EDSU Journal of Engineering and Technology (EDSUJET)

Statistical and Mechanical Performance Analysis of Conventional Concrete and Shredded Plastic – Modified Concrete

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Received: 10 October 2025, Accepted: 28 October 2025, Published: 30 November 2025

KEYWORDS

Plastic
Modified Concrete
Shredded
Mechanical Performance
Statistical Analysis

ABSTRACT

In an effort to combat the global plastic waste crisis and advance sustainable building practices, this study explores the use of shredded polyethylene terephthalate (PET) as a partial substitute for granite aggregates in concrete. The mechanical and statistical performance of conventional and PET-modified concrete (0%, 2.5%, 5%, and 10% replacement) was assessed. According to ASTM C128 material characterization, sharp sand (specific gravity 2.58, Cu = 6.0, Cc = 0.67), was suitable. ANOVA and regression analysis of the compressive and flexural strength tests revealed that low PET dosages (≤5%) produced 28-day compressive strengths of 28.13 MPa and 27.47MPa, surpassing ASTM C39 structural thresholds, with negligible flexural strength reductions (≈2%). 10% PET, however, decreased compressive strength by 71.3% to 9.16 MPa, making it unsuitable for structural use because of increased porosity and poor bonding. ANOVA revealed that PET and granite had a significant impact ($p < 0.001$), and regression modelling showed that the strength decreased by 2.26 MPa for every 1% increase in PET (R^2= 89.6%). Higher PET dosages are appropriate for non-structural applications, while lower dosages (≤5%) promote sustainable structural concrete. To improve environmentally friendly concrete applications, future studies should examine PET surface treatments and durability.

21. INTRODUCTION

The most popular building material in the world, concrete is the foundation of contemporary construction and is prized for its strength, adaptability, and durability. However, there are serious environmental consequences associated with its production, such as the loss of natural aggregates, high energy consumption, and significant emissions of carbon dioxide (CO_2), which make up roughly 7–8% of greenhouse gas emissions worldwide (Mehta & Monteiro, 2014; Miller et al., 2018). Environmental problems are made worse by the growing global plastic waste crisis, which is characterized by over 350 million tons of plastic produced annually and less than 9% recycled (Geyer et al., 2017). Incorporating recycled materials into concrete, like shredded PET plastic, presents a viable way to address these problems by lowering plastic waste, protecting the environment, and encouraging environmentally friendly building techniques. Shredded PET has drawn attention as a way to partially replace conventional aggregates in concrete, addressing environmental issues and the need for sustainable building materials. Because of its flexibility and low weight, PET, a thermoplastic frequently found in plastic bottles, can improve the ductility and impact resistance of concrete (Choi et al., 2005; Saikia & de Brito, 2014). However, there are drawbacks to its use because too much PET can impair mechanical performance by increasing porosity and weakening the cement matrix's bond, which reduces compressive and flexural strengths (Albano et al., 2009; Hannawi et al., 2010).

