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Effect of HDPE and PET Plastic Waste Use in The Manufacture of Lightweight Concrete

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ARTICLE INFO

Article history:
Received 5 August 2026
Revised 25 August 2026
Accepted 27 August 2026
Available online 31 August 2026

How to cite: N. Nursyamsi, S. Hani, R. A. P. Purwadi, A. T. Nasution, I. Irfani, T. P. P. Habeahan, M. J. Agustian, and R. Y. B. Marpaung, "Effect of HDPE and PET Plastic Waste Use in The Manufacture of Lightweight Concrete," Journal of Civil Engineering and Public Infrastructure Management (JCE-PIM), vol. 1, no. 3, pp. 69–77, 2026

ABSTRACT

Plastic waste is a persistent environmental concern because it degrades slowly and continues to accumulate. This study investigates polyethylene terephthalate (PET) and high density polyethylene (HDPE) waste as partial aggregate substitutes in lightweight concrete, examining workability, density, and mechanical performance. Three substitution schemes were examined: PET replacing fine aggregate, HDPE replacing coarse aggregate, and a balanced PET-HDPE combination. Individual PET and HDPE replacement levels ranged from 0% to 50%, while the combined series ranged from 0%:0% to 25%:25% by aggregate volume. Pumice with a maximum particle size of 19.5 mm was used as coarse aggregate, and silica fume was added at 10% of cement mass. A total of 255 specimens were prepared. At 28 days, the mixtures were evaluated for slump, SSD condition unit weight, dry unit weight, compressive strength, splitting tensile strength, flexural strength, and elastic modulus using applicable standards. Increasing plastic content generally reduced workability, unit weight, strength, and stiffness. The reduction in slump was associated with the flat and irregular shape of the plastic particles, while the decline in mechanical properties was mainly related to weaker bonding at the plastic paste interface. PET substitutions of 20-50% and HDPE substitutions of 30-50% satisfied the density criterion adopted for lightweight concrete. These results show that PET and HDPE waste can reduce concrete self-weight and contribute to plastic waste utilization, but the replacement level must be selected by considering the accompanying loss of mechanical performance. The study provides a comparative basis for selecting and further optimizing plastic modified lightweight concrete mixtures for practical engineering applications.

Keywords: *HDPE; Lightweight concrete; PET; Plastic waste*

1. Introduction

Plastic waste remains a major environmental issue in Indonesia because it degrades slowly and can persist in terrestrial and marine environments. The waste quantity reported in [1] is 5,556,223.09 tons, of which 65.02% is managed, leaving a considerable fraction that may continue to accumulate. Waste reduction therefore depends not only on disposal, but also on efforts to reduce consumption and recover materials that can be reused. The 3R approach, consisting of reuse, reduce, and recycle, remains one of the practical strategies for reducing waste generation and environmental pollution [2]. In civil engineering, recycling can be applied by incorporating waste materials into construction products. Studies on autoclaved aerated concrete waste [3] and coffee husk derived materials [4] illustrate the broader effort to convert waste streams into useful cement based materials.

Among plastic wastes, PET and HDPE have been investigated as aggregate substitutes because of their low density and availability. Nursyamsi and Adil [5] reported that increasing PET and HDPE substitution generally reduced the compressive strength of concrete. Nursyamsi and Zebua [6] likewise showed that PET particle

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gradation influenced both the density and compressive strength of lightweight concrete. These findings indicate that the performance of plastic modified concrete depends not only on the amount of plastic used, but also on its particle characteristics and the aggregate fraction being replaced.

Fresh concrete behavior can also vary with the plastic form and the surrounding material system. Irwan et al. [7] reported improved workability in concrete containing lightweight PET fibre and fly ash, attributing the increase to the spherical fly ash particles that reduced internal friction between the cementitious materials and aggregates. This result is relevant to the present study because it shows that the effect of plastic on workability cannot be considered independently of particle shape, binder composition, and aggregate characteristics.

