Mechanical properties and life-cycle assessment of mortar with granulated polyethylene terephthalate as fine aggregate replacement

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ABSTRACT

The construction sector generates substantial environmental impacts and contributes significantly to plastic waste accumulation. This study quantifies the mechanical and environmental effects of partially replacing fine aggregate in mortar with granulated polyethylene terephthalate (PET) at 0%, 5%, 10%, and 15% by weight of fine aggregate. Mortar performance was evaluated for compressive strength at 7 and 28 days, while environmental impacts were assessed via life-cycle indicators: embodied carbon (EC), embodied energy (EE), abiotic depletion potential (ADP), and eco-strength efficiency (ESE). At 5% PET substitution, 28-day compressive strength increased by 9.73% relative to plain mortar. Density decreased by 2.55%, and ADP decreased by 2.15%, indicating a measurable reduction in mineral resource depletion. Increasing PET substitution to 10% and 15% reduced compressive strength by 2.89–16.59% and eco-strength efficiency by 39.10–54.91%, while embodied carbon increased by 59.47–84.98%, and embodied energy increased by 55.40–79.16% demonstrating that higher PET content elevates energy and carbon burdens. Workability changes were minor 4.55–11.11% and did not significantly affect environmental outcomes. These results provide quantified evidence of the trade-off between mechanical performance and environmental impacts in PET-modified mortar. The optimal substitution level for balancing compressive strength enhancement with reduced resource depletion is 5%, as higher levels lead to increased embodied impacts despite lower mineral extraction.

Keywords: mortar, granulated PET plastic, mechanical properties, embodied carbon, embodied energy, abiotic depletion potential.

INTRODUCTION

The construction sector is responsible for a significant portion of global environmental impact, accounting for approximately 40% of total global energy consumption and a significant proportion of energy-related carbon dioxide emissions, driving the growing demand for sustainable building materials and more environmentally friendly construction practices (Taherkhani et al., 2023). Therefore, life cycle assessment (LCA) is an essential tool for evaluating the environmental performance of construction materials throughout their life cycle. Plastic pollution has become a major global environmental challenge, with increasing impacts on ecosystems and waste management systems worldwide (Rocha et al., 2025). The continuous growth in plastic consumption has made it a major contributor to environmental pollution, with global annual consumption now approaching nearly 100 million tons (Nayanathara and Ratnayake, 2024). The rapid accumulation of plastic waste has intensified the need for sustainable recycling strategies and alternative applications. One promising approach is the utilization of recycled

plastic materials in construction, which can simultaneously reduce plastic waste and decrease the consumption of natural resources. Plastic materials are composed of various types of polymers, including polypropylene (PP), polyethylene (PE), and polyethylene terephthalate (PET). To date, the plastic waste management system is considered ineffective in reducing the amount of waste produced, so the disposal process is still inefficient and has the potential to cause long-term environmental impacts (Evode et al., 2021).

PET plastic is generally used as single-use packaging, especially for drinking water bottles, which are immediately discarded after use and contribute significantly to the accumulation of plastic waste. Therefore, the reuse of PET waste in construction materials has increasingly attracted attention as a strategy to mitigate plastic waste accumulation and promote sustainable resource management (Sobuz et al., 2025). Previous study have shown that incorporating recycled PET into cement-based materials can reduce the consumption of natural aggregates while providing a potential recycling pathway for plastic waste (Ranjan et al., 2023). From a materials perspective, PET waste has been investigated in various construction applications, including mortar (Youn et al., 2026), bricks (Shaibur et al., 2025), masonry (Ranjan et al., 2025), and concrete (Wu et al., 2025), primarily focusing on mechanical performance and durability characteristics. However, from an environmental engineering standpoint, comprehensive evaluations of the environmental implications of PET incorporation using LCA approaches remain limited (Wu et al., 2025).

The use of plastic waste in cement-based materials offers several advantages, particularly in reducing dependence on non-renewable natural resources such as natural aggregates in the form of sand and stone (Babafemi et al., 2018). An environmentally friendly waste management approach can also be implemented through processing plastic into fiber. Saxena et al. (2018) reported that substituting fine aggregate with PET plastic contributes to increasing the impact resistance and energy absorption capacity of concrete. Giama and Papadopoulos (2015) emphasized that the environmental impact associated with cement use in concrete is most reliably evaluated using the LCA approach, which has become widely recognized and applied in this field. In addition, the combination of coarse and fine aggregate substitution using plastic waste in mortar and concrete is reported to be able to increase the abrasion resistance and ductility of the material under bending loads. Previous studies have reported that the incorporation of PET aggregates can reduce the mechanical performance of cement-based materials, as demonstrated by (Bamigboye et al., 2021) who found that replacing 10% of natural aggregate in concrete with PET reduced compressive strength by up to 38% when compared to conventional concrete. Nevertheless, this study focused primarily on mechanical qualities and did not assess mechanical performance and environmental indicators for various PET substitution levels in concrete. Basha et al. (2020) reported that substituting 10% of the aggregate with recycled PP granules enhanced both compressive strength and modulus of rupture; however, higher replacement levels led to reductions in strength and ultrasonic pulse velocity (UPV). LCA has become an important approach for evaluating the environmental performance of construction materials by quantifying impacts throughout their life cycle, including resource extraction, processing, and manufacturing. Indicators such as embodied energy (EE) and embodied carbon (EC) are commonly used to estimate the energy consumption and greenhouse gas emissions associated with material production, while abiotic depletion potential (ADP) reflects the consumption of non-renewable mineral resources. In the context of sustainable construction, these indicators offer substantial information about the environmental implications of incorporating recycled materials into cement-based composites.

