concrete.

The novel contribution of the present study is to implement one of the previously manufactured RPAs (i.e. RP2F1A) [34, 35] as a replacement for pumice lightweight coarse aggregate (LWA). The effect of various replacement levels (i.e. 25, 50, 75 and 100%), on a volumetric basis, on the fresh, hardened and microstructure properties was investigated. Moreover, the influence of fully replacing Lytag aggregate (LYA) with RP2F1A on the same properties was examined. Furthermore, predictive models were proposed for the mechanical properties of the concrete mixes containing RP2F1A.

2.0 Materials and methods

2.1 Materials

Portland cement from a local manufacturer, with a specific gravity of 3.15, was used throughout this study; which satisfied the requirements of ASTM C150/C150M. Various types of coarse aggregates; which included RP2F1A, LWA and LYA (see Fig. 1); were used together with normal-weight fine aggregate for the preparation of concrete mixes. In this study, LWA was the locally available, naturally occurring pumice lightweight aggregate. The LYA, a commercially available lightweight aggregate, was supplied by Lytag Limited (manufacturer of LYA in the UK). The RP2F1A, which is the key material in this study, was manufactured by the authors by mixing recycled plastic (LLDPE) and red dune sand filler at proportions of 30 and 70%, respectively, to form a homogeneous mix [34, 35]. This was followed by compressing and heating the mix using a compression moulding press technique to turn it into solid sheets or slabs, which were then cooled and finally crushed to form the aggregate. The LWA and LYA were used for the preparation of the control mixes; whereas the RP2F1A was used for investigating the effect of replacement level on concrete performance.

RP2F1A LWA LYA

Figure 1: Various types of coarse aggregate used in this study (RP2F1A, LWA and LYA)

The particle shape and surface texture of RP2F1A, LWA and LYA were qualitatively examined using an optical microscope. The RP2F1A, LWA and LYA had sub-angular, angular and rounded particle shapes, respectively; while their textures were partially rough (fibrous), porous and smooth, respectively.

The physical properties of the aggregates are listed in Table 1. The specific gravity and absorption tests for the coarse aggregates were performed according to ASTM C127 [36]; while unit weight and void content were measured in accordance to ASTM C330/C330M [37].

Table 1: Physical properties of coarse and fine aggregates used in this study

Test	**Coarse Aggregate**			**Fine Aggregate**	
	LWA	**LYA**	**RP2F1A**	**Crushed sand**	**Red sand**
Bulk Specific Gravity (OD Basis)	1.41	1.44	1.48	2.59	2.62
Bulk Specific Gravity (SSD Basis)	1.67	1.69	1.52	2.69	2.63
Apparent Specific Gravity	1.41	1.91	1.54	2.77	2.64
Dry Unit Weight (kg/m^3)	697	889	750	1599	1589.6
Void Content (%)	50	39.02	51.8	38.14	39.2
Absorption (%)	18.6	16.82	2.75	1.67	0.28
Fineness Modulus	6.5	-	6.32	3.89	1.54
Type	Uncrushed	Pelletising	Crushed	Crushed	Uncrushed
Particle Shape	Angular	Rounded	Sub angular	-	-
Surface Texture	Porous	Smooth	Partially rough/ Fibrous	-	-
Nominal Maximum Size (mm)	10	10	10	4.75	1.18

As shown in Table 1, the unit weight of RP2F1A, LWA and LYA was 750, 697 and 889 kg/m^3 respectively; whereas water absorption was 2.75, 18.6 and 16.82%, respectively. These results indicate that the unit weights are comparable; while the water absorption of RP2F1A was 85 and 84% lesser compared to those of LWA and LYA, respectively. In the case of the normal-weight fine aggregate, the unit weight, specific gravity and water absorption were measured based on ASTM C29/C29M [38] and ASTM C128 [39]. The test results are also presented in Table 1.

The particle size distribution curves for RP2F1A and LWA were obtained in line with ASTM C330/C330M [37] as shown in Figure 2. It is worth noting that the grading of LYA was prepared in the lab to match that of LWA because the former aggregate was supplied in single grades by the manufacturer. The fine aggregate used was a combination of 65% red sand and 35% crushed sand (see Table 1) in order to satisfy the requirements of ASTM C136/C136M [40] as shown in Figure 3.

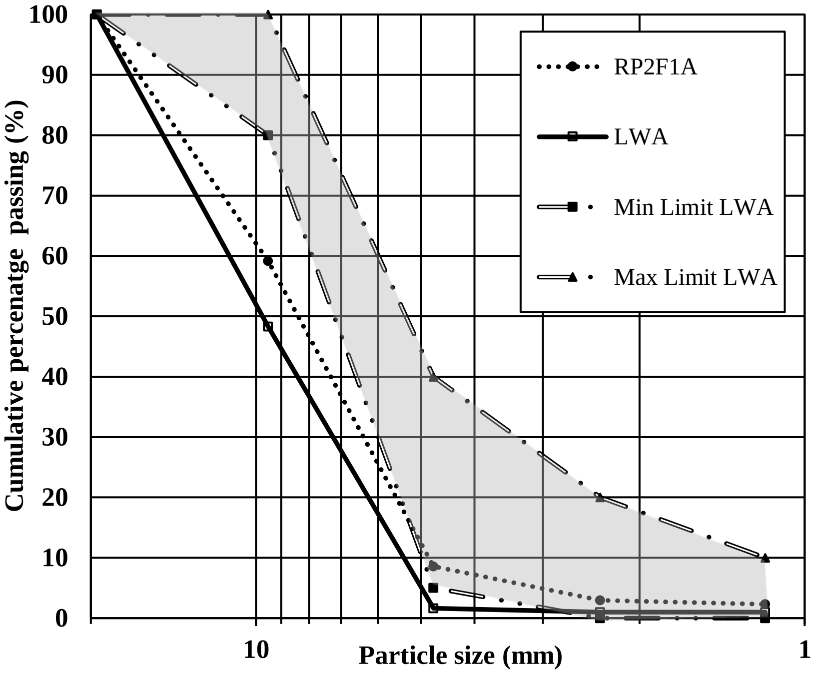


Figure 2: Particle size distribution curves for RP2F1A and LWA together with the grading limits for lightweight aggregate

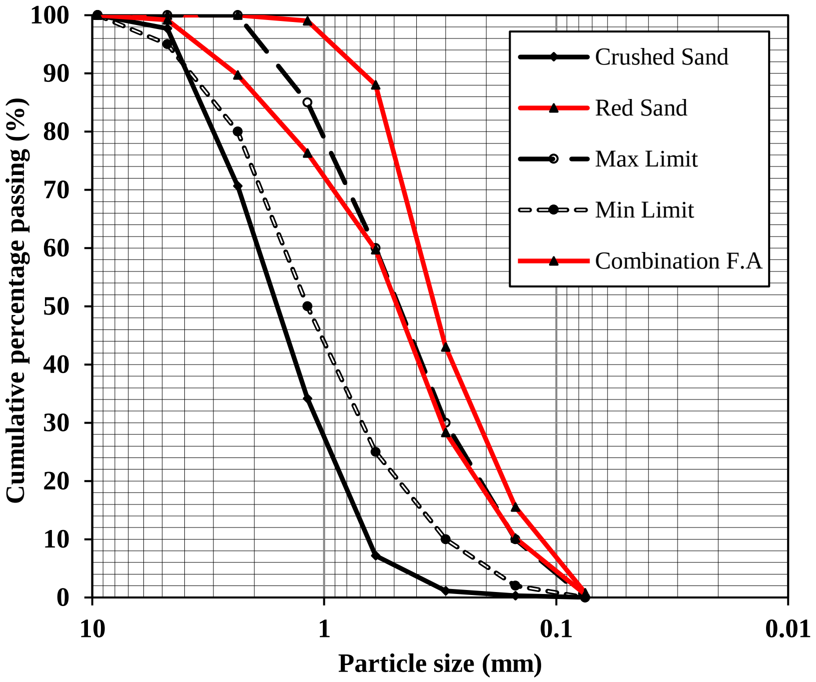


Figure 3: Particle size distribution curves for red sand, crushed sand and the combination of red and crushed sand

2.2 Mix proportions

A total of six mixes were considered in this study. The reference mix (LWC) was designed using LWA according to ACI 211.2 [41] to give a minimum slump of 100 mm and a minimum compressive strength of 30 MPa at 28 days for non-air entrained concrete. For comparison purposes, a second mix (LAC) was designed using LYA. The remaining four mixes included RP2F1A as replacement for LWA on a volumetric basis at 25, 50, 75 and 100% replacement levels.