To find the ideal PET replacement levels that strike a balance between sustainability and structural integrity, this trade-off requires careful research. With an emphasis on the effects of different PET replacement levels on compressive and flexural strengths, this study compares the mechanical and statistical performance of conventional concrete with PET-modified concrete. The study quantifies the variability in mechanical properties and creates predictive models to direct real-world applications by utilizing statistical tools like regression modeling and analysis of variance (ANOVA). Managing plastic waste and satisfying the construction industry's need for long-lasting, environmentally friendly materials are the two main challenges at the heart of the research problem. While higher dosages frequently result in significant strength reductions due to weak interfacial transition zones (ITZ) and increased void content, previous studies have demonstrated the potential of low PET dosages (≤5%) to maintain acceptable mechanical properties (Sharma & Bansal, 2016; Almeshal et al., 2020). In order to guarantee adherence to standards like ASTM C128 and BS EN 12620, the scope of this work includes the characterization of aggregate materials, such as sand, granite, and shredded PET. Additionally, the mechanical qualities of concrete mixes containing PET replacements at 0% (control), 2.5%, 5%, and 10% are assessed, and the outcomes are subjected to rigorous statistical analysis. By offering data-driven insights into the best way to use PET in concrete, this study advances the field of sustainable construction and aids in the creation of environmentally friendly materials that support the objectives of global sustainability (Lepech et al., 2018). This study improves knowledge of recycled plastic integration in concrete and provides guidance for real- world construction applications by addressing the trade-off between mechanical performance and environmental benefits. According to Hannawi et al. (2010), PET aggregates reduce the compactness and strength of the concrete matrix by causing voids because of their smooth surfaces and lower density. The need for careful dosage optimization was also highlighted by Frigione (2010), who observed a 30% reduction in compressive strength when 10% PET was used as a fine aggregate replacement. Admixtures, aggregate properties, and mix design all have a significant impact on the mechanical properties of concrete, including flexural strength (roughly 10–15% of compressive strength) and compressive strength (usually 20–50 MPa for conventional mixes) (Mehta & Monteiro, 2014). According to ASTM C39 standards, low replacement levels (≤5%) in PET-modified concrete have been demonstrated to preserve compressive strengths within allowable bounds for structural applications, frequently surpassing 25 MPa (Almeshal et al., 2020). Although less impacted at low dosages, flexural strength also drastically decreases at higher PET content because of decreased matrix cohesion and aggregate interlock (Saikia & de Brito, 2014). Concrete that has been PET-modified also shows changed durability characteristics. According to Singh et al. (2022), low PET dosages improve resistance to water and chloride ion penetration by reducing permeability, which is advantageous for long-term durability. A balanced approach to replacement levels is necessary because higher dosages of porosity result in increased water absorption and decreased resistance to environmental degradation (Gu & Ozbakkaloglu, 2016). To measure the impact of plastic aggregates on concrete performance, statistical techniques such as regression modeling and analysis of variance (ANOVA) have been used. ANOVA was utilized by Almeshal et al. (2020) to verify that mechanical properties are significantly influenced by aggregate type and replacement level, with p-values indicating strong statistical significance. With studies revealing high R2 values for predictive accuracy, regression models have further clarified the connection between PET content and strength reduction (Sharma et al., 2021). Notwithstanding these developments, there are still unmet research needs, especially in the area of thorough statistical modeling of the durability and mechanical performance of PET-modified concrete under various curing conditions and replacement levels.

To maximize performance, more research is also needed to determine how PET particle size, shape, and surface treatment affect bonding with the cement matrix (Hameed & Fadhil, 2021). This study fills these gaps by employing a Taguchi-based experimental design and statistical tools such as ANOVA and regression to systematically evaluate the mechanical properties of PET- modified concrete at replacement levels of 0%, 2.5%, 5%, and 10%. This work intends to contribute to the creation of useful guidelines for the use of PET in the production of concrete by expanding on previous findings and offering a solid framework for comprehending the trade-offs between sustainability and structural performance.

2. MATERIALS AND METHODS

Ordinary Portland Cement (OPC), produced by BUA Cement Company and meeting BS 12 (1996) specifications, served as the main binder for this investigation. A sufficient particle size distribution for strength development and durability was ensured by the cement's 4.2% fineness modulus. Locally sourced sharp river sand was used as the fine aggregate. The sand was cleaned and dried before use to get rid of harmful substances like clay and silt. Sieve analysis was used to determine its specific gravity and particle size distribution in order to confirm that it complied with the standard grading specifications for structural concrete. Because of its high crushing resistance and angularity, which improve particle interlocking and concrete strength, crushed granite with a maximum nominal size of 20 mm was used as the coarse aggregate. Furthermore, granite was partially replaced by weight with shredded polyethylene terephthalate (PET) made from used plastic bottles. After being collected and cleaned, the PET plastics (Figure 1) were mechanically shred into irregular pieces that ranged in size from 1 mm to 20 mm. The goal of this substitution was to encourage sustainable waste management techniques while evaluating the impact of plastic waste on the mechanical performance of concrete. Throughout the study, concrete specimens were mixed and cured using potable water that was free of organic matter, salts, and other contaminants. As advised for M15 grade concrete, the water– cement ratio was kept at 0.55 to guarantee sufficient workability without excessive bleeding or segregation.