Therefore, in this study, LCA-based indicators, including EC, EE, and ADP, are applied to evaluate the environmental performance of mortar incorporating granulated PET as a partial replacement for fine aggregate. Cement production is widely acknowledged as highly energy-intensive and a major contributor to CO_2 emissions. These findings indicate that the use of PET as an aggregate replacement still faces significant challenges, particularly related to the reduction in mechanical performance of the material, despite the potential benefits of increasing service life and sustainability aspects. This study aims to address this gap by conducting a combined mechanical and life-cycle-based environmental assessment of mortar incorporating granulated PET. Specifically, the research

evaluates the effects of PET substitution on workability, density, compressive strength, embodied carbon, embodied energy, global warming potential, and eco-strength efficiency. By doing so, the study seeks to provide quantitative insights into the trade-offs between mechanical performance and environmental benefits, advancing the application of ecological engineering principles in sustainable construction. The central hypothesis is that optimized levels of PET incorporation can enhance the ecological efficiency of mortar without critically compromising structural performance, thereby offering a pathway to more sustainable, resource-efficient building materials.

MATERIALS AND METHODOLOGY

Materials

Cement

The binder used in this study was Portland cement composite (PCC), a widely available type suitable for general construction purposes. The cement had a specific gravity of 3.08. Table 1 presents the mechanical properties of the cement utilized in this research. The mechanical properties of the cement, including compressive strength, initial and final setting time, and fineness, were determined using standard test procedures in accordance with (SNI 7064: 2014, 2014).

Fine aggregate

The fine aggregate used was natural river sand collected from the Palu River, Central Sulawesi Province. The maximum particle size of the sand was 4.75 mm. Its properties, including fineness modulus, saturated surface-dry (SSD) specific gravity, and water absorption were determined using standard test procedures in accordance with (SNI 1979 : 2016, 2016) and provided in Table 2. Prior to mixing, the sand was sieved and dried to a consistent moisture condition to ensure reproducibility.

Granulated PET plastic

Granulated PET plastic was used as a partial replacement for fine aggregate at substitution levels of 5%, 10%, and 15% by weight of fine aggregate. The PET was obtained from post-consumer plastic bottles collected from local recycling sources. The waste bottles were cleaned and mechanically shredded using a plastic granulator to produce PET particles with a controlled size distribution comparable to fine aggregate. Prior to mixing, the PET particles were washed with clean water to remove impurities and sieved to obtain a uniform particle size. Figure 1 shows the granulated PET particles used in this study. The PET granules had a specific gravity of approximately 1.35 g/cm³.

Figure 1. Granulated PET

Table 2. Physical properties of fine aggregate

Description	Result
Fine modulus, %	2.94
Bulk density, ssd	2.36
Absorption, %	1.09
Particle size range (mm)	0.15–4.75

Table 1. Mechanical properties of cement

Mechanical properties	Specific gravity	Bulk density	Fineness		Time of setting (min)		Compressive strength (MPa)		
			Air permeability	Residue on 45 mic	Initial set	Final set	3 days	7 days	28 days
Blended cement	3.08	1.19	370	16.19	131	226	13.4	22.7	31.1

Table 3. Mix design of a 1 m³ mortar

Mix design	PET percentage (%)	Fine Aggregate (kg)	Cement (kg)	Water (kg)	PET (kg)
Plain mortar	0.0	1400.5	509.3	246.5	0.0
Mortar PET 5%	5	1301.4	498.1	241.1	68.5
Mortar PET 10%	10	1206.5	487.5	235.9	137.5
Mortar PET 15%	15	1115.7	477.3	231.0	196.9

Mix design

The mix proportions of mortar constituents, including cement, fine aggregate, and granulated PET, are summarized in Table 3. Mortar preparation was conducted using a laboratory mortar mixer under controlled conditions to ensure reproducibility. The water-to-cement (w/c) ratio was kept constant at 0.48 for all mixtures to ensure direct comparability between the plain mix and the PET-modified mortars. The procedure consisted of the following steps. Cement and water were blended at medium speed for 30 seconds to form a homogeneous paste. Fine aggregate in SSD condition and granulated PET particles were gradually incorporated into the cement paste and mixed at medium speed for 2 minutes. The mixture was then homogenized at high speed for an additional 2 minutes to ensure uniform dispersion of all constituents. The fresh mortar was cast into cubic molds and stored under laboratory conditions at 28 ± 2 °C for 24 hours. After demolding, specimens were immersed in water and cured continuously until the designated testing age.

Workability and dry density

Workability of the fresh mortar mixtures was evaluated using a flow table test according to (ASTM C1437, 2020). The measured flow diameter provides an indication of mortar consistency and suitability for casting. Dry density was determined following (ASTM C642, 2021), utilizing three cube specimens of 50 × 50 × 50 mm for each mixture after 28 days of curing. Three cube specimens (50 × 50 × 50 mm) from each mixture were weighed after 28 days of curing, and the density of each specimen was calculated using Equation 1. Specimens were surface-dried with an absorbent cloth before weighing on a digital balance (±0.01 g), and their dimensions were measured with a digital caliper (±0.01 mm) to calculate volume. Prior to the dry density and compressive strength tests, all hardened mortar specimens were visually inspected to evaluate their surface condition.

$$\rho = \frac{m}{V} \qquad (1)$$

where: ρ is density of mortar (kg/m³), m is mass of the specimen (kg), and V is volume of mortar (m³).

Prior to testing, visual observations were conducted on the hardened mortar specimens to evaluate their surface condition. The specimens exhibited uniform and intact surfaces without signs of segregation, paste loss, or visible cracking. This condition indicates that the mixing, casting, and compaction processes were properly performed, resulting in well-consolidated specimens suitable for further testing. Figure 2 presents the prepared specimens prior to the density and compressive strength tests.