The concrete mixes containing LYA and RP2F1A were designed relative to LWC by keeping the amount of cement and free water constant. For a given mix, the quantities of LWA, RP2F1A or LYA were calculated, as explained below, using the replacement level; unit weight of LWA, RP2F1A or LYA; and the quantity of LWA used in the reference mix (i.e. LWC).

- Amount of RP2F1A or LYA (kg/m^3) = (replacement level/100) × [(unit weight of RP2F1A or LYA/unit weight of LWA) × (quantity of LWA)]

- Amount of LWA (kg/m^3) = [1- (replacement level/100)] × (quantity of LWA)

The volume (and subsequently weight) of the normal-weight fine aggregate was calculated by subtracting the total volume of the aforementioned ingredients from 1 m^3. Finally, the total water amount was adjusted according to the absorption and moisture content of the aggregates.

All mixes were prepared, cast and cured in accordance with ASTM C192/C192M [42]. Table 2 details the proportions per 1 m^3 of each concrete mix. In this Table, LWC and LAC refer to the concrete mixes including 100% LWA and LYA, respectively. The designation “RP2F1CX” refers to a concrete mix containing RP2F1A at a replacement level of X% on a volumetric basis. For example, RP2F1C25 is the concrete mix containing RP2F1A at a replacement level of 25% on a volumetric basis.

Table 2: Proportions of the investigated mixes per cubic metre

Concrete type	**Water / cement ratio**	**Total water (kg/m^3)**	**Free water (kg/m^3)**	**Cement (kg/m^3)**	**Fine aggregate (kg/m^3)**	**Coarse aggregate**		
						LWA (kg/m^3)	**RP2F1A (kg/m^3)**	**LYA (kg/m^3)**
LWC	0.5	296.2	225	450	922	352	-	-
LAC		302.3			759	-	-	452
RP2F1C25		282.4			918	264	95	-
RP2F1C50		269.6			913	176	189	-
RP2F1C75		255.6			909	88	284	-
RP2F1C100		241.1			906	-	378	-

2.3 Testing

The fresh concrete properties considered in this study were slump and fresh density. In addition to characterising the stress-strain relationships, tests were carried out to examine hardened concrete properties; namely dry density, compressive strength, splitting tensile strength, flexural strength and modulus of elasticity. Furthermore, a microscopic investigation of the concrete samples was performed using an FE-SEM (field emission scanning electron microscope), Versa 3D, and an optical microscope to explore the microstructure and interfaces between aggregate and cement mortar.

The mechanical tests were conducted at 28 days in accordance with the test standards given in Table 3. The results of the hardened properties were calculated as the average of three measurements.

Table 3: Testing standards

Test type	**Standard used**
Slump	ASTM C143/C143M [43]
Fresh density	ASTM C138/C138M [44]
Dry density	BS EN12390-7 [45]
Compressive strength	ASTM C39/C39M [46]
Flexural strength	ASTM C580−02 [47]
Splitting tensile strength	BS EN 12390-6 [48]
Modulus of elasticity and stress-strain curve	ASTM C469/C469M [49]

3.0 Results and discussion

3.1 Fresh properties

3.1.1 Slump

Workability and flow characteristics of fresh concrete are normally measured using slump. The effect of replacing LWA with RP2F1A on slump is shown in Figure 4.

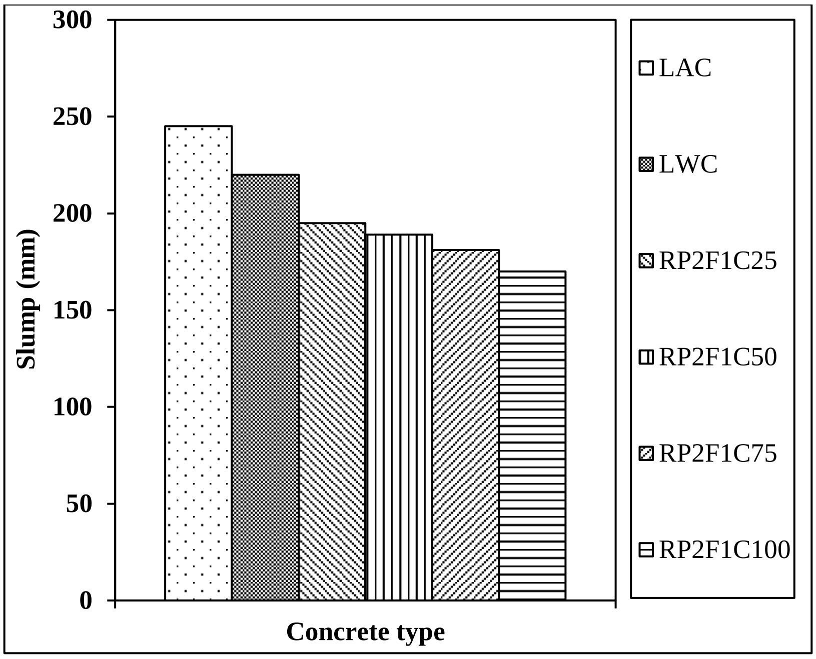


Figure 4: Slump results

The decrease in the slump of the RP2F1C mixes compared with that of LWC ranged from 11 to 23% (25 to 50 mm) as the replacement level was increased from 25 to 100%. This result is comparable to those of Jansen et al. [30] and Slabaugh et al. [33] who reported slump reduction of 7 to 16% due to replacing CA with SLA. The decrease in the slump of the RP2F1C mixes is due to the sub-angular shape and fibrous surface texture of the RP2F1A particles. The sub-angular shape increases the surface area of the aggregate particles covered by the cement paste and thereby reduces the flow ability of the mix, as observed by Rahmani et al. [10]. Additionally, the fibrous surface texture increases the friction between aggregate particles.

LAC had the highest slump (245 mm) which was 11% (25 mm) higher than that of LWC. The reduction in the slump of RP2F1C100 compared with that of LAC was 31% (75 mm). The higher slump of LAC is not only due to the relatively high water absorption of LYA (see Table 1), that might not be absorbed totally during the mix and can lead to segregation but also can be ascribed to the shape and texture of the spherical and smooth particles. To verify the homogeneity of the mix, a sample of LAC was cut 24 hours after casting and, as can be seen in Figure 5, no segregation could be detected.

Figure 5: Section of a LAC sample

Although the RP2F1C concrete mixes had relatively high slump values, this could still be beneficial in the casting and pumping of this type of concrete over a long distance and/or in congested reinforcement areas.

3.1.2 Fresh density

Figure 6 compares the fresh density of the concrete mixes containing RP2F1A with that of LWC and LAC. In some cases, the actual fresh density of a lightweight concrete could be significantly different from the theoretical fresh density. Such a variation would necessitate altering the mix proportions. This was not the case in this study where the actual and theoretical fresh density results were quite comparable for a given concrete mix. For example, the theoretical and experimental fresh density results for LAC (1963 and 1935 kg/m^3, respectively) differed by less than 2%.