Tensile behavior has likewise been examined in concrete products containing PET and HDPE. The studies cited in [8] and [9] generally reported lower tensile resistance after plastic waste was introduced into the mixture. The reduction was associated with the formation of voids and weaker interfaces between the plastic particles and the surrounding cementitious matrix. These findings suggest that the tensile response of plastic modified concrete is particularly sensitive to particle distribution and interfacial bonding.

Other studies have shown that lower replacement levels or different concrete systems may produce different responses. Hameed and Ahmed [10] found that limited PET addition could improve selected mechanical properties of lightweight concrete. Guendouz et al. [11] reported that plastic waste used as a sand substitute could reduce concrete density while improving compressive and flexural performance. Mohammed [12] also showed that well graded PET could be incorporated into recycled reinforced concrete beams within an acceptable replacement range. These findings show that the performance of plastic modified concrete is strongly influenced by plastic type, dosage, grading, the aggregate fraction being replaced, and the concrete system in which the material is used.

The differences among previous findings also show that a replacement percentage reported as beneficial in one study cannot be transferred directly to another concrete system. The response may change when the plastic replaces a different aggregate fraction, when lightweight aggregate is used, or when PET and HDPE are introduced together. This is important for engineering applications because a reduction in concrete density is useful only when the resulting material retains the performance required for its intended use.

Accordingly, the main research gap addressed in this study is the limited direct comparison of PET, HDPE, and their combination within the same lightweight concrete mixture and testing program. A common experimental basis is needed to compare how the three substitution arrangements affect workability, density, and mechanical behavior.

The present study uses pumice as the natural coarse aggregate and silica fume at 10% of the cement mass. PET is used as a fine aggregate substitute and HDPE as a coarse aggregate substitute, with individual replacement levels from 0% to 50%; the combined series uses equal PET:HDPE proportions from 0%:0% to 25%:25%. The mix design follows ACI 211.2-98 [13], while the lightweight concrete density criterion and testing procedures are based on the standards adopted in this study [14], [15]-[16]. All mixtures were evaluated using the same specimen preparation, curing age, and testing program. The objective is to determine the effect of increasing PET, HDPE, and combined PET HDPE substitution on workability, densit related properties, compressive strength, splitting tensile strength, flexural strength, and elastic modulus, and to assess the balance between reduced concrete weight and retained mechanical performance. Equal PET and HDPE proportions were used in the combined series so that both plastic types increased together without making the relative PET to HDPE proportion an additional variable.

2. Method

This study employed a laboratory experimental program conducted at the Concrete Laboratory of the University of North Sumatera. Natural pumice was used as the coarse aggregate, while PET and HDPE waste were introduced through the three substitution arrangements listed in Table 1. Silica fume was added at 10% of the cement mass. The experimental work consisted of material characterization, mixture proportioning, specimen preparation, and testing of fresh and hardened concrete.

2.1. Plastic Lightweight Concrete Constituent Materials

The lightweight concrete was produced using the following constituent materials:

- Cement: composite Portland cement (PCC) produced by PT. Semen Padang.
- Water: PAM water obtained from the Concrete Laboratory of the University of North Sumatera.

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- Fine aggregate: sand originating from Binjai.
- Coarse aggregate: pumice with a maximum size of 19.5 mm.
- Polyethylene terephthalate (PET): PET plastic waste obtained from a plastic waste recycling industry located in Coal Regency.
- High density polyethylene (HDPE): HDPE plastic waste obtained from a plastic waste recycling industry located in Coal Regency.
- Silica fume: material supplied by PT. Sika Indonesia and added at 10% of the cement mass.

a b c

Figure 1 (a) HDPE plastic waste pieces; (b) PET plastic waste; (c) pumice.

2.2. Mix Design and Manufacture of Test Objects

The lightweight concrete mix design was prepared according to ACI 211.2-98 [13] for a target compressive strength of 17 MPa. PET and HDPE were tested separately at replacement levels of 0%, 10%, 20%, 30%, 40%, and 50%. The combined mixtures contained PET:HDPE ratios of 0%:0%, 5%:5%, 10%:10%, 15%:15%, 20%:20%, and 25%:25%, equivalent to total plastic contents of 0%, 10%, 20%, 30%, 40%, and 50%. Equal PET and HDPE proportions were selected to keep their contributions comparable while the total plastic content increased. Three specimens were prepared for each test and mixture variation, giving 255 specimens in total: 180 for the separate PET and HDPE series and 75 for the combined series. The values presented in the result figures are the mean of three specimens.