Figure 1: PET Plastic used

2.1 Mix Design

The Department of Environment (DOE) method, which is frequently used for mix design in the UK and abroad, was used to determine the proportions of the concrete mix. The mix ratio used was 1:3.2:2.34 (cement: fine aggregate: coarse aggregate) by weight, with M15 as the target grade. At four different percentages 0%, 2.5%, 5%, and 10% shredded PET was added to the mixtures to partially replace granite. The precise weight measurements of the necessary amounts of cement, sand, granite, PET, and water were made for each mix. The mixing process adhered to BS 1881-125 (1986). To create a workable and homogenous concrete, the dry ingredients were first mixed until the cement and aggregates were evenly distributed. Water was then added gradually while mixing.

After that, the newly mixed concrete was put into ordinary steel molds. 150 × 150 × 150 mm cubes were cast for the compressive strength test, and 500 × 100 × 100 mm beams were made for the flexural strength test. To remove trapped air and guarantee proper compaction, the concrete was compacted in three layers using a vibrating table. To stop moisture loss, wet burlap was placed over the top surfaces after they were finished with a trowel. The specimens were demolded and placed in a curing tank filled with drinkable water at room temperature in the laboratory after a 24-hour period. In accordance with standard procedure for evaluating the strength of concrete, the curing times that were chosen were 7, 14, 21, and 28 days.

2.2 Test Conducted

2.2.1 Sieve Analysis and Specific Gravity

In compliance with BS EN 12620 (2013), sieve analyses was performed on the fine aggregate. The aggregates were separated into various fractions using a stack of sieves with progressively smaller mesh sizes, and the percentage of material that passed through each sieve was noted. The particle size distribution curve was determined thanks to this analysis, and its suitability for concrete production was verified by comparing it to the standard grading envelope. Using the pycnometer method, the specific gravity of aggregates was ascertained in compliance with BS 812-2 (1995). Oven-dried sand was utilized for the fine aggregate, and granite and PET particle samples were used for the coarse aggregate. The density of the materials, which has a direct impact on the final concrete's unit weight, strength, and durability, was revealed by the specific gravity values.

2.2.2 Compressive Strength Test

The test for compressive strength was carried out in compliance with BS EN 12390-3 (2019). Cube specimens were positioned in the middle of a 2000 kN capacity compression testing machine between steel platens. Up until failure, the load was applied steadily and gradually without shock at a regulated rate of 0.6 N/mm² per second. The compressive strength was computed by dividing the failure load by the cube's cross-sectional area, and the maximum load at failure was noted. To track the strength development over time, tests were performed on specimens that had been cured for 7, 14, 21, and 28 days.

2.2.3 Flexural Strength Test

The two-point loading method was used to determine flexural strength in compliance with BS EN12390-5 (2009). On two supports with a span length of 400 mm, beam specimens measuring 500× 100 × 100 mm were positioned, and loads were applied at two equally spaced points along the span. Until the specimen failed in flexure, the load was gradually increased. The failure load, span length, and cross-sectional dimensions of the beam were used to compute the flexural strength, also known as the modulus of rupture. In structural applications where bending stresses are present, this test yielded important information about the tensile behavior of concrete.

2.2.4 Statistical Analysis

Statistical tools were used to assess the impact of replacing concrete with shredded PET on its mechanical properties in order to supplement the experimental investigations. The effects of input parameters on output responses were systematically analyzed using a Taguchi Design of Experiments (DOE) approach. To ascertain the statistical significance of PET replacement levels on compressive and flexural strength, analysis of variance (ANOVA) was performed. To create predictive models that link PET content to strength values, regression analysis was also carried out. Specialized statistical software was used for all statistical calculations, guaranteeing precision and dependability in the results' interpretation.

3. RESULTS AND DISCUSSION

3.1 Sieve Analysis and Specific Gravity Result

According to Neville (2011), the fine aggregate's specific gravity of 2.58 is within the 2.5–2.7 range that is advised for natural sands used in structural concrete. With effective particle sizes of D10 = 0.15 mm, D30 = 0.30 mm, and D60 = 0.90 mm, the sieve analysis yielded a coefficient of uniformity (Cu) of 6.0 and a coefficient of curvature (Cc) of 0.67 (Figure 2).