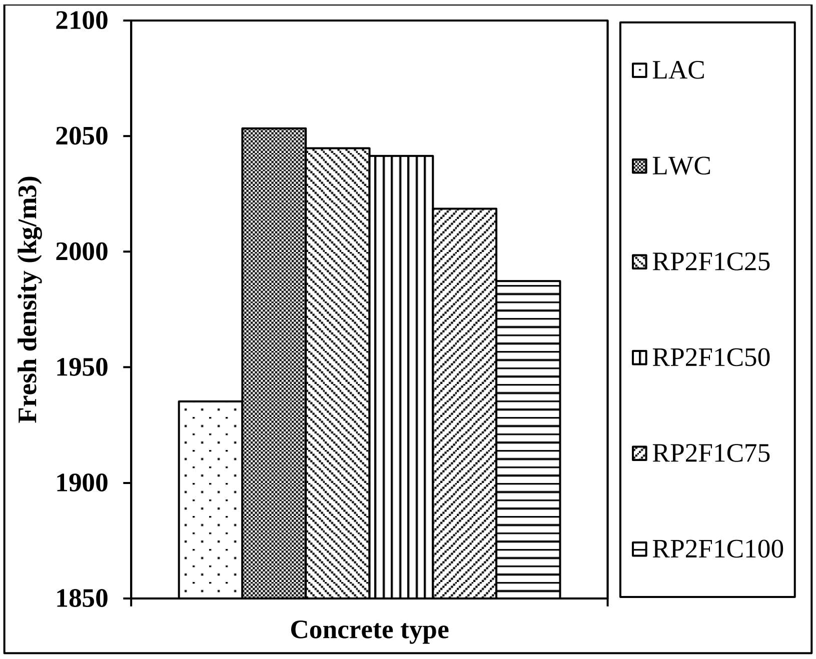


Figure 6: Fresh density results

LWC had a marginally (i.e. less than 4%) higher fresh density (2053 kg/m^3) than any RP2F1C mix. Additionally, there was marginal difference (i.e. less than 3%) between the fresh density of LAC (1935 kg/m^3) and RP2F1C100 (1987 kg/m^3) which both included manufactured lightweight aggregate only as CA. These results are consistent with those of other studies [9-10, 12, 18, 22] where substituting normal-weight FA or CA directly with plastic at replacement levels ranging from 15 to 50% decreased the fresh density by 3 to 18%.

Overall, the results confirm that RP2F1A can be used to totally replace LWA or LYA aggregates without significantly affecting fresh density.

3.2 Hardened properties

The following sections present the hardened properties of the concrete mixes considered in this study and compare their mechanical properties with the requirements of ASTMC330/C330M [37] (see Table 4).

Table 4: Lightweight concrete properties according to ASTM C330/C330M [37]

Average 28-day density, max (kg/m^3)	Average 28-day splitting tensile strength, min (MPa)	Average 28-day compressive strength, min (MPa)
1840	2.3	28
1760	2.1	21
1680	2.1	17

3.2.1 Dry density

Figure 7 presents the dry density results for the concrete mixes considered in this study. LAC and LWC had a dry density of 1744 and 1803 kg/m^3, respectively; whereas the RP2F1C concrete mixes had dry density results ranging from 1786 to 1872 kg/m^3.

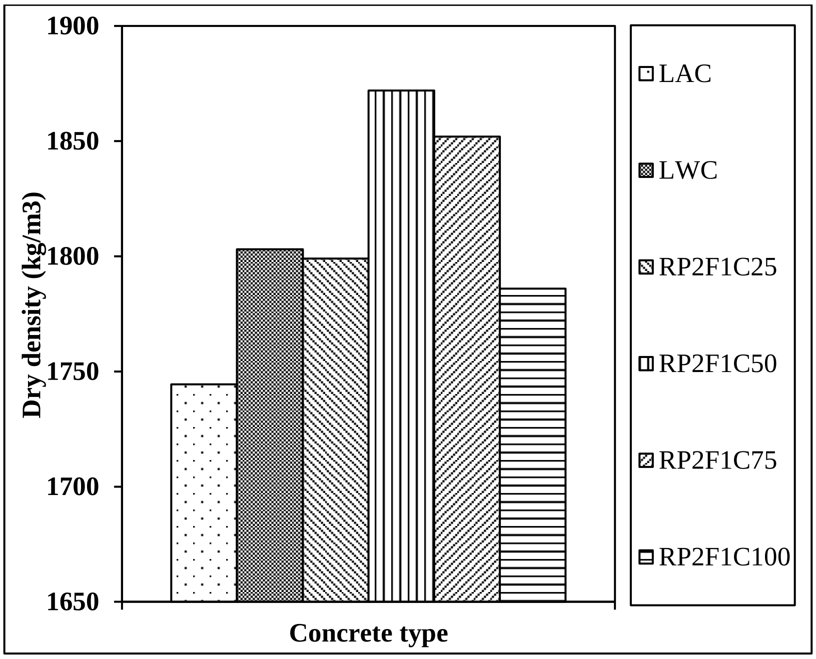


Figure 7: Dry density results

Similar to the case of fresh density, there was a marginal difference (less than 4%) in dry density between any of the RP2F1C mixes and LWC. This is attributable to the comparable dry unit weights of RP2F1A and LWA (see Table 1). Moreover, RP2F1C100 and LYA, which both included manufactured lightweight aggregate only as CA, had dry density results that differed by less than 3%. These findings are in good agreement with studies [11, 19] where high replacement levels (i.e. 75 to 100%) of normal-weight CA or FA with plastic resulted in a marginal decrease (i.e. 6 to 10%) in dry density. On the other hand, the RP2F1C concrete mixes were less sensitive to the reduction in dry density (i.e. 15 to 23%) reported elsewhere [27, 30, 33] due to replacing normal-weight CA or FA with SLA or WPLA at levels varying from 75 to 100%.

The dry density results of the PR2F1C concrete mixes were either within or slightly (i.e. less than 2%) higher than the uppermost limit (1840 kg/m^3) given by ASTMC330/C330M [37] (see Table 4). This suggests that the produced lightweight concrete mixes, with up to 100% replacement level, could be useful in applications where low density is required. This result is important as the use of lightweight concrete can help reduce element size and consequently reduce the cost of materials, handling and transporting, and ultimately the overall cost.

3.2.2 Compressive strength

Figure 8 shows the 28-day compressive strength results for the concrete mixes considered in this study. The LAC and LWC had a 28 day compressive strength of 32.6 and 31.7 MPa, respectively; whereas the RP2F1C concrete mixes had compressive strength results ranging from 12.0 to 26.9 MPa.

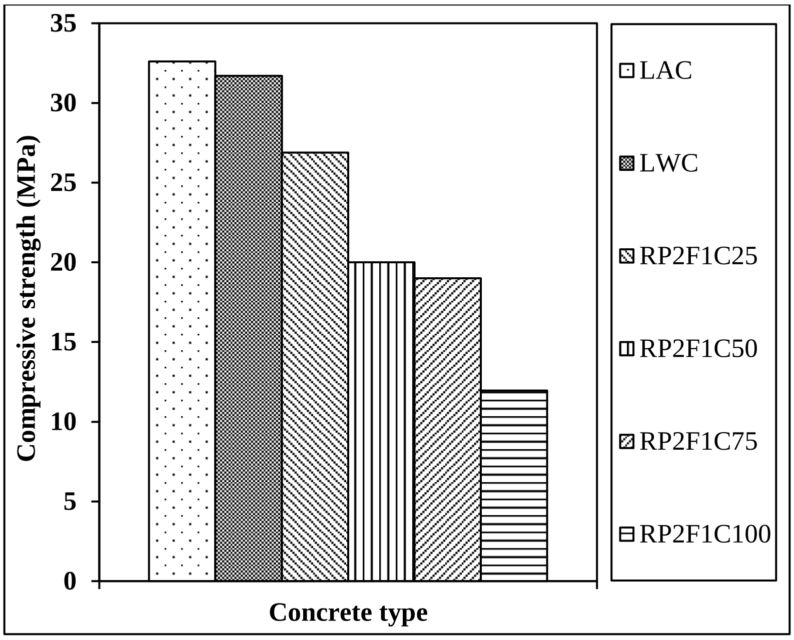


Figure 8: 28 day compressive strength results

The decrease in the compressive strength of the RP2F1C mixes compared with that of LWC ranged from 15 to 62% (4.8 to 19.7 MPa) as the replacement level was increased from 25 to 100%. Similarly, RP2F1C100 had a 28 day compressive strength that was 63% (20.6 MPa) less than that of LAC. These results are in agreement with those reductions (ranging from 32 to 81%) reported in the literature [27, 29-31, 33] where 75 to 100% of normal-weight CA or FA was replaced with plastic-based aggregates (i.e. SLA or WPLA).