Table 1. Specimen variations.

Variations	Substitution 1	Substitution 2	Substitution 3	Substitution 4	Substitution 5
HDPE plastic	10%	20%	30%	40%	50%
PET plastic	10%	20%	30%	40%	50%
HDPE and PET plastic	5% : 5%	10% : 10%	15% : 15%	20% : 20%	25% : 25%

The test program included slump, SSD condition unit weight, dry unit weight, compressive strength, splitting tensile strength, flexural strength, and elastic modulus. Slump testing followed SNI 1972:2008 [17]. Beam specimens measuring 15 cm x 15 cm x 53 cm were used for the flexural strength test in accordance with SNI 4431:2011 [15], while cylindrical specimens measuring 15 cm in diameter and 30 cm in height were used for the compressive strength, splitting tensile strength, and elastic modulus tests. The hardened concrete mechanical tests were conducted at 28 days. The same specimen geometry, curing age, and test procedure were maintained within each parameter to allow direct comparison among the PET, HDPE, and combined PET-HDPE series.

2.3. Material Properties Test

Before mixture proportioning, the constituent materials were tested to determine the physical properties relevant to the mix design and interpretation of the concrete response [17], [16]. The measured properties included fineness modulus, SSD specific gravity where applicable, unit weight, absorption, and sludge content.

Table 3 summarizes the measured properties of sand, pumice, PET, and HDPE. The unit weights of PET (307.943 kg/m³) and HDPE (336.774 kg/m³) are substantially lower than those of sand (1466.271 kg/m³) and pumice (515.591 kg/m³), providing the main basis for the expected reduction in concrete unit weight as plastic substitution increases. PET and HDPE have fineness modulus values of 6.0095 and 6.734, respectively, compared with 6.8728 for pumice. The pumice absorption of 49.345% reflects the highly porous nature of the lightweight aggregate. These properties are considered in the interpretation of the fresh and hardened concrete results.

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Table 3. Material properties test results.

Types of testing	Sand	Pumice	PET	HDPE
Fineness modulus (FM)	2.73	6.8728	6.0095	6.734
Specific gravity, SSD	2.54	1.31296	–	–
Unit weight (kg/m³)	1466.271	515.591	307.943	336.774
Absorption (%)	3.036	49.345	–	–
Sludge content (%)	3.8	0.8	0.8	0.7

3. Results and Discussion

3.1. Slump

The slump test was conducted according to SNI 1972:2008 [17] to evaluate the workability of the fresh concrete. Figure 2 compares the PET, HDPE, and combined PET-HDPE mixtures over the investigated substitution range.

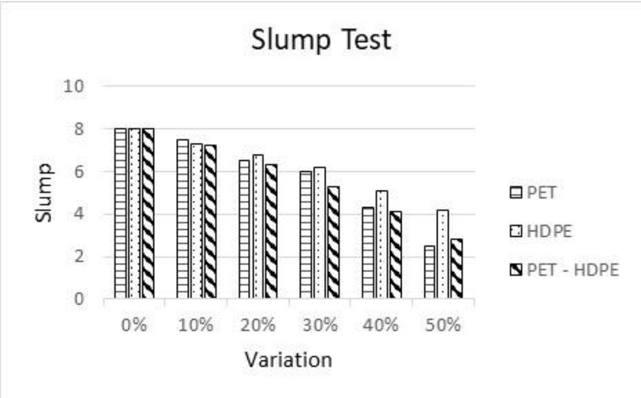

Figure 2 Slump test results.