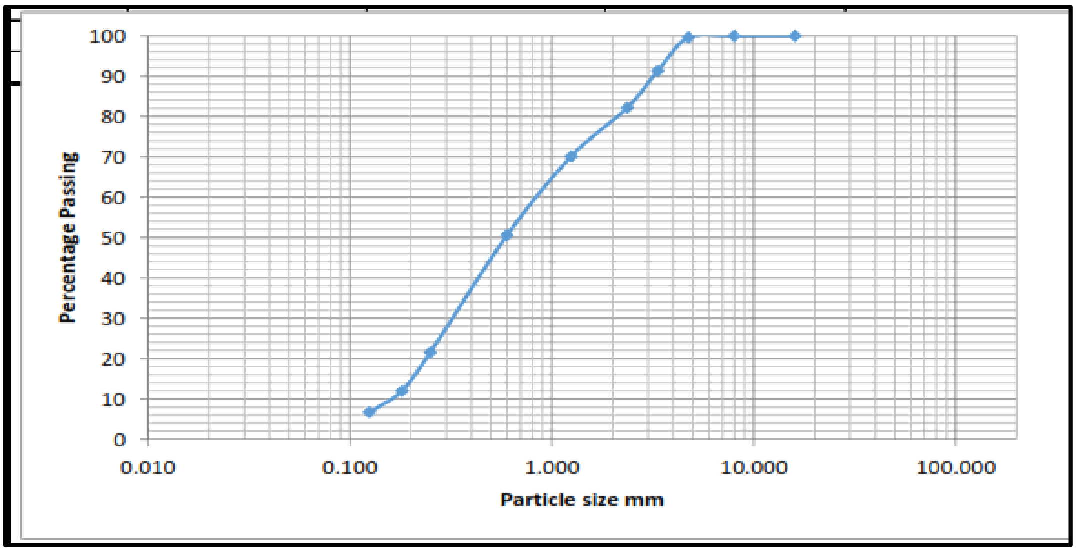

Figure 2: Sieve Analysis Result

According to ASTM C33 (2016), these values show a moderately distributed, well-graded sand that is appropriate for use in concrete. The Cc value within the permissible range (1–3) indicates that the sand grading is consistent, while the Cu > 4 confirms sufficient particle size spread for improved packing and fewer voids. All things considered, the sand was judged appropriate for creating concrete that was both workable and long-lasting. While the shredded PET particles had irregular shapes and a relatively lower density, the coarse aggregate (granite) had angular shapes and a high specific gravity, which enhanced strength through interlocking. The overall density and strength of concrete decrease with increasing PET replacement, a phenomenon later confirmed in mechanical testing, due to the difference in specific gravity between granite (≈2.65) and PET (≈1.37, as reported by Ismail & Al-Hashmi, 2008).

The sand sample analyzed in Figure 4.1 exhibited a specific gravity of 2.58, which falls within the typical range of 2.55 to 2.65 for clean, naturally occurring quartz sands, as reported by Neville (2011). According to ASTM C128 (ASTM, 2015), the standard specific gravity for fine aggregates used in concrete should range between 2.4 and 2.9, confirming that the tested sand is well-suited for use as a fine aggregate in concrete production. This value indicates that the sand is primarily composed of quartz or similar dense minerals, with minimal impurities that could adversely affect concrete performance. However, the specific gravity of 2.58, being on the lower end of the typical range for quartz sands, suggests the possibility of a moderate presence of porous or organic material, though it remains within acceptable limits for most civil engineering applications, including structural and non-structural concrete elements.