Compressive strength

Compressive strength tests were conducted according to (ASTM C 109/C – 08, 2009). Cubic

Figure 2. Mortar specimens prepared for density and compressive strength

specimens were tested using a standard compressive testing machine with a maximum load capacity of 2000 kN. The machine applied a load at a rate of 1.35 kN/s, and a time sensor recorded the duration until specimen failure. The calibration status of the machine was verified before the experimental program commenced, and routine checks were performed periodically throughout the testing phase to maintain consistency. Three specimens were tested for compressive strength in each mixture, and the average value was reported. Compressive strength ($f'm$) was calculated using Equation 2. Figure 3 presents the device used to evaluate the compressive strength of the mortar.

$$f'm = \frac{P}{A} \tag{2}$$

where: P is the maximum applied load at failure (N) and A is the cross-sectional area of the specimen (mm^2).

Embodied carbon and eco-strength efficiency

The main environmental impact categories, including embodied carbon (EC), embodied energy (EE), abiotic depletion potential (ADP), and eco-strength efficiency (ESE), were assessed using the CML 2001 baseline method, as described by (Xing et al., 2023) and (Guinée et al., 2011).

The environmental impact of each mortar mixture was assessed through EC, representing greenhouse gas emissions from material production, processing, transportation, and mixing. Table 4 summarizes the EC values for each constituent, derived from literature sources. The EC for the mortar mixture was calculated using Equation 3.

Compressive strength is one of the most fundamental mechanical parameters in concrete/mortar. Therefore, the compressive strength value can be used as an indicator in assessing the ecological performance and strength efficiency of the material. ESE is calculated as the ratio of compressive strength to embodied carbon, as evaluated using Equation 4.

$$EC = \sum_{i=1}^{n} (Wi \times CO_{2i\text{-}e}) \tag{3}$$

where: EC is embodied carbon (kg.CO$_2$/m^3), Wi is total amount in kg of material, n is total raw materials in mixture, i to produces 1 m^3 mortar, and CO_{2i-e} is the equivalent CO_2 value of material i in kg CO_2/kg.

$$\text{Eco-strength efficiency} = \frac{\textit{Average 28-days compressive strength of mortar}}{\textit{Total embodied carbon of mortar}} \tag{4}$$

Figure 3. Setup for compressive strength test of mortar

Table 4. Embodied carbon standard values for mortar components

Description	Embodied cabon (kg.CO$_2$/kg)	Reference
Fine aggregate	0.0139	(Turner and Collins, 2013)
Cement	0.82	(Collins, 2010)
Water	0	(Kurda et al., 2018)
PET	2.04	(Hammond et al., 2011)

Table 5. Embodied energy standard values for mortar components

Description	Embodied energy (MJ/kg)	Reference
Fine aggregate	0.017	(Adesina, 2020)
Cement	6.641	(Chen and Wang, 2022)
Water	0.002	(Kurda et al., 2018)
PET	14.8	(The Association of Plastic Recyclers White Paper, 2020)

Embodied energy

Embodied energy represents the cumulative primary energy consumed across all stages of material production, including raw material extraction, processing, transportation, and final manufacturing. This metric provides insight into the total energy demand associated with each mortar mixture and supports a life-cycle-based evaluation of environmental sustainability. EE in this study was calculated using a coefficient-based approach, where the mass fraction of each constituent material (wi) was multiplied by its corresponding embodied energy coefficient obtained from a recognized LCI database. The Embodied energy of each mixture was calculated using Equation 5, obtained from recognized databases Table 5.

$$EE = \sum_{i=1}^{n} (Wi \times EEi) \qquad (5)$$

where: *EE* is embodied energy energy of that constituent (MJ/m^3), *Wi* is total amount in kg of material, n is total raw materials in mixture, *i* to produces 1 m^3 mortar, and *EE$_i$* is the equivalent embodied energy value of material *i* in kg MJ/kg.

Abiotic depletion potential

Abiotic depletion potential quantifies the potential depletion of non-renewable mineral resources attributable to material production and use. ADP is expressed in kg Sb-equivalent and is a key indicator for assessing the sustainability of construction materials from a resource conservation perspective.

For each mortar mixture, ADP-element was calculated according to Equation 6, obtained from established life-cycle assessment databases in Table 6. This calculation accounted for resource extraction, processing, and transportation stages, enabling a comprehensive evaluation of PET incorporation on mineral resource use.

$$ADP = \sum_{i=1}^{n} (Wi \times ADPi) \qquad (6)$$

where: *ADP* – element is abiotic depletion potential of constituent *i* (kg Sb-eq/m^3), *Wi* is total amount in kg of material, *n* is total raw materials in mixture, *i* to produces 1 m^3 mortar, and *ADP$_i$* is the equivalent ADP-element value of material *i* in kg Sb-eq.