As shown in Figure 2, slump generally decreases as the plastic substitution level increases, indicating a gradual loss of workability. The flat and irregular plastic particles increase the surface area that must be coated by paste and interfere with the movement and packing of the fresh mixture. The combined PET-HDPE series follows the same overall tendency, indicating that the reduction in workability is not confined to one plastic type. This behavior differs from the increase in workability reported for PET fibre concrete containing fly ash [7]. In that study, the improvement was attributed to the spherical fly ash particles, which reduced internal friction. The comparison suggests that the workability of plastic modified concrete is governed by the interaction among plastic geometry, binder composition, and aggregate characteristics rather than by plastic content alone.

3.2. SSD Specific Gravity

Figure 3 presents the mass per unit volume of the concrete in saturated surface dry (SSD) condition. Although the original test description uses the term SSD specific gravity, the plotted unit is kg/m³; the results are therefore discussed here as SSD condition unit weight.

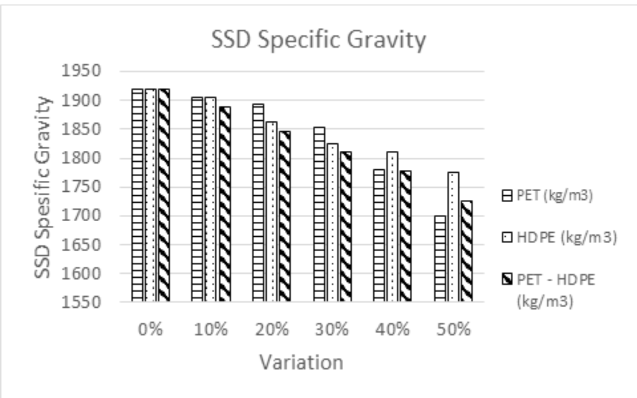

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Figure 3 SSD specific gravity test results.

The SSD condition unit weight decreases as the plastic content increases in all three substitution arrangements. This trend is consistent with the lower unit weights of PET and HDPE shown in Table 3 relative to sand and pumice. Replacing part of the natural aggregate skeleton with lighter plastic particles reduces the mass of concrete occupying the same volume. The decrease supports the use of PET and HDPE for lightweight concrete production, although the accompanying changes in mechanical performance must also be considered.

3.3. Dry Unit Weight

Figure 4 presents the dry unit weight after moisture in the accessible pore system has evaporated. The dry unit weight is therefore lower than the corresponding SSD condition value because pore water no longer contributes to the measured mass.

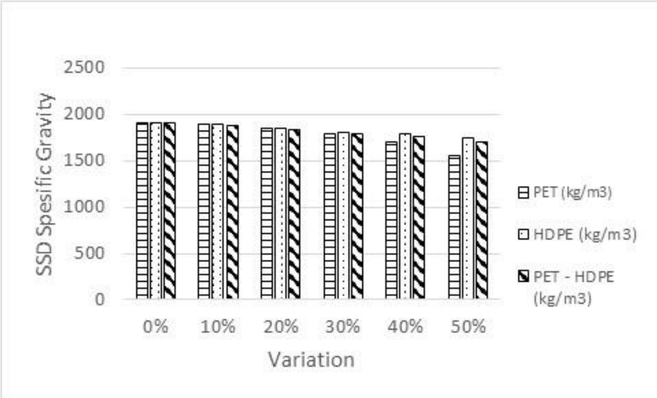

Figure 4 Dry unit weight test results.

Dry unit weight decreases with increasing plastic substitution, confirming that PET and HDPE can reduce the mass of the concrete. The trend is consistent with the lower unit weights of the two plastic materials in Table 3. Based on the density criterion adopted in this study [14], PET mixtures containing 20-50% replacement and HDPE mixtures containing 30-50% replacement fall within the stated lightweight concrete range. The result demonstrates the benefit of plastic substitution for weight reduction, but density compliance alone is not sufficient for structural selection because strength and stiffness also decline as the replacement level increases.

3.4. Compressive Strength

Compressive strength was measured at 28 days using cylindrical specimens. Figure 5 compares the compressive response of the PET, HDPE, and combined PET-HDPE mixtures over the substitution range.