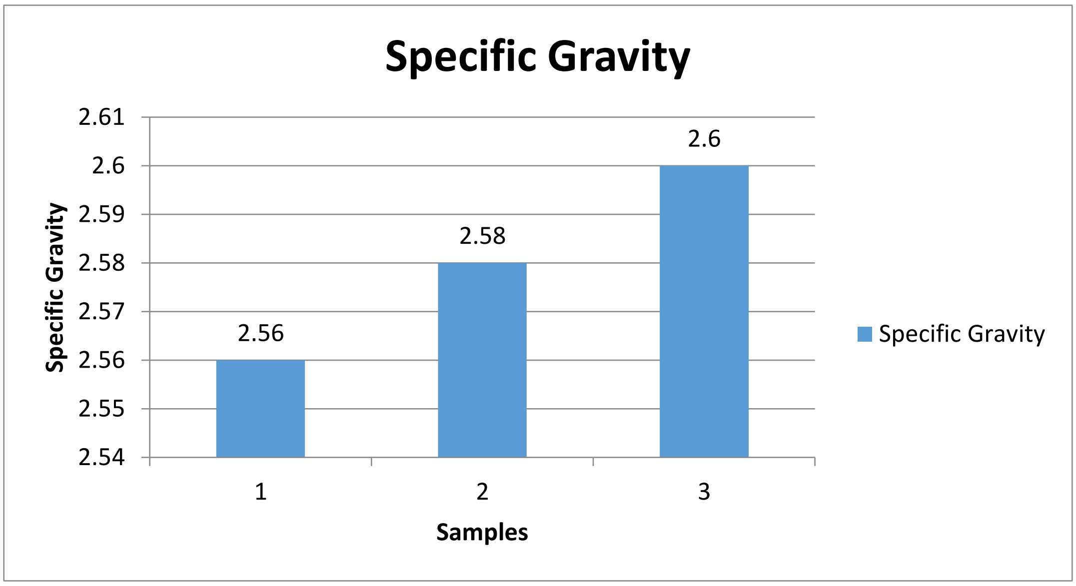

Figure 2b: Specific Gravity Result

3.2 Design of Experiment and ANOVA

To statistically validate the influence of PET replacement on strength, an analysis of variance (ANOVA) was conducted. The results are presented in Table 1.

Table 1: ANOVA Summary for Concrete Strength

Source	DF	Seq SS	Adj MS	F-Value	P-Value
	3	1.68485	0.56162	2215.29	
	3	1.63148	0.54383	2145.12	
	9	0.00228	0.00025	—	
Total	15	3.31862	—	—	—

At a very high level of statistical confidence ($p < 0.001$), the results demonstrate that the strength of concrete is significantly influenced by both granite and PET content. Granite and PET both contribute nearly equally to the observed strength variability, as indicated by the nearly equal sequential sums of squares (Granite = 1.68485; PET = 1.63148). This is consistent with research by Saikia and de Brito (2014), who found that the kind and amount of aggregates including plastic alternatives strongly influence how concrete compresses. The remarkably high F-values (>2000) support the results' robustness and demonstrate how even slight variations in the PET content have a substantial impact on the mix's mechanical characteristics. Excellent model fit was indicated by the small residual error (0.00228).

3.3 Compressive Strength Result

The Compressive Strength results are presented in Table 2.

Table 2: Compressive Strength (MPa) at Different Ages

PET (%)	7 Days	14 Days	21 Days	28 Days
0	29.38	29.87	31.33	**31.87**
2.5	24.76	25.82	27.91	**28.13**
5	24.18	25.02	27.11	**27.47**
10	9.11	9.69	8.31	**9.16**

With a 28-day strength of 31.87 MPa, the control mix (0% PET) surpassed the target grade strength of M15, indicating proper mix design and quality. Compressive strength gradually declined as the PET content of mixes containing PET replacement increased. The strength decreased slightly to 28.13 MPa (≈11.7% reduction compared to control) at 2.5% PET and to 27.47 MPa (≈13.8% reduction) at 5% PET. These comparatively minor decreases show that strength is not significantly harmed by limited PET incorporation. Frigione (2010) actually reported similar results, finding that PET replacement below 5% improved ductility and toughness while only slightly affecting compressive performance.