Table 6. Abiotic depletion potential standard values for mortar components

Description	ADP-element (kg.Sb-eq/kg)	Reference
Fine aggregate	3.37.E-10	(Ohemeng and Naghizadeh, 2023)
Cement	3.73.E-03	(Bakka' et al., 2024)
Water	1.57E-11	(Ohemeng and Naghizadeh, 2023)
PET	8.43E-06	(ArmaPET Life Cycle Assessment, 2025)
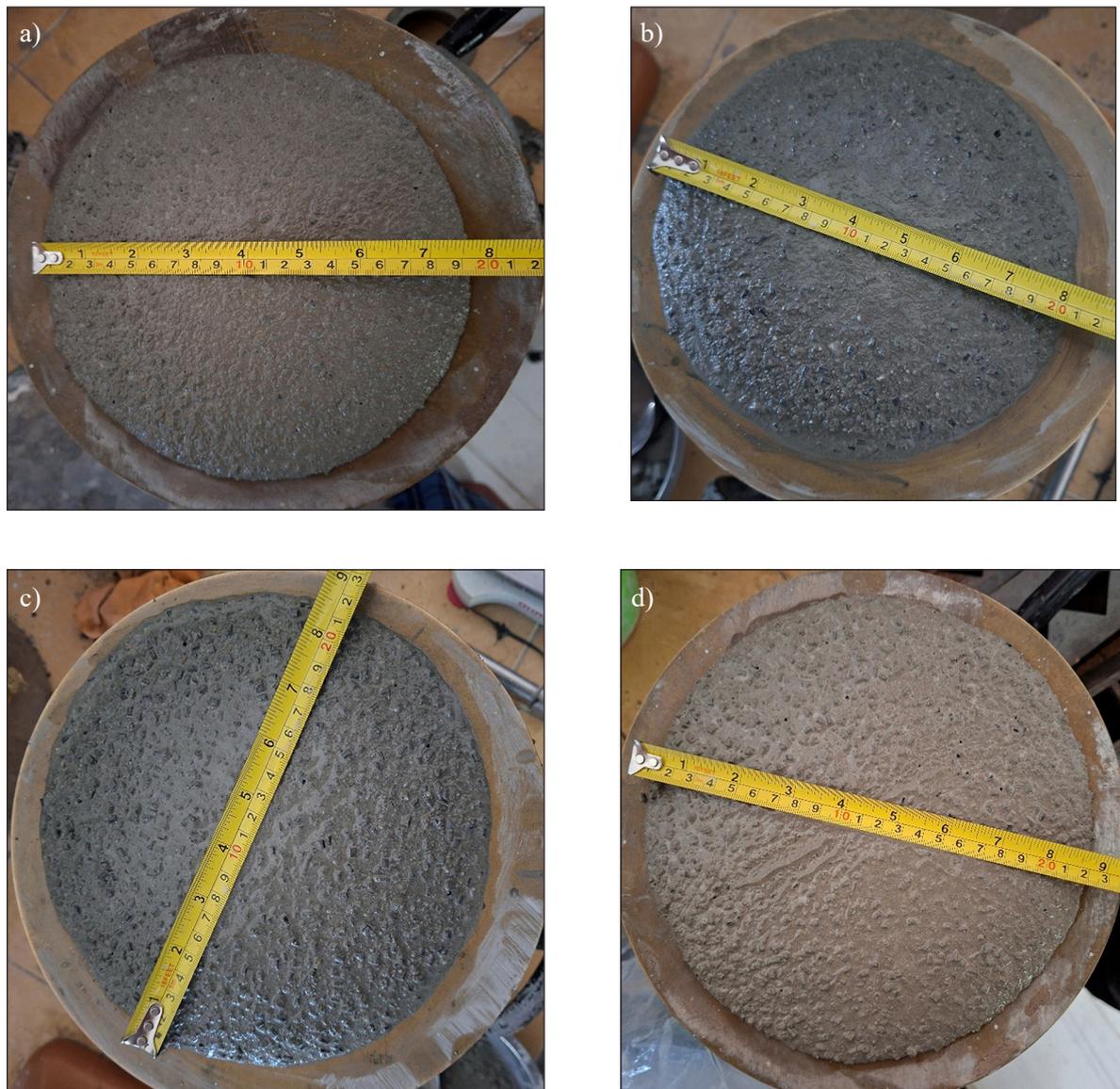
Figure 4. Slump flow of fresh mortar (a) plain mortar, (b) mortar PET 5%, (c) mortar PET 10%, (d) mortar PET 15%

RESULT AND DISCUSSION

Workability

The workability of various combinations was evaluated in their fresh condition to ascertain the effect of using plastic waste as a substitute for fine aggregate. The results of the workability test of the plain mortar and the various mortar mixtures with plastic waste are shown in Figure 4 and Figure 5. Based on detailed observation in Figure 5, it can be seen that the workability of plain mortar is 198 mm, and the substitution of 5% PET, 10% PET, and 15% PET shows that the flowability also increases, and the PET improvement factor values are 4.55%, 8.59%, and 11.11% compared

to the plain mortar, respectively. The spherical shape of plastic particles reduces surface contact and friction within the mixture, resulting in lower water demand and improved workability, as reflected by higher slump flow values. Compared with natural mineral aggregates, PET particles generally exhibit smoother surfaces and lower surface roughness, which reduces internal friction within the mortar matrix. As a consequence, the mobility of the mixture increases, leading to higher flow values. In addition, PET has negligible water absorption compared to natural sand, allowing more free water to remain within the cement paste. This excess free water contributes to improved workability without requiring additional mixing water. This result is consistent with

previous studies conducted by (Marof and Šiller, 2025), which reported similar behavior when natural fine aggregates were partially substituted with plastic materials. The observed increases in slump flow with PET substitution indicate that the mortar mixtures become more flowable due to the smooth and hydrophobic characteristics of PET particles, which reduce friction and water absorption relative to natural sand. Several studies on recycled PET foamed mortars showed reductions in workability with increasing PET content, which underscores the dependence on particle shape and mix design (particle angularity) rather than polymer content (Mydin et al., 2025). From the life-cycle assessment perspective, improved workability may enable reductions in mixing water, thereby indirectly influencing the life-cycle environmental profile of the mortar. However, in this study, the water-to-cement ratio was maintained constant at 0.484, and no reduction in water demand was implemented. Therefore, the environmental implications of enhanced flowability were not directly captured in the LCA model. The reduction in mixing water did not significantly affect the embodied carbon, embodied energy and abiotic depletion potential of the mortar. Based on the LCA inventory database used in this study, water has an embodied carbon value of 0 $kgCO_2$/kg, embodied energy of 0.002 MJ/kg (Kurda et al., 2018), and ADP of 1.57×10^{-11} kg Sb-eq/kg (Ohemeng and Naghizadeh, 2023). These values are negligible compared to cement production, which dominates the environmental burden of mortar. Therefore, although improved workability enables reductions in mixing water and enhances mix efficiency, its direct influence on the assessed environmental indicators remains minimal within the defined system boundary.