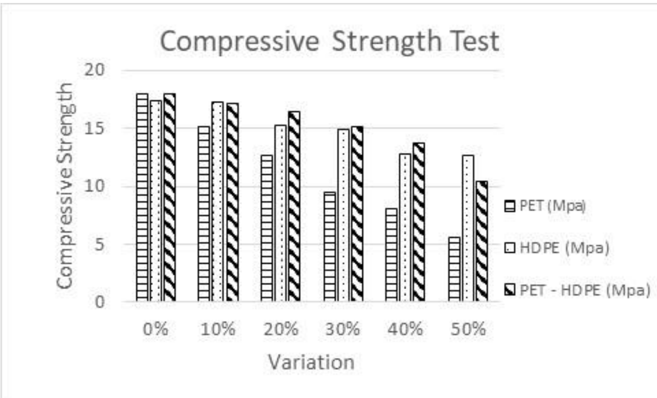

Figure 5 Compressive strength results

Figure 5 shows a general reduction in compressive strength as plastic substitution increases. PET and HDPE have smoother surfaces than the natural aggregates used in the mixture, which can weaken adhesion at the plastic paste interface. As the replacement level rises, a larger proportion of the load transfer system depends on these interfaces, reducing the capacity of the concrete to resist compression. A similar downward trend was reported by Nursyamsi and Adil [5], while Nursyamsi and Zebua [6] showed that PET gradation also influences compressive strength. Hameed and Ahmed [10] found that better compressive performance could occur at relatively low PET contents, whereas Guendouz et al. [11] reported strength improvement when

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plastic waste was used as a sand substitute. These differences are reasonable because the concrete matrices, plastic forms, aggregate skeletons, and replacement mechanisms differ among the studies. The comparison confirms that the effect of plastic substitution is specific to the material system and cannot be transferred directly from one concrete mixture to another.

3.5. Split Tensile Strength

Splitting tensile strength was measured at 28 days using cylindrical specimens to assess resistance to tensile splitting. Figure 6 presents the PET, HDPE, and combined PET-HDPE results across the investigated replacement levels.

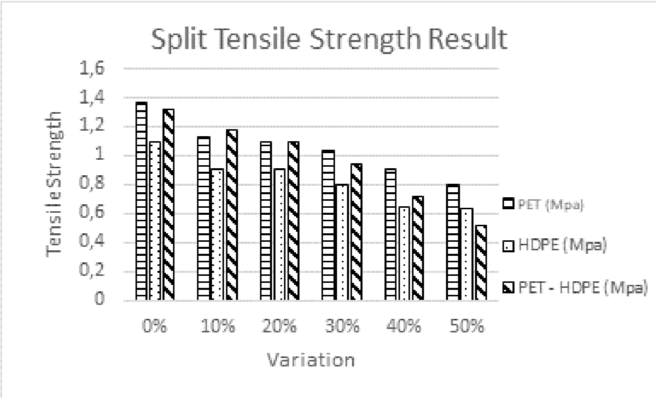

Figure 6 Split tensile strength results.

The splitting tensile strength generally decreased as the plastic content increased. A similar tendency was reported in previous studies using PET and HDPE modified concrete [8], [9]. The reduction may be associated with the weaker bond between the plastic particles and cement paste, which facilitates crack initiation and propagation under tensile loading. As the proportion of plastic increases, the number of plastic paste interfaces also increases, resulting in a less effective transfer of tensile stress through the concrete matrix. However, Hameed and Ahmed [10] reported that a relatively low PET content could maintain or improve tensile performance, indicating that the effect of plastic addition also depends on the replacement level and characteristics of the mixture. These findings suggest that excessive PET or HDPE substitution tends to reduce the splitting tensile strength, while lower replacement levels may provide a better balance between plastic waste utilization and tensile performance.

3.6. Flexural Strength

Figure 7 presents the 28 day flexural strength of the PET, HDPE, and combined PET-HDPE mixtures. Flexural strength generally decreases as the replacement level increases, although the HDPE series shows some non monotonic variation at the higher percentages.