The reduction in the compressive strength of the RP2F1C mixes is related to the weak resistance of the interfacial transition zone (ITZ) between the RP2F1A and the cement paste matrix. This weak resistance results from the weak bonding between RP2F1A and the cement matrix as further explained in Section 3.2.7. The deterioration in the compressive strength can also be related to the hydrophobic nature of the plastic existing in the RP2F1A matrix, which prevents good bonding and generates a wall effect as explained in Section 3.2.7. This observation is consistent with those reported elsewhere [18, 22].

The RP2F1C mixes with 25, 50 and 75% replacement levels had compressive strength results higher than 17 MPa as required by ASTMC330/C330M [37]. However, of these mixes, only RP2F1C25 meets both the density and the compressive strength requirements listed in Table 4. Thus, the results suggest that RP2F1C25 could potentially be used in structural applications where low density and moderate strength are required.

3.2.3 Flexural strength

Figure 9 shows the flexural strength results for the concrete mixes considered in this study. LAC and LWC had a flexural strength of 4.8 and 6.2 MPa, respectively; whereas the RP2F1C concrete mixes had flexural strength results ranging from 3.5 to 4.5 MPa.

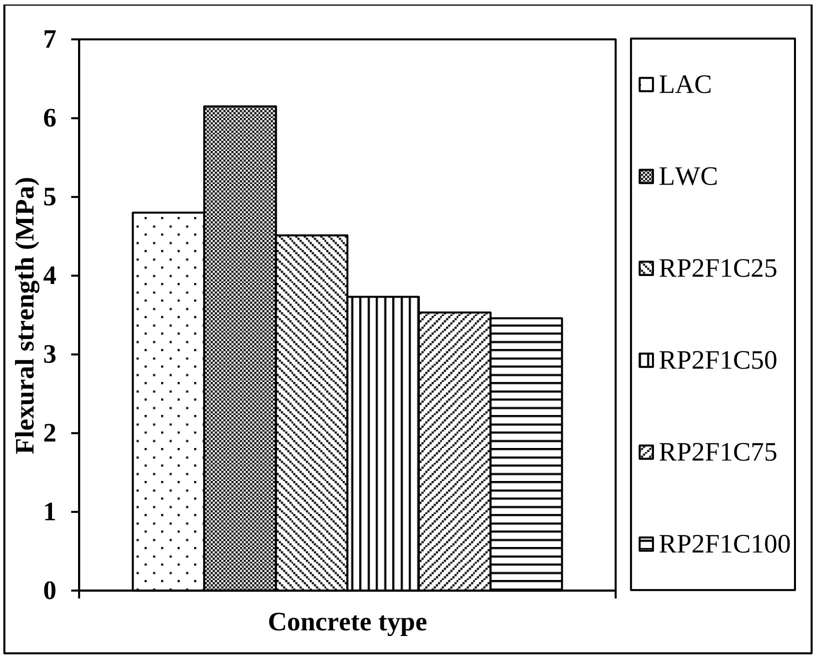


Figure 9: Flexural strength results

The reduction in the flexural strength of the RP2F1C mixes compared with that of LWC ranged from 27 to 44% (1.7 to 2.7 MPa) as the replacement level was increased from 25 to 100%. Additionally, RP2F1C100 had a flexural strength that was 27% (1.3 MPa) less than that of LAC. These results are in broad agreement with the findings of Saikia and de Brito [12] and

Rai et al. [24] who observed a reduction of 40 to 50% due to the increase in plastic replacement from 15 to 75%.

Similar to the case of compressive strength, the decrease in flexural strength may be explained by the weak adhesion between the RP2F1A and the cement paste due to the hydrophobic nature of plastic [22, 24]. It can also be ascribed to the reduction in the amount of rigid natural aggregate that was replaced by lightweight aggregate [9].

3.2.4 Splitting tensile strength

Figure 10 presents the splitting tensile strength results for all concrete mixes. LAC and LWC had a splitting tensile strength of 2.4 and 2.6 MPa, respectively. The splitting tensile strength of the RP2F1C concrete mixes ranged from 1.8 to 2.3 MPa.

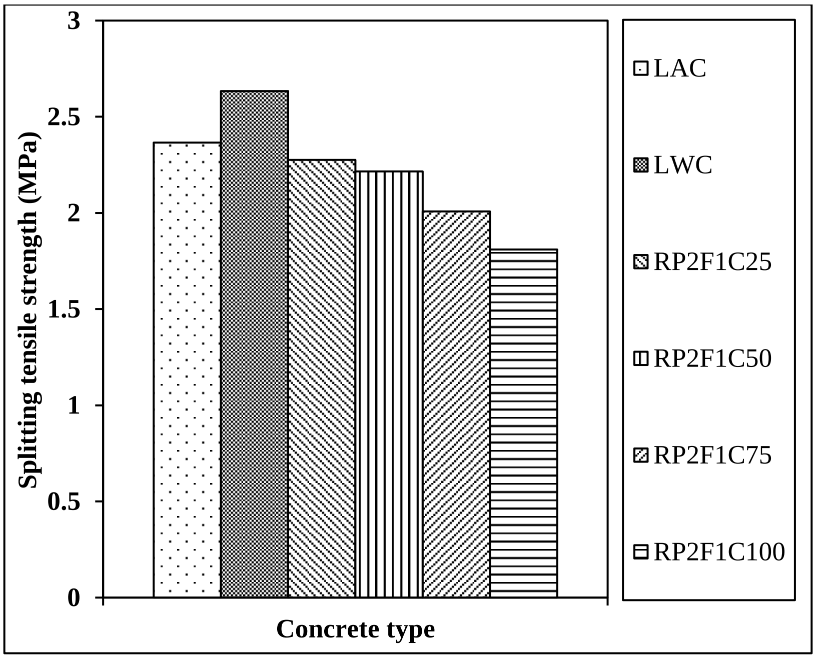


Figure 10: Splitting tensile strength results

The decrease in the splitting tensile strength of the RP2F1C mixes compared with that of LWC ranged from 12 to 31% (0.3 to 0.8 MPa) as the replacement level was increased from 25 to 100%. Moreover, RP2F1C100 had a splitting tensile strength that was 25% (0.6 MPa) less than that of LAC. These results are in line with the findings of Choi et al. [27] and Jansen et al. [30]

who reported splitting tensile strength reductions of 33 and 26% as a result of substituting 75 and 100% of normal-weight CA and FA with synthetic plastic aggregates, respectively. Additionally, the percentage reduction in the splitting tensile strength of the RP2F1C concrete mixes is less than that reported in the extant literature. For example, reductions of 47 and 60% were reported due to replacing 50 and 80% of normal-weight CA with plastic, respectively [16, 17].

Similar to the explanation given for the reduction in compressive and flexural strengths, the splitting tensile strength of the RP2F1C concrete mixes decreases due to the weak bond between the RP2F1A and the cement paste. This is supported by the SEM and optical images depicted in Figures 13 and 14, respectively (see Section 3.2.7).

The splitting tensile strength of the RP2F1C mixes with 25 and 50% replacement levels was higher than 2.1 MPa as required by ASTMC330/C330M [37]. However, similar to the case of compressive strength, only RP2F1C25 meets both the density and the splitting tensile strength requirements listed in Table 4. This result further confirms the potential of RP2F1C25 as a sustainable lightweight structural concrete mix.

3.2.5 Modulus of elasticity

Figure 11 shows the static modulus of elasticity results for all concrete mixes. LAC and LWC had an elastic modulus of 18.9 and 17.3 GPa, respectively. The elastic modulus of the RP2F1C concrete mixes ranged from 7.9 to 15.4 GPa.