Density

The density results of the control mortar and PET-modified mixtures are presented in Figure 6. The plain mortar exhibited a density of 2224 kg/m^3. The incorporation of granulated PET as a partial replacement for fine aggregate at levels of 5%, 10%, and 15% reduced the density by 2.55%, 4.43%, and 4.97%, respectively, compared to the control mortar. The decrease in bulk density with increasing PET content is physically expected due to the lower specific gravity of plastic compared to mineral aggregates. This trend aligns with findings reported elsewhere for recycled PET in lightweight cementitious composites (Mydin et al., 2025). Consequently, partial replacement of sand with PET decreases the overall mass per unit volume of the mortar mixture. This characteristic may provide advantages in applications requiring lightweight construction materials. However, excessive incorporation of low-density particles may also influence the internal packing structure of the mortar, potentially affecting mechanical performance.
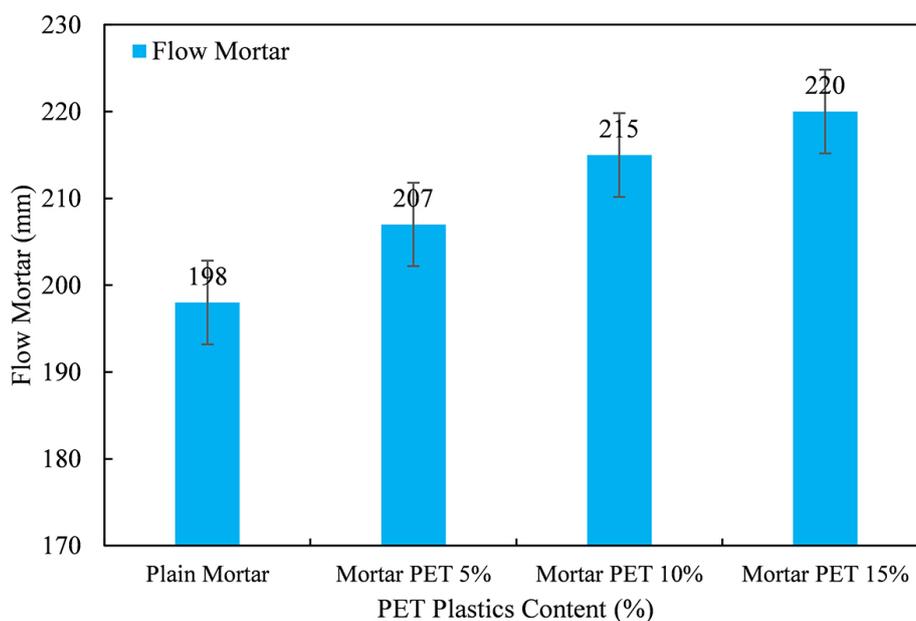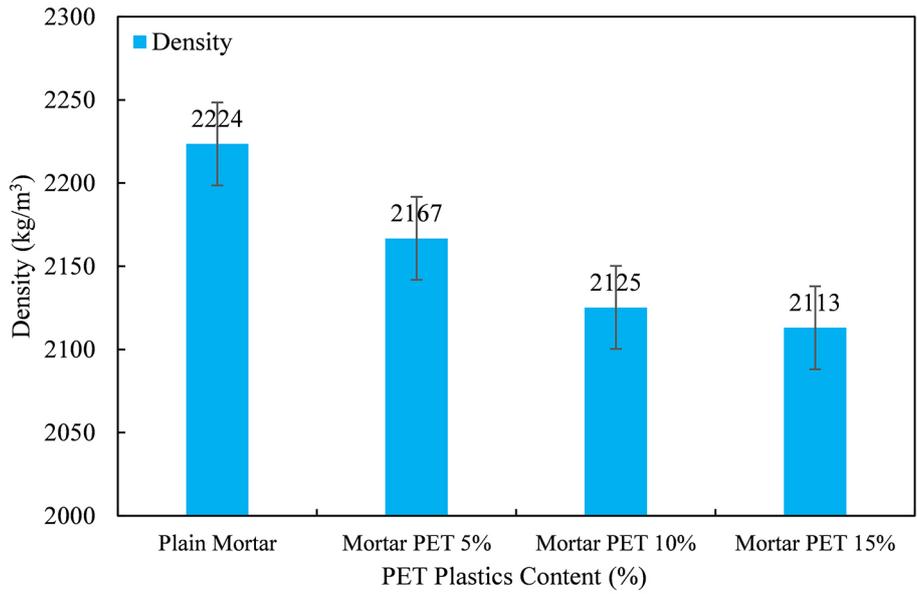