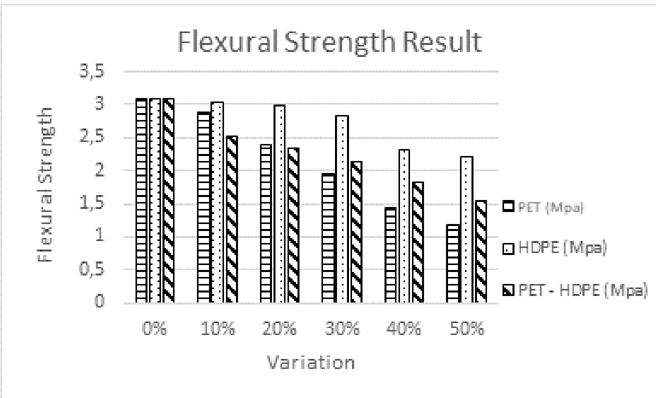

Figure 7 Flexural strength results.

Flexural strength is controlled by tensile cracking in the extreme tension zone of the specimen. The overall reduction therefore indicates that increasing plastic content weakens load transfer across the aggregate paste system. The non monotonic response in the HDPE series suggests that particle distribution and local packing can partly modify this general trend. The present results differ from studies by Hameed and Ahmed [10] and

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Guendouz et al. [11], which reported improved flexural performance at comparatively limited plastic contents in different concrete systems. Mohammed [12] also demonstrated that well graded PET could be used in recycled reinforced concrete beams without immediately compromising their intended application. These comparisons underline the importance of plastic dosage, gradation, replacement route, and structural configuration when flexural performance is considered.

3.7. Elastic Modulus

Figure 8 shows that elastic modulus generally decreases as plastic substitution increases. The three substitution arrangements follow the same overall trend, but the variation in elastic modulus is less pronounced than the variation observed in flexural strength.

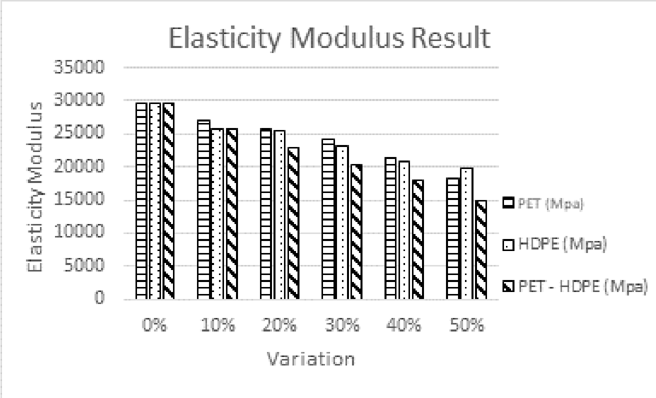

Figure 8 Elastic modulus results.

The smaller change in elastic modulus compared with flexural strength is not contradictory. Elastic modulus represents the overall stiffness of the composite within the initial elastic range and is influenced by the combined response of the cement matrix, pumice, and plastic particles throughout the specimen. Flexural strength, in contrast, depends on the initiation and propagation of tensile cracks and is therefore more sensitive to local weak interfaces, particle orientation, and defects in the tension zone. Plastic substitution can consequently produce a moderate reduction in overall stiffness while causing a larger decrease in crack controlled flexural capacity. This distinction also helps explain why results reported for other plastic modified concretes cannot be compared on replacement percentage alone [11], [12].

Overall, the test results show a clear trade off between self weight and mechanical performance. Increasing PET or HDPE content reduces unit weight and can bring the concrete into the lightweight range, but the same increase is accompanied by lower workability, strength, and stiffness. For non structural or lightly loaded applications where weight reduction is important, mixtures that satisfy the density criterion may warrant further evaluation. For reinforced or load bearing use, however, density alone cannot be used as an acceptance criterion. The standards adopted in this study provide the basis for mixture proportioning, density classification, and testing [14]-[17], but the present results should not be interpreted as establishing a code approved PET or HDPE replacement limit.