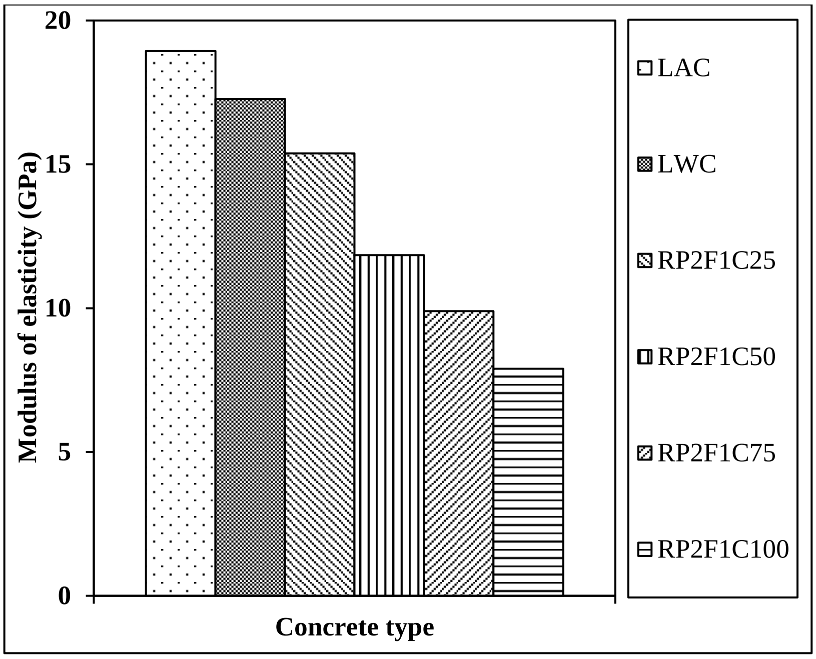


Figure 11: Elastic modulus results

The addition of RP2F1A negatively impacts the elastic modulus of concrete. The decrease in the elastic modulus of the RP2F1C mixes compared with that of LWC ranged from 11 to 54% (1.9 to 9.4 GPa) as the replacement level was increased from 25 to 100%. Furthermore, RP2F1C100 had an elastic modulus that was 58% (11 GPa) less than that of LAC. Nonetheless, the reduction in the elastic modulus of the RP2F1C concrete mixes is still lower than that reported in previous studies where plastic particles were used as direct replacement for CA. For example, reductions ranging from 57 to 73% were reported as a result of substituting 50 to 80% of normal-weight CA with plastic [13, 16, 17]. The reduction in the elastic modulus of the RP2F1C concrete mixes can be explained by the relatively lower elastic modulus of RP2F1A compared to that of LYA and LWA. The low elastic modulus of RP2F1A is attributed to the low modulus of elasticity of the plastic present in its matrix.

Of the RP2F1C concrete mixes, RP2F1C25 has potential for use in structural applications. This is based on the relatively small difference in elastic modulus (i.e. 11% (1.9 GPa)) between LWC and RP2F1C25.

3.2.6 Stress-strain behaviour

Figure 12 depicts the stress-strain behaviour of the concrete mixes considered in this study.

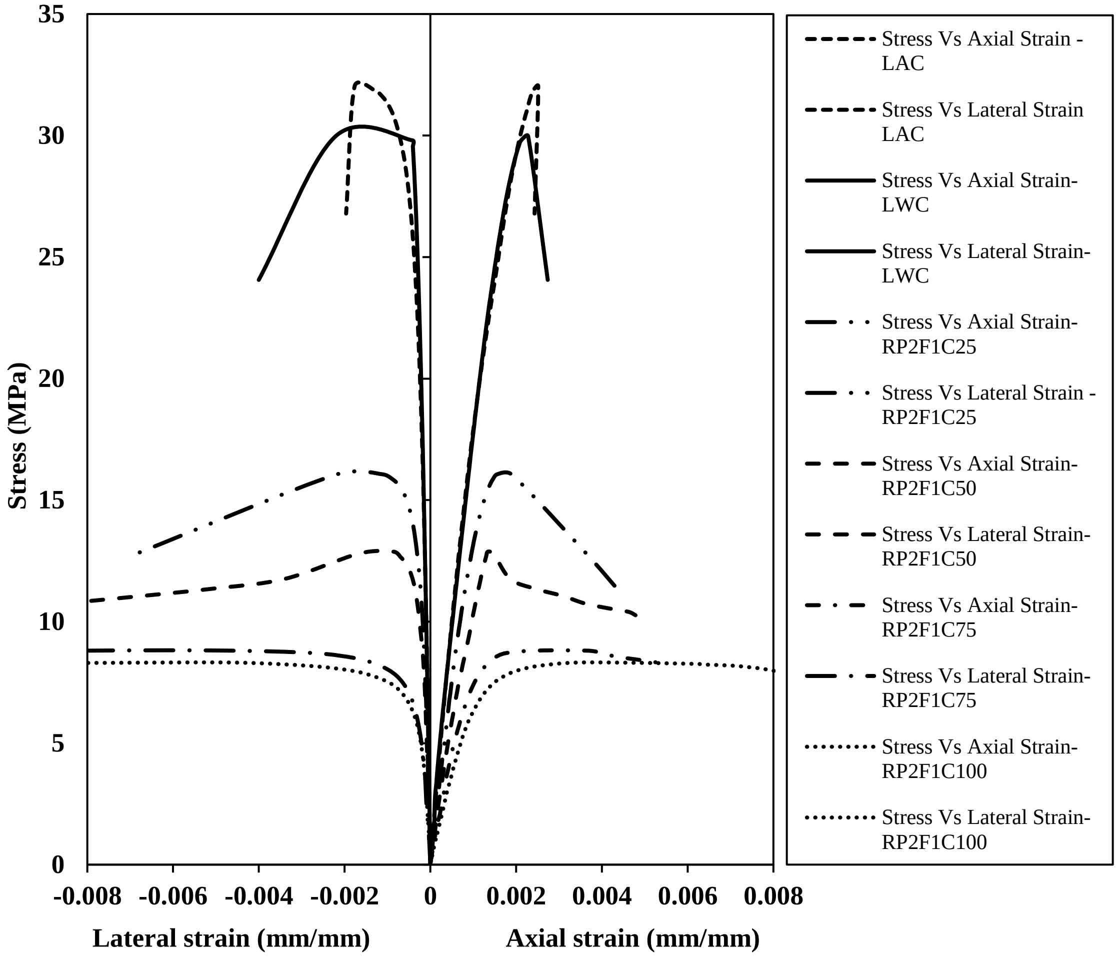


Figure 12: Stress-strain curves

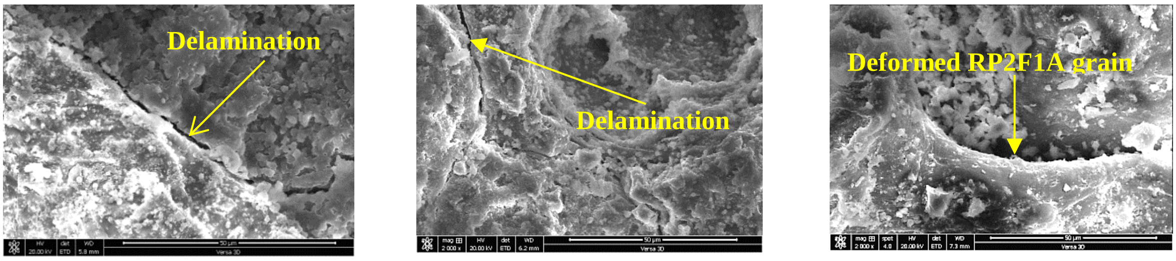
It can be seen that both LWC and LAC had comparable behaviour where the stress-axial strain response is quasilinear up to the peak stress. The sharp drop in stress is a characteristic of brittle failure. This behaviour is significantly affected by the addition of RP2F1A. For the RP2F1C mixes, the peak stress decreased whereas the stress-strain response became more ductile as the replacement level was increased from 25 to 100%. This finding is consistent with the results of Babu et al. [15] who observed an increase in the steepness of the stress–strain response with the reduction of plastic replacement in the mix. As can be seen in Figure 12, RP2F1C100 had the most ductile behaviour. A similar finding was reported by Kashi et al. [29], Jansen et al.

[30] and Malloy et al. [31]; who all observed that concrete made with SLA kept deforming at the peak load before fully disintegrating. The ductility, or reduced brittleness, of the RP2F1C mixes is a unique feature not shared by conventional lightweight concrete. This feature would prove useful in applications where failure occurs due to dynamic and/or repeated loads, e.g. pavements.

3.2.7 Microscopic investigation

A detailed analysis of the microstructure of LAC, LWC and RP2F1C100 was performed using SEM imaging and an optical microscope, as shown in Figures 13 and 14 respectively. The microscopic investigation was performed on small thin sections of concrete samples. These samples were taken from the un-fractured side of the flexural strength specimens using a diamond cutter under running water without applying mechanical force.