Compressive strength, however, fell sharply to 9.16 MPa at 10% PET, a 71.3% decrease from the control. Given that PET is hydrophobic and lacks the rough surface texture of natural aggregates, this steep decline can be attributed to the poor interfacial bonding between PET and cement paste (Sharma et al., 2021). Albano et al. (2009) also noted that the low stiffness of PET particles causes premature cracking under load and localized stress concentrations. All mixes gained strength between 7 and 28 days, but the relative difference between the control and PET-modified mixes widened at higher PET percentages. The strength development across curing ages followed anticipated hydration trends. This demonstrates that any toughness advantages are outweighed by the dilution effect at PET concentrations above 5%.

3.4 Flexural Strength Result

The flexural strength results are presented in Table 3. According to Neville (2011), the control concrete's 28-day flexural strength of 4.216 MPa was in line with the usual values recorded for concretes of grades M15–M20.

Table 3: Flexural Strength (MPa) at Different Ages

Curing Age	0%	2.5%	5%	10%
7 days	4.166	4.047	4.029	**2.742**
14 days	4.177	4.078	4.055	**2.865**
21 days	4.206	4.133	4.113	**2.543**
28 days	4.216	4.138	4.122	**2.753**

According to Neville (2011), the control concrete's 28-day flexural strength of 4.216 MPa was in line with the usual values recorded for concretes of grades M15–M20. Low-level PET substitution does not significantly reduce flexural resistance, as evidenced by the marginal reductions of 1.8% and 2.2% that occurred with PET incorporation at 2.5% and 5%, respectively. It's interesting to note that this implies that PET particles, as also noted by Rahmani et al. (2013), can preserve flexural strength by giving the matrix ductility and crack-arresting qualities even though they reduce compressive strength. However, flexural strength dropped to 2.753 MPa (a reduction of about 34.7%) at 10% PET. This demonstrates that too much PET reduces the concrete beams' capacity to support tension because it weakens matrix-aggregate bonding and increases void content. Silva et al. (2013) found similar results, emphasizing that when substitution exceeds 5–7%, plastic-modified concretes perform poorly under flexural loading.

3.5 Regression Analysis Result

Regression analysis was used to further measure PET's impact on compressive strength. The model that was acquired was: **Compressive Strength (MPa) = 34.04 – 2.258 × PET (%)** with a regression coefficient (R^2) of 89.6%, the PET content accounts for almost 90% of the variation in compressive strength.

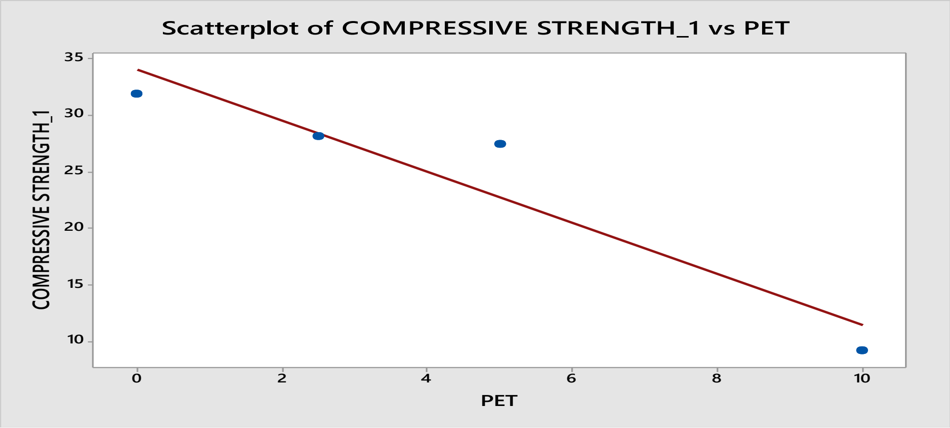

Figure 3: Scattered Plot of Compressive Strength Test

PET has a statistically significant negative correlation with strength, according to the p-value (0.053), but the effect only becomes noticeable when replacement is greater than 5%. This is in line with the thresholds recommended in ASTM C39 (2018), which discourages replacing coarse aggregate with weak substitutes in excess because of the significant decline in performance. The negative slope (–2.258) shows that compressive strength drops by about 2.26 MPa for every 1% increase in PET replacement. This relationship is consistent with earlier research by Sharma et al. (2021) and Ismail and Al-Hashmi (2008), which found that strength decreased linearly as plastic content increased.