Figure 5. Workability of mortar mixes

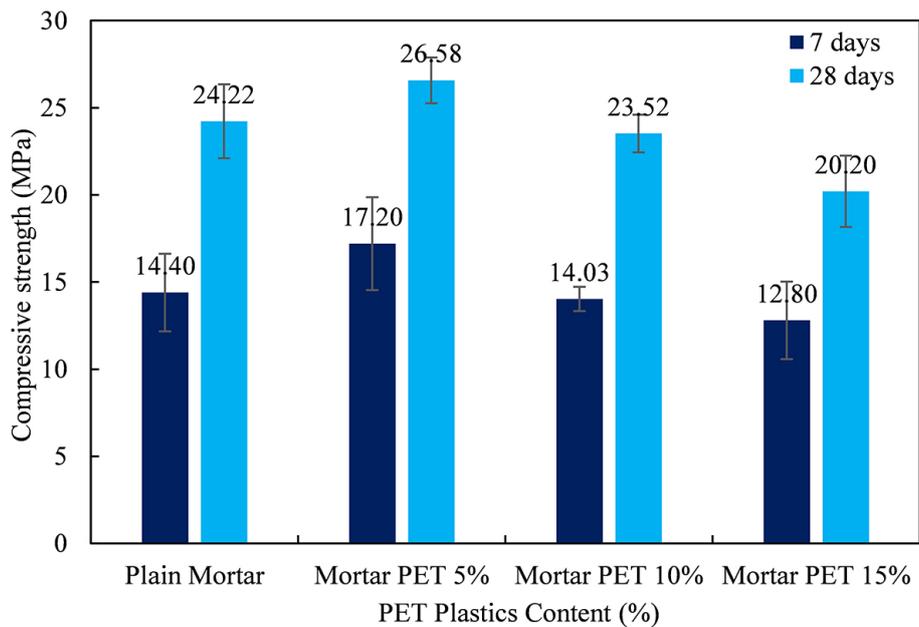**Figure 6.** Density of mortar mixes

Figure 7. Compressive strength of mortar mixes

This observation is consistent with the broader objective of developing lightweight materials with improved sustainability performance. The incorporation of PET contributes to a lower-density matrix while simultaneously promoting plastic waste valorization. From a life-cycle perspective, such material efficiency and waste utilization strategies support more sustainable resource management. Additionally, reduced material density may theoretically influence structural dead loads and transport efficiency.

Compressive strength

Figure 7 presents the compressive strength results of the control mortar and mortar mixtures incorporating plastic waste. At 7 days, the plain mortar achieved a compressive strength of 14.40 MPa. The incorporation of 5% PET as a partial replacement for fine aggregate enhanced the compressive strength by 19.44% compared to the control. However, increasing the replacement level to 10% and 15% resulted in strength reductions of 2.59% and 11.11%, respectively,

compared to the plain mortar. At 28 days, the plain mortar achieved a compressive strength of 24.22 MPa. The incorporation of 5% PET as a partial replacement for fine aggregate enhanced the compressive strength by 9.73% compared to the control. However, increasing the replacement level to 10% and 15% resulted in strength reductions of 2.89% and 16.59%, respectively, compared to the plain mortar. The experimental results indicate that compressive strength initially increased at a PET substitution level of 5%, which may be attributed to the adequate interfacial bonding between PET particles and the surrounding fine aggregate within the mortar matrix. At this level, PET particles may fill void spaces between natural aggregates, resulting in a denser microstructure and improved stress distribution under compressive loading. However, when the PET content increases to 10% and 15%, the compressive strength decreases significantly, which is consistent with previous studies by (Umasabor and Daniel, 2020). This behavior can be attributed to the reduced interfacial bond strength within the mortar matrix, lower water absorption capacity, and the lower elastic modulus of PET plastic waste compared to natural aggregates. (Islam et al., 2016) further reported that plastic aggregates exhibit negligible water absorption capacity, leading to the accumulation of excess water within the interfacial transition zone (ITZ). This localized increase in water content promotes higher porosity in the ITZ, which consequently reduces compressive strength. Moreover, the inherently

smooth surface texture of most plastic aggregates weakens the mechanical interlocking and bond strength between the cement matrix and the aggregates, ultimately resulting in lower mortar strength. From an environmental performance perspective, compressive strength is not merely a mechanical property but also an indicator of whether mortar can adequately satisfy structural performance requirements. Mortars with lower strength may require greater material volume or thicker structural elements to sustain equivalent loads, potentially increasing environmental impacts through higher resource consumption and greater production-related carbon emissions. In this study, the strength enhancement observed at 5% PET substitution indicates a more favorable balance between structural functionality and environmental considerations, whereas higher PET contents reduce this functional efficiency.

Embodied carbon and eco-strength efficiency

Figure 8 presents the embodied carbon and eco-strength efficiency values of the mortar mixtures used in this study. The plain mortar mixture has an embodied carbon value of 437.07 $kgCO_2/m^3$. The analysis shows that substituting 5%, 10%, and 15% of fine aggregate with granulated PET resulted in an increase in embodied carbon values of 29.57%, 59.47%, and 84.98% compared to the plain mortar, respectively. This increasing trend indicates that the processing steps for granulated PET plastic still contribute significant carbon emissions in the production cycle. Although PET
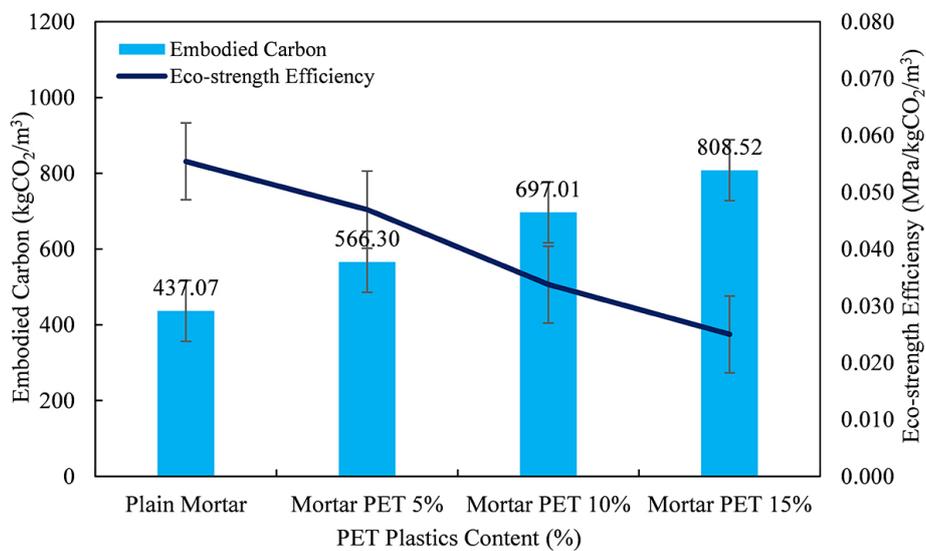