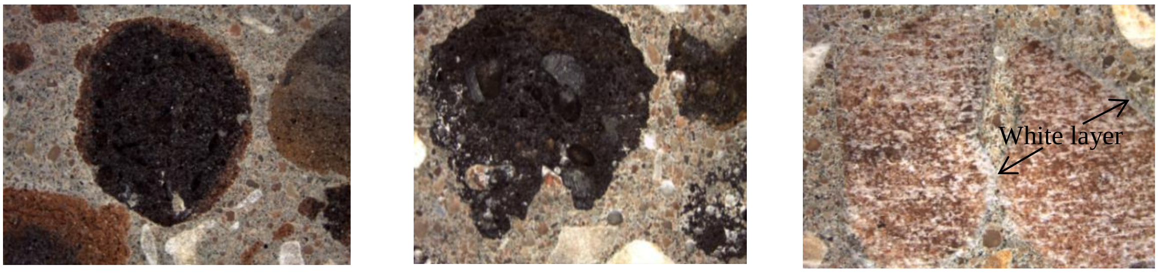
As can be seen in Figure 13, the SEM images show delamination and a major crack formation in LAC and LWC due to a weak interfacial transition zone (ITZ). In the case of RP2F1C100, the fibrous structure of the aggregate surface, which works as cross-linking bridges, changes the mode of failure where any major crack formation disappears due to the relatively high deformability of the RP2F1A particles compared with that of LYA and LWA. Therefore, during load application, stress transfer from the cement matrix to the RP2F1A particles, which have a low modulus of elasticity, results in the relatively higher deformation of the RP2F1A particles. This ultimately leads to the collapse of the RP2F1A composite. This may explain the reason behind the strength deterioration of the RP2F1C mixes compared with that of LWC and LAC.



(a) (b) (c)

Figure 13: SEM images of (a) LAC, (b) LWC and (c) RP2F1C100 (28 days, enlargement: 2000×)

The microscopic images shown in Figure 14 indicate that the LWA and LYA have a porous structure. In addition, LWA and LYA have sharp boundaries which refine the ITZ and make it stronger than the ITZ formed in RP2F1C100. Diffused boundaries were observed in RP2F1A due to its fibrous structure which affects the mode of failure of RP2F1A and explains its ductile behaviour. Moreover, in the case of RP2F1C100, there is a thin white layer between the RP2F1A and the cement matrix. This phenomenon can be explained by the fact that the impervious nature of RP2F1A hinders the water-cement reaction around the surface of the aggregate, which eventually creates a wall or layer at this interface. Therefore, this layer prevents good bonding, which can also be taken as another justification for the lower strength achieved by the RP2F1C mixes.



(a) (b) (c)

Figure 14: Optical microscopic images of (a) LAC, (b) LWC and (c) RP2F1C100

4.0 Correlation between mechanical properties

4.1 Correlation between splitting tensile strength and compressive strength

Experimental results from the extant literature [8, 10-11, 27] were used to examine the correlation between the 28-day splitting tensile strength (f_t) and the 28-day cylinder compressive strength (f_c). Figure 15 presents the variation of f_t with f_c for lightweight concrete containing plastic aggregate. Using regression analysis, the relationship between f_t and f_c may be expressed as follows.

$$f_t = 0.50(f_c)^{0.50} \qquad \text{(Eq. 1)}$$

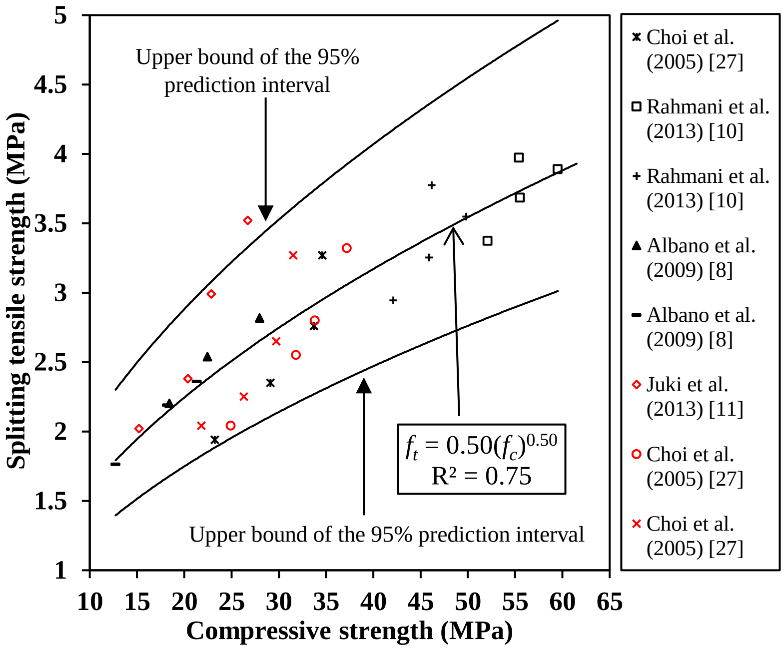


Figure 15: Correlation between splitting tensile strength and compressive strength

As can be seen in Figure 15, Equation 1 shows that f_t is a power function of f_c. This implies that the ratio of f_t to f_c decreases with increasing strength.

Figure 16 compares the predictions of Equation 1 as well as those of empirical models from the published literature, i.e. ACI 318-99 [51] (Eq. 2) and Neville [52] (Eq. 3), with the splitting tensile strength results of this study.

$$f_t = 0.56(f_c)^{0.50} \qquad \text{(Eq. 2)}$$

$$f_t = 0.23(f_c)^{0.67} \qquad \text{(Eq. 3)}$$

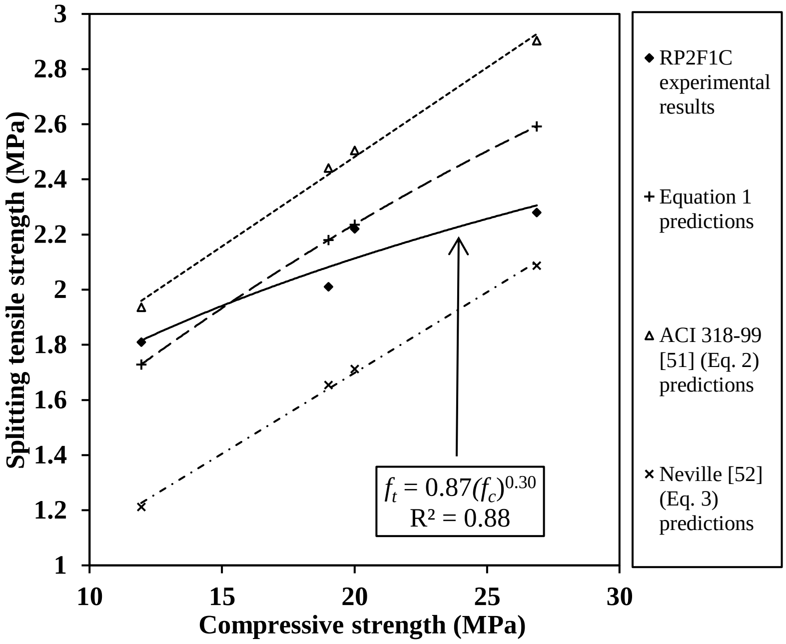


Figure 16: Comparison between the experimental results and the predictions of the analytical models relating splitting tensile strength to compressive strength

As can be seen in Figure 16, the predictions of Equation 1 are more accurate compared to those of ACI 318-99 and Neville models. ACI 318-99 [51] empirical model overestimates the splitting tensile strength results by 7 to 27.3%; whereas Neville's model [52] underestimates the experimental results by 8.5 to 33%. This is not surprising given that, unlike Equation 1, ACI 318-99 and Neville models were not developed specifically for lightweight concrete containing plastic aggregate. Figure 16 shows also that the difference between the predictions of Equation 1 and the experimental results increases with increasing strength. This reflects the need for a more accurate model. Equation 4 is therefore proposed for predicting the splitting tensile strength of the RP2F1C concrete mixes.

$$f_t = 0.87(f_c)^{0.30} \qquad \text{(Eq. 4)}$$

Table 5 presents the percentage difference between the predictions of Equations 1 to 4 and the experimental results. Table 5 clearly shows that Equation 4 provides excellent estimates, i.e. within ± 5%, for the splitting tensile strength of the RP2F1C concrete mixes.