The present data are not sufficient to define a universal replacement limit for recycled reinforced concrete because reinforced member behavior, reinforcement bond, long term durability, and field performance were not examined. Within the combined series, 5% PET + 5% HDPE (10% total plastic) is the lowest replacement level tested and is therefore the most conservative starting point for further structural verification. This value should not be equated directly with the acceptable PET replacement reported by Mohammed [12], because that study used a different material system and evaluated reinforced concrete beams. An acceptable replacement percentage must therefore be established for the specific concrete mixture and structural application.

Equal PET and HDPE proportions were used so that the contribution of both waste components increased at the same rate as the total plastic content increased. This approach improves comparison within the combined series, but it does not establish that a 1:1 PET:HDPE ratio is optimal. PET dominant and HDPE dominant mixtures may produce different combinations of workability, density, strength, and stiffness because the two plastics replace different aggregate fractions and have different unit weights. Unequal PET:HDPE ratios should therefore be examined in future optimization studies.

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This study is limited to laboratory scale specimens, the materials and particle forms used in the experimental program, balanced PET:HDPE ratios, and predominantly 28 day testing. Three specimens were tested for each mixture and parameter; however, only mean values are reported, so the variability of the results cannot be evaluated from the available data. Long term durability, water penetration, shrinkage, creep, behavior at elevated temperature, reinforcement bond, interfacial microstructure, field constructability, and reinforced member performance were not investigated. These aspects should be addressed before the mixtures are considered for routine structural or infrastructure use. Future work should also report statistical dispersion, examine unequal PET:HDPE ratios, and validate promising mixtures at member and field scale.

4. Conclusion

Based on this research, the following conclusions were obtained:

1. The slump of lightweight concrete containing PET and HDPE is lower than that of the control mixture and decreases as the replacement level increases. The flat and irregular plastic particles restrict the movement of the fresh mixture and increase paste demand, making workability an important consideration at higher plastic contents.
2. PET and HDPE reduce both SSD condition and dry unit weight because their unit weights are lower than those of sand and pumice. The reduction in unit weight is the principal benefit of using these wastes in lightweight concrete.
3. PET mixtures containing 20-50% replacement meet the lightweight concrete density criterion adopted in this study, whereas the control and 10% PET mixture remain outside the stated range. PET can therefore reduce concrete weight effectively, although the associated reduction in mechanical properties must be considered.
4. HDPE mixtures containing 30-50% replacement meet the adopted lightweight concrete density criterion, while the lower HDPE replacement levels do not. The higher replacement required compared with PET is consistent with the measured unit weights of the two plastic materials.
5. Increasing PET and HDPE replacement generally reduces compressive strength, splitting tensile strength, flexural strength, and elastic modulus. The reduction is associated mainly with weaker plastic paste interfaces and changes in particle packing. Flexural strength shows greater sensitivity than elastic modulus because flexural failure is controlled by local tensile cracking, whereas elastic modulus reflects the overall stiffness of the composite in the initial elastic range.
6. The use of PET and HDPE waste as partial aggregate substitutes has practical potential where reduced self weight and plastic waste utilization are important. The results are most applicable as experimental evidence for lightweight concrete development, and replacement levels should be selected by considering density and mechanical performance together rather than waste utilization alone.
7. For applications in which mechanical property retention is the main concern, the lower replacement levels provide the more conservative basis for further investigation. In the combined series, 5% PET + 5% HDPE (10% total plastic) may be used as a starting point for additional structural verification, but it should not be treated as a validated design limit. The acceptable PET replacement reported for recycled reinforced concrete beams in [12] cannot be transferred directly because the grading, mixture, and structural system are different.
8. The findings are limited by the laboratory scale of the study, the use of balanced PET:HDPE ratios only, the absence of reported statistical dispersion, and the lack of long term durability, microstructural, reinforcement bond, and field scale evaluation. Further research should quantify result variability, investigate unequal PET:HDPE ratios, evaluate durability and constructability, and validate promising mixtures in reinforced members and field scale applications.

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