Figure 8. Embodied carbon and eco-strength efficiency of mortar mixes

is classified as a recycled material, its preparation for construction applications involves several energy-intensive stages, including collection, sorting, washing, crushing, and granulation. Consequently, increasing the proportion of PET in the mixture leads to a proportional increase in embodied carbon values. ESE is defined as the ratio of 28-day compressive strength to embodied carbon, making compressive strength the primary indicator of a material's mechanical performance. The plain mortar mixture has an eco-strength efficiency value of 0.055 MPa/kgCO$_2$/m^3. The analysis indicates that the substitution of fine aggregate with granulated PET at levels of 5%, 10%, and 15% led to a reduction in eco-strength efficiency by 15.31%, 39.10%, and 54.91% compared to the plain mortar, respectively. Although the use of PET offers advantages in terms of waste diversion, increasing the proportion of PET shows a downward trend in ESE values. This declining trend is due to a combination of increased production carbon content and a tendency for mechanical performance to decline at higher substitution levels. This increase ultimately reduces the mortar's ecological efficiency. The increase in embodied carbon with increasing PET replacement is consistent with other LCA studies showing that processing and recycling of plastics can carry significant energy and emission burdens relative to natural aggregates (Ghani et al., 2024). LCA of mortars with PET aggregates reported similar trends where PET preparation steps (washing, grinding) contributed to increased global warming potential (Lazorenko et al., 2024). A

sensitivity analysis further indicates that recycled materials do not inherently ensure environmental benefits. Although PET utilization supports waste diversion, energy-intensive processing stages may increase embodied carbon and weaken ecological performance. In a projected improvement scenario, where enhanced recycling efficiency reduces carbon intensity from 2.04 to approximately 0.60 (about a 70% reduction), ecological strength efficiency would improve markedly, potentially shifting eco-efficiency rankings among mixtures.

Embodied energy

Figure 9 presents the variation in EE of mortar mixtures incorporating PET as a partial replacement for fine aggregates. The reference mortar exhibited the lowest embodied energy value of 3406.40 MJ/m^3. In contrast, PET substitutions of 5%, 10%, and 15% increased the embodied energy by 27.54%, 55.40%, and 79.16%, respectively, compared to the plain mortar. The trend of increasing embodied energy with PET content reinforces that mechanical recycling processes are energy demanding – often more so than extraction and preparation of natural aggregates. Similar findings have been reported in comparative LCA studies involving PET aggregate substitution, where optimizing processing steps significantly improved energy outcomes (Lazorenko et al., 2024). This observation is consistent with previous studies (Irlan et al., 2025) that utilized PP plastic as a fine aggregate substitute. The elevated
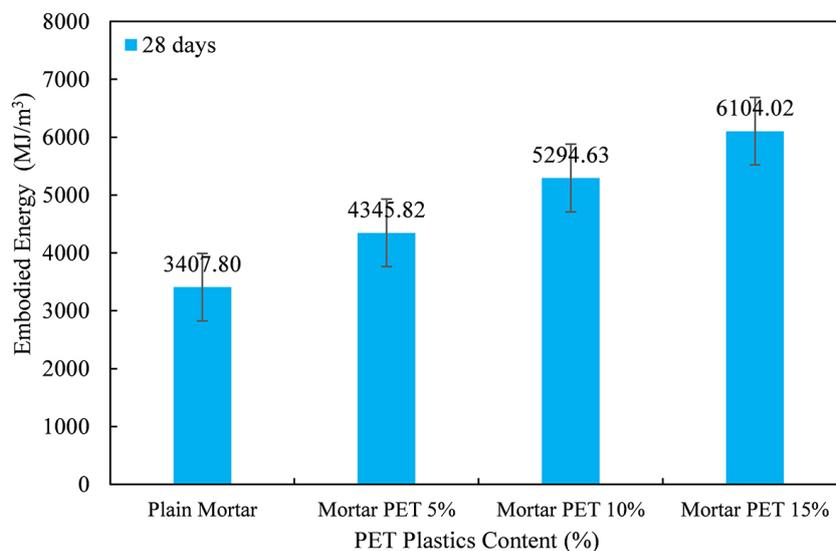

Figure 9. Embodied energy of mortar mixes

embodied energy can largely be attributed to the energy-intensive phases within the PET life cycle, including collection, sorting, washing, crushing, granulation, and, in certain cases, thermal reprocessing. Consequently, the total energy consumption per kilogram of PET material generally exceeds that required for the production of conventional natural mineral aggregates. As a result, the cumulative energy demand of PET processing significantly exceeds that of conventional material aggregates. From a sustainability perspective, these findings highlight the importance of evaluating recycled materials through a life cycle framework. While recycled plastics contribute to waste reduction and support circular material flows, their environmental benefits must be offset by the energy demand associated with recycling processes. Therefore, determining an optimal substitution level is essential to balance resource recovery benefits with the environmental burdens associated with material processing. In environmental engineering, the cumulative energy demand (CED) of a material is a key metric that influences resource use efficiency and the potential for renewable energy integration. For instance, engaging renewable electricity grids or improving material preparation efficiency can reduce the life-cycle embodied energy of PET-modified mortars, altering the environmental trade-offs significantly. A hypothetical renewable energy scenario was introduced assuming that 50% of electricity used in PET processing is supplied from renewable sources. This transition would reduce fossil energy dependence and significantly lower the embodied energy of PET-modified mortars. As a result, the environmental performance of recycled plastic utilization would improve, making waste-derived construction materials more sustainable. The scenario demonstrates that the sustainability of recycled materials strongly depends on energy system decarbonization.