Table 5: Percentage difference in model predictions for the splitting tensile strength

Concrete type	Percentage difference between the predicted and experimental results			
	Eq. 1	**Eq. 2**	**Eq. 3**	**Eq. 4**
RP2F1C25	13.7	27.3	-8.5	2.4
RP2F1C50	0.7	12.8	-22.9	-3.7
RP2F1C75	8.4	21.5	-17.7	4.7
RP2F1C100	-4.5	7.0	-33.0	-1.2

4.2 Correlation between flexural strength and compressive strength

The experimental results described in Section 4.1 were also used to examine the relationship between the 28-day flexural strength (f_r) and f_c. Figure 17 shows the correlation between f_r and f_c for lightweight concrete containing plastic aggregate.

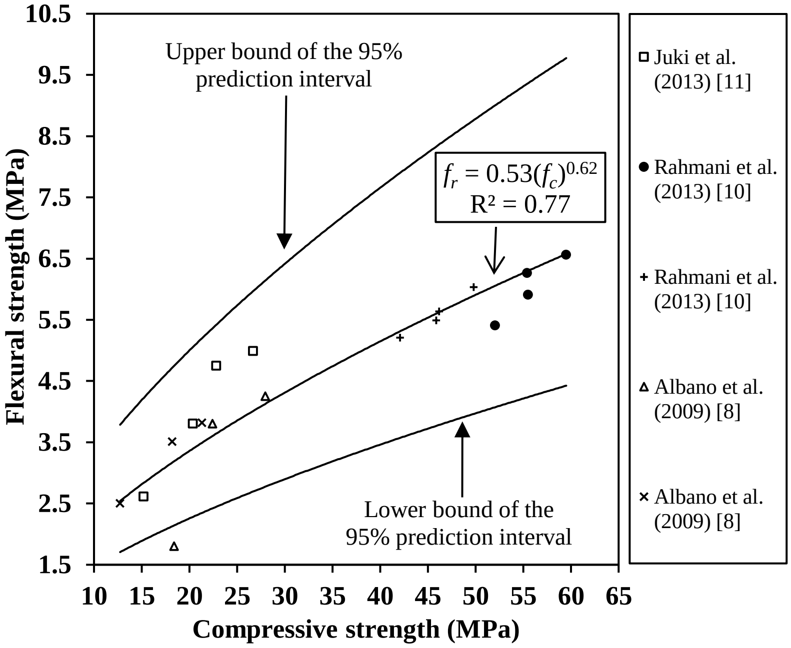


Figure 17: Correlation between flexural strength and compressive strength

Equation 5, which is based on regression analysis, gives the relationship between f_r and f_c.

$$f_r = 0.53(f_c)^{0.62} \qquad \text{(Eq. 5)}$$

Equation 5 as well as the empirical models proposed by ACI 318-95 [53] (Eq. 6) and Raphael [54] (Eq. 7) were used to predict the flexural strength of the RP2F1C concrete mixes.

$$f_r = 0.62(f_c)^{0.50} \qquad \text{(Eq. 6)}$$

$$f_r = 0.44(f_c)^{0.67} \qquad \text{(Eq. 7)}$$

As can be seen in Figure 18, both Equation 5 and Raphael's [54] empirical model underestimate the flexural strength of the RP2F1C concrete mixes by 6.8 to 13.1% for f_c values ranging from 19.0 to 26.9 MPa. Additionally, both models significantly underestimate the flexural strength at f_c = 12.0 MPa. The ACI 318-95 [53] empirical model significantly underestimates the flexural strength, by 23.4 to 38.1%, throughout the tested strength range. This was to be expected because, as explained previously, the ACI 318-95 [53] empirical model was not developed specifically for lightweight concrete containing plastic aggregate.

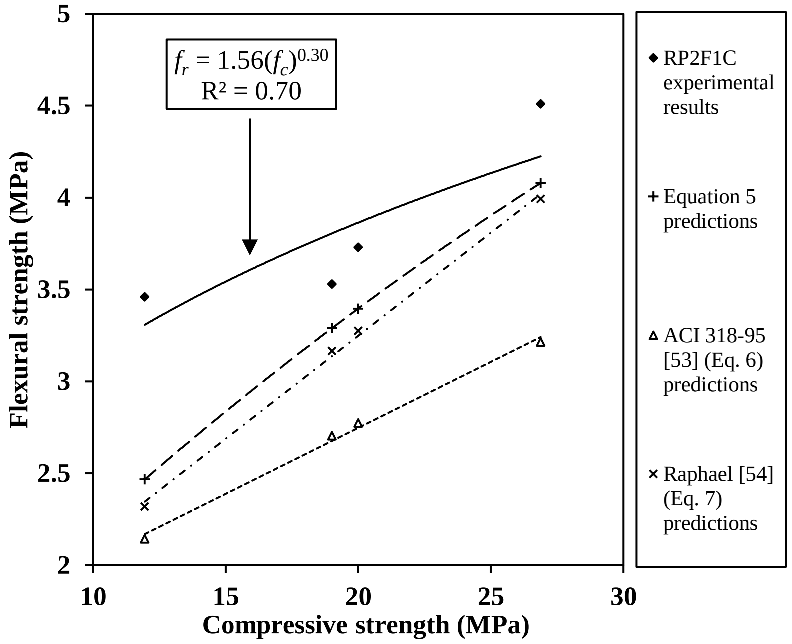


Figure 18: Comparison between the experimental results and the predictions of the analytical models relating flexural strength to compressive strength

The results shown in Figure 18 demonstrate the need for an improved model. Thus, Equation 8 is suggested for predicting the flexural strength of the RP2F1C concrete mixes.

$$f_r = 1.56(f_c)^{0.30} \qquad \text{(Eq. 8)}$$

Table 6 compares the percentage difference between the predictions of Equations 5, 6, 7 and 8 and the experimental results. As can be seen in Table 6, Equation 8 gives the best predictions, i.e. within ± 7.2%, for the flexural strength of the RP2F1C concrete mixes.

Table 6: Percentage difference in model predictions for the flexural strength

Concrete type	**Percentage difference between the predicted and experimental results**			
	Eq. 5	**Eq. 6**	**Eq. 7**	**Eq. 8**
RP2F1C25	-9.6	-28.7	-12.5	-7.2
RP2F1C50	-9.0	-25.7	-13.1	2.7
RP2F1C75	-6.8	-23.4	-11.2	6.9
RP2F1C100	-28.7	-38.1	-33.5	-5.1

4.3 Correlation between modulus of elasticity and compressive strength

Similar to the cases of the splitting tensile strength and flexural strength, a relationship between the modulus of elasticity (E_c) and f_c was deduced using experimental results from the extant literature [8, 10, 13, 27]. Figure 19 illustrates the variation between E_c and f_c for lightweight concrete containing plastic aggregate. Based on regression analysis, the relationship between E_c and f_c may be expressed as follows.