4. CONCLUSION

Base on the results obtained, the following conclusions were made;

i. With minimal strength reductions (11.7% and 13.8%) in comparison to the control (31.87 MPa), low PET dosages (≤5%) yield concrete with acceptable mechanical performance, achieving 28-day compressive strengths of 28.13 MPa (2.5% PET) and 27.47 MPa (5% PET), surpassing the 25 MPa threshold for structural concrete per ASTM C39 (2018).

ii. Concrete with low PET dosages (≤5%) has acceptable mechanical performance, with 28-day compressive strengths of 28.13 MPa (2.5% PET) and 27.47 MPa (5% PET) exceeding the ASTM C39 (2018) structural concrete threshold of 25 MPa. They also show only minor strength reductions (11.7% and 13.8%) when compared to the control (31.87 MPa).

iii. The flexural strengths at 2.5% and 5% PET (4.138 MPa and 4.122 MPa) exhibit slight decreases (≈2%) in comparison to the control (4.216 MPa), suggesting that PET's fiber- like behavior improves tensile and crack-bridging qualities, making it appropriate for structural applications.

iv. Due to poor interfacial bonding, increased porosity, and PET's hydrophobic nature, it is not suitable for structural use. A 28-day compressive strength of 9.16 MPa (71.3% reduction) and a flexural strength of 2.753 MPa (34.7% reduction) are the results of significant mechanical declines caused by a 10% increase in PET replacement.

v. With minimal strength reductions (11.7% and 13.8%) in comparison to the control (31.87MPa), low PET dosages (≤5%) yield concrete with acceptable mechanical performance, achieving 28-day compressive strengths of 28.13 MPa (2.5% PET) and 27.47 MPa (5% PET), surpassing the 25 MPa threshold for structural concrete per ASTM C39 (2018).

vi. Flexural strengths at 2.5% and 5% PET (4.138 MPa and 4.122 MPa) exhibit slight decreases (≈2%) in comparison to the control (4.216 MPa), suggesting that PET's fiber- like behavior improves tensile and crack-bridging qualities, making it appropriate for structural applications.

vii. Due to poor interfacial bonding, increased porosity, and PET's hydrophobic nature, it is not suitable for structural use. A 28-day compressive strength of 9.16 MPa (71.3% reduction) and a flexural strength of 2.753 MPa (34.7% reduction) are the results of significant mechanical declines caused by a 10% increase in PET replacement.

viii. In non-structural applications where high strength is not essential, like lightweight fillers, pavements, or insulation panels, the 10% PET mix is feasible.

ix. PET and granite play crucial roles in concrete performance, as evidenced by the ANOVA that shows they significantly affect strength ($p < 0.001$) and contribute almost equally to variability (50.8% and 49.2%).

x. The ≤5% threshold for structural applications is reinforced by regression analysis, which provides a predictive tool for mix design (Compressive Strength = 34.04 – 2.258 PET, R^2 = 89.6%) and quantifies a 2.26 MPa strength reduction per 1% PET increase.

Recommendations

i. Low dosages of PET (≤5%) promote environmentally friendly building practices by making sustainable concrete possible, which lessens the need for natural aggregates and minimizes plastic waste while also supporting global sustainability objectives.

ii. To increase the use of recycled plastics in construction, future studies should investigate PET surface treatments, hybrid mixes with additional cementitious materials, and long- term durability.

NOMENCLATURE

%	Percentage
MPa	MegaPascal

Abbreviations

PET	Polyethylene Terephthalate
ANOVA	Analysis of Variance
Cu	Coefficient of Uniformity
Cc	Coefficient of Curvature

ACKNOWLEDGEMENTS

I thank Almighty Allah for His guidance, Dean of Faculty Prof. John Wasiu for his support and my supervisor Engr. Dr. Ibrahim A.O. for his mentorship. Appreciation is extended to the Faculty of Engineering, Civil Engineering Department staff of Edo State University Iyamho and my family, especially my wife, for their constant encouragement.

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