Abiotic depletion potential (ADP-element)

Figure 10 illustrates the abiotic depletion potential (ADP-element) of mortar mixtures incorporating PET as a partial replacement for fine aggregate. The plain mortar had the highest ADP value, which was 1.90 kg Sb-eq/m³. In contrast, the incorporation of PET at replacement levels of 5%, 10%, and 15% resulted in reductions of 2.15%, 4.22%, and 6.19% compared to the plain mortar, respectively. The reduction in ADP values is primarily associated with the decreased demand for virgin mineral resources when recycled PET replaces a portion of natural aggregates. Cement-based materials typically rely heavily on non-renewable resources extracted from natural deposits, particularly for cement production and aggregate mining. These extraction processes contribute significantly to the depletion of abiotic resources. By partially substituting natural aggregates with recycled PET, the overall consumption of virgin mineral resources is reduced, leading to lower ADP values. Despite the higher embodied energy and carbon associated with PET processing, the reduction in mineral extraction provides
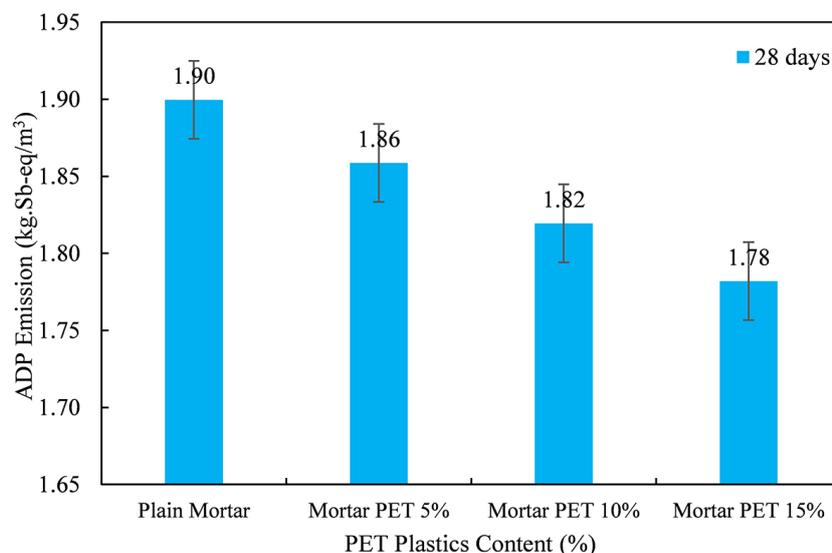
Figure 10. Abiotic depletion potential of mortar mixes

a measurable environmental benefit from a resource depletion perspective. Therefore, the environmental performance of PET-modified mortar should be interpreted as a trade-off between increased processing impacts and reduced reliance on virgin raw materials. This finding highlights the potential contribution of recycled plastics in improving resource efficiency in construction materials. The partial substitution of natural fine aggregates with recycled PET reduces reliance on primary mineral extraction, thereby mitigating resource depletion impacts. A comparable trend was reported by (Kim et al., 2016) in a life cycle assessment study, where increasing the incorporation of recycled materials in concrete mixtures led to a reduction in ADP values compared to the plain mortar. Unlike climate and energy indicators, ADP decreased with increasing PET content, reflecting reductions in the demand for virgin mineral resources. This aligns with literature showing that recycled materials can lower depletion metrics by substituting high-impact virgin resources (Patrisia et al., 2025). From an environmental performance perspective, the strength-normalized ADP indicator provides a functional measure of resource efficiency by relating abiotic resource use to mechanical capacity. The 5% PET mixture exhibits the lowest ADP per MPa value (0.070 kg Sb-eq/MPa), compared with the plain mortar (0.078 kg Sb-eq/MPa), PET 10% (0.078 kg Sb-eq/MPa), and PET 15% (0.088 kg Sb-eq/MPa), indicating the most efficient use of natural resources relative to structural performance. Although higher PET substitutions continue to reduce total ADP values, their normalized indicators increase due to declining compressive strength, which lowers functional environmental efficiency. These results demonstrate that moderate PET incorporation provides superior resource-use efficiency, with 5% substitution representing the most environmentally favorable level when mechanical performance is considered.

CONCLUSIONS

This study investigated the mechanical and environmental performance of mortar incorporating granulated PET as a partial replacement for fine aggregate at substitution levels of 0%, 5%, 10%, and 15%. Based on the experimental and environmental assessment results, the following conclusions can be drawn:

1. PET incorporation improved fresh-state workability and reduced mortar density, which may contribute to reduced structural dead loads and improved transport efficiency.

2. A 5% PET substitution enhanced compressive strength, indicating improved structural performance. Higher substitution levels reduced strength due to weaker interfacial bonding and increased porosity, leading to lower functional structural efficiency.

3. Life-cycle assessment revealed a climate trade-off. Although PET utilization promotes plastic waste diversion, embodied carbon increased and Eco-Strength Efficiency declined with increasing PET content due to energy-intensive recycling processes.

4. The environmental limitations of PET-modified mortars can be mitigated through improved recycling efficiency. Enhanced PET processing that reduces carbon intensity (e.g., from 2.04 to substantially lower levels) would decrease embodied carbon and improve eco-efficiency performance.

5. Similarly, embodied energy burdens can be significantly reduced through renewable energy integration in recycling infrastructure, highlighting the importance of energy system decarbonization for sustainable material recovery.

6. In contrast to climate indicators, abiotic depletion potential decreased with PET incorporation because recycled PET reduces reliance on virgin mineral extraction. Strength-normalized indicators showed that the 5% PET mixture achieved the most efficient resource utilization relative to structural performance.

7. Overall, recycled PET is not inherently a low-carbon solution under current processing conditions. Moderate substitution levels (5%) provide the most balanced mechanical–environmental performance, while broader sustainability improvements depend on recycling technology optimization, renewable energy adoption, and integration with low-carbon cementitious materials.

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