$$E_c = 2.50(f_c)^{0.64} \qquad \text{(Eq. 9)}$$

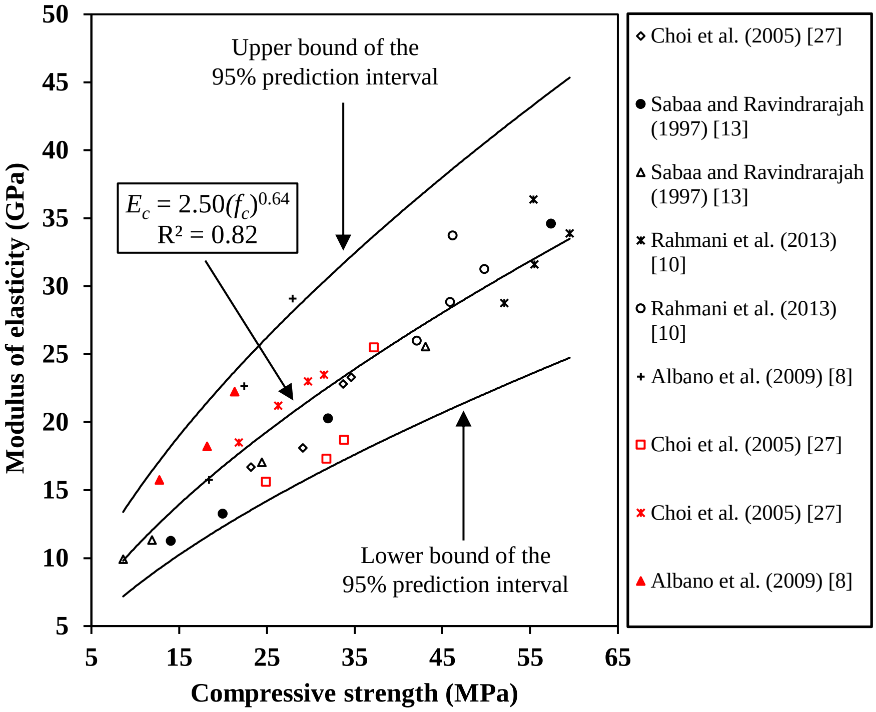


Figure 19: Correlation between elastic modulus and compressive strength

Equation 9 together with empirical models from the published literature; i.e. ACI 318-05 [55] (Eq. 10), BS 8110 [56] (Eq. 11), and Perry et al. [57] (Eq. 12); were used to predict the elastic modulus of the RP2F1C concrete mixes.

$$E_c = (\gamma_w)^{1.5} \times (43 \times (10^{-6})) \times (f_c)^{0.50} \qquad \text{(Eq. 10)}$$

$$E_c = (\gamma_w)^{2.0} \times (17 \times (10^{-7})) \times (f_c)^{0.33} \qquad \text{(Eq. 11)}$$

$$E_c = (\gamma_w)^{1.53} \times (7 \times (10^{-5})) \times (f_c)^{0.25} \qquad \text{(Eq. 12)}$$

In Equations 10-12, γ_w is the dry density of concrete in kg/m^3.

Figure 20 depicts the comparison between the predictions of Equations 9 to 12 and the experimental results for the elastic modulus of the RP2F1C concrete mixes. All models overestimate the elastic modulus of the RP2F1C concrete mixes. The predictions of Equation 9 are 33.6 to 66.4% higher than the corresponding experimental results. The remaining three models predicted the elastic modulus of RP2F1C25 with an error of 10.6, 6 and -1.0% for

Equations 10, 11 and 12, respectively. However, the three models overestimated the elastic modulus of the remaining RP2F1C mixes by 26.9 to 55.9%. Hence it can be concluded that none of the investigated models can be used to accurately predict the elastic modulus of the RP2F1C concrete mixes.

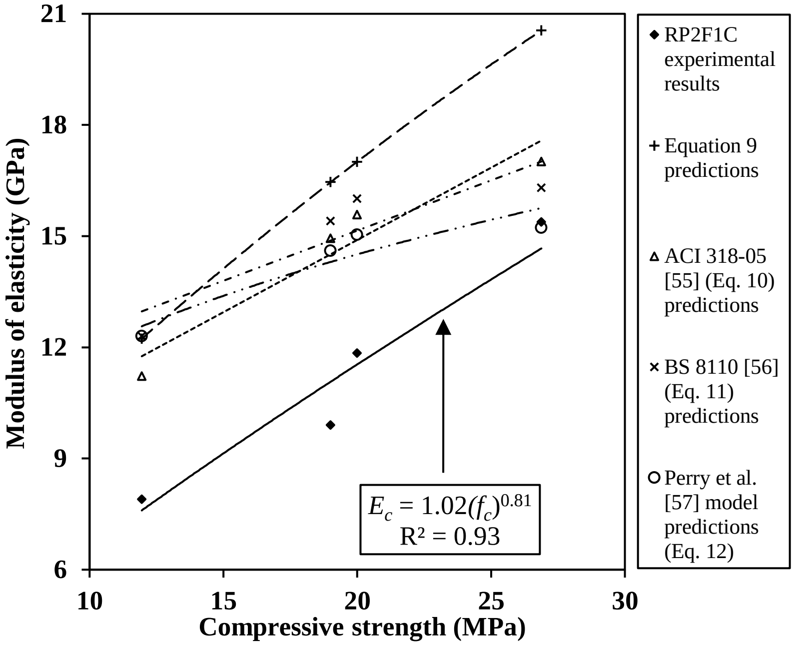


Figure 20: Comparison between the experimental results and the predictions of the analytical models relating elastic modulus to compressive strength

As can be seen in Figure 20, regression analysis suggests that the elastic modulus of the RP2F1C concrete mixes is best given by Equation 13.

$$E_c = 1.02(f_c)^{0.81} \qquad \text{(Eq. 13)}$$

Table 7 gives the percentage difference between the predictions of Equations 9 to 13 and the experimental results. As can be seen in Table 7, Equation 13 offers the best predictions for the elastic modulus of the RP2F1C concrete mixes with an error ranging from -2.5 to 11.9%.

Table 7: Percentage difference in model predictions for the elastic modulus

Concrete type	**Percentage difference between the predicted and experimental results**				
	Eq. 9	**Eq. 10**	**Eq. 11**	**Eq. 12**	**Eq. 13**
RP2F1C25	33.6	10.6	6.0	-1.0	-4.6
RP2F1C50	43.6	31.5	35.2	26.9	-2.5
RP2F1C75	66.4	51.1	55.8	47.6	11.9
RP2F1C100	55	42.2	55.8	55.9	-3.6

Equations 4, 8 and 13 provide excellent predictions for the experimental results of this study. However, further research is required to confirm their applicability to concrete mixes with different manufactured plastic aggregates, W/C ratios and cement contents.

5.0 Conclusions

This paper examines the effect of RP2F1A, a manufactured plastic aggregate, on the fresh, hardened and microstructure properties of lightweight concrete. The manufactured plastic aggregate was used as replacement for pumice lightweight aggregate between 25-100%, on a volumetric basis, at intervals of 25%. It was also used as full replacement for Lytag aggregate. This paper also presents predictive models for the mechanical properties of the concrete mixes incorporating RP2F1A. The main conclusions of this study are detailed below.

- The slump of the RP2F1C concrete mixes decreased, by 11-23% (25-50 mm) compared to that of LWC, with the increase in replacement level from 25 to 100%. However, the difference in fresh and hardened density between the RP2F1C concrete mixes and the control mixes was insignificant (i.e. less than 4%).
- The control mixes had better mechanical properties than the RP2F1C concrete mixes. The compressive strength, flexural strength, splitting tensile strength and elastic modulus of the RP2F1C concrete mixes decreased by 15-62%, 27-44%, 12-31% and 11-54%, respectively, with the increase in replacement level from 25-100%. Totally

replacing LYA with RP2F1A had a similar detrimental effect on the mechanical properties.

- The results demonstrate that RP2F1C25, the concrete mix containing RP2F1A at a replacement level of 25%, meets the requirements of ASTMC330/C330M; which increases its potential for use as a sustainable lightweight structural concrete mix.
- The control mixes had a quasilinear stress-strain response up to the peak stress followed by sudden failure. In contrast, the RP2F1C concrete mixes had a ductile post-peak behaviour that was enhanced by the increase in replacement level. Therefore, the RP2F1C mixes can potentially be used in those applications subjected to dynamic and/or repeated loads, such as pavements.
- SEM images showed that the brittle failure of the control mixes is attributable to a major crack formation due to a weak interfacial transition zone. On the other hand, the ductile failure of RP2F1C100 can be ascribed to the high deformability of the RP2F1A particles. Optical microscope images indicated sharp boundaries between LWA/LYA and the cement matrix, contrary to the diffused boundaries observed between RP2F1A and the cement matrix.
- The predictions of the proposed models were in good agreement with the experimental results for the mechanical properties of the RP2F1C concrete mixes. Until further research is carried out, the proposed models should only be used for the studied type of concrete at a W/C of 0.50.

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