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Physical and mechanical characteristics of geopolymer concrete incorporating PET wastes as partial replacement of fine aggregate

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Abstract:
This research aims to address the environmental and sustainability issues associated with traditional concrete using geopolymer concrete and PET waste as alternatives. The methodology involves performing physical tests on density and absorption, and mechanical tests on the modulus of elasticity, compression, splitting, flexure, energy absorption, and axial strain. Fine aggregates (sand) are partially replaced with 5; 10; 15; 20; and 30 % by equivalent weight percentages of PET waste particles while keeping all other proportions constant. Additionally, the ultrasonic pulse velocity is determined. Specimens were evaluated at 7 and 28 d to assess the impact of PET incorporation. Results indicate that adding PET particles alters the properties of the resulting concrete. The physical properties (density and ultrasound velocity) decrease as the PET ratios increase, and the absorption rate increases. In terms of strength, results show that the specimens containing partial substitution ratios ranging within 5-15 % present 3,49-9,09 %; 2,20-10,09 %; and 8,45-10,26 % increments in tensile, compressive, and flexural strengths, respectively, compared with the reference specimens. The results also indicate a rise in the energy absorption and axial strain of the specimens with replacement percentages ranging from 5-30 %, and the modulus of elasticity decreases as the PET content increases. The strength parameters decrease when the PET content exceeds 15 %. In conclusion, replacing 10 % of sand with PET particles in geopolymer concrete enhances strength-related properties. Specifically, the tensile, compressive, and flexural strengths of the specimens are enhanced by 20,27; 12,70; and 14,28 %, respectively, compared to the reference specimen.

Keywords:
geopolymer concrete; PET wastes; Ground Granulated Blast Furnace Slag (GGBFS); sand replacement

1 Introduction

To accommodate global population growth, which now exceeds seven billion, the demand for concrete has surged. However, raw materials used to produce concrete are depleting, prompting researchers to explore sustainable alternative materials as full or partial substitutes for various concrete constituents. The ratio of additives to concrete and their effects on concrete properties are critical factors that must be considered in numerous studies [1]. Various materials can be added to concrete to alter its engineering characteristics. Although some of these additions may negatively affect other concrete constituents, they may enhance others [2-3]. Additive materials, such as fibre/rubber [4-6], plastics [7-8], slag [9-12] and resin/polyethylene terephthalate (PET) [13], can enhance the engineering properties of concrete. Geopolymer concrete (GPC) is a type of concrete that combines natural aggregates, silica sand, and gravel using a polymer binder as an additive or alternative to cement [14]. Polymeric concrete has better mechanical properties, chemical resistance, and ductility [15]. Moreover, using ground granulated blast furnace slag (GGBFS) and fly ash can improve the mechanical properties of concrete and decrease manufacturing expenses [16]. The strength of GPC made with fly ash ranged from 15-50 MPa, and that of GGBFS geopolymer concrete ranged from 25-70 MPa. Durability tests, including alkali–silica reaction, acid attack, and sulphate attack, conducted on GPC have shown that GPC yields positive results for up to 84 days compared with concrete made with ordinary Portland cement (OPC) [17-19]. Fly ash is better at creating GPC than traditional OPC because the former has higher initial strength, durability, cost efficiency, and lower carbon emissions than the latter. This reduced the amount of waste produced [20]. This polymer is sturdier than OC [21-29].

Gokulram and Anuradha [30] examined the utilisation of Class F fly ash and ground granulated blast furnace slag (GGBS) by considering two types of structures. Sharma and Singh [31] used equal amounts of fly ash and GGBS (50 % each) in their study. The increase in global energy intake requires consideration of each contemporary strength problem and its environmental results. Plastics persist in the environment for centuries because of their resistance to deterioration. To address this issue, PET waste can be reused by incorporating it into concrete mixes at a volume ratio of 0,25 %. PET fibres, when added to concrete mixes, PET fibres can increase the flexural, tensile, and compressive strengths of concrete, absorb energy, enhance ductility, and reduce the workability and elastic modulus. Early studies found that the optimal fibre percentage for the mechanical properties of concrete ranges from 1,0-1,5 % [32].

Because PET is utilised in various forms and amounts as a substitute for sand in concrete, the mechanical characteristics of mixtures with PET as a filler vary. Choi et al. [33] discovered that incorporating PET into concrete mixtures as a substitute for fine aggregates reduced compressive strength and density. Similarly, Albano et al. [34] observed that the tensile strength, compressive strength, and elastic modulus of regular concrete decreased when PET particles were included. Rahmani et al. [35] demonstrated that substituting PET bottle waste for fine aggregates in concrete results in reduced slump, modulus of elasticity, and pulse velocity as the amount of PET waste increases. Ismail et al. [36] reported that increasing the PET waste content decreased the flexural and compressive strengths of concrete. Prabhu et al. [37] showed that a 1 % replacement of sand by volume is the optimum percentage for enhancing the tensile and compressive strengths. Khanna et al. [38] concluded that the compressive strength increases to its maximum when the fly ash content is 10 % and PET waste plastic (even with 30 % by volume of fibres) is used as a partial substitute. Aslam et al. [39] found that including waste pumice aggregate (WPA) as a lightweight aggregate in concrete resulted in reduced workability, density, and strength metrics as well as heightened water absorption, diminished impact energy, and lower ultrasonic pulse velocity. Aslam et al. [40] showed that concrete with 0 % recycled coarse aggregates and varying amounts of plastic particles exhibited better workability than concrete with 50 or 100 % recycled coarse aggregates. The addition of polyethylene terephthalate particles decreased the compressive and split tensile strengths. The study concluded that plastic particles, curing days, and recycled aggregate interacted synergistically to impact the compressive and splitting tensile strengths

of the concrete. Noshin et al. [41] concluded that recycled aggregate concrete with 10-12 % rice husk ash is suitable for enhancing concrete properties. However, acid water curing negatively impacts the hardened properties of concrete, reducing its compressive strength compared with normal water curing. Noshin et al. [42] concluded that replacing up to 25 % of natural aggregates with recycled aggregates is preferable for reducing construction costs and addressing environmental pollution issues. In addition, it was observed that the splitting tensile strength of a concrete batch should range between 9 and 11 % of its compressive strength. Furthermore, Noshin et al. [43] concluded that certain factors such as quarry dust, curing duration, and rice husk ash interact synergistically to influence the compressive and splitting tensile strengths of concrete.
This study used GPC made from GGBFS in place of OPC and incorporated PET waste to improve its mechanical properties and reduce its weight. In this study, PET plastic waste was broken down into small particles that matched the size of natural sand. PET was substituted with a portion of fine aggregates in the reference mix at weight percentages of 5; 10; 15; 20; and 30 %, respectively. A typical blending ratio of 1:1,5:3 is used. Using PET plastic residues in GPC hazardous wastes that are non-biodegradable can help remove waste from the environment, thereby preventing further pollution.

2 Methodology

This experiment examined the effects of replacing fine aggregates in geopolymer concrete with varying percentages of PET waste. Various tests were conducted on geopolymer concrete samples containing various weight percentages of waste made of PET. The ideal weight percentage was determined by comparing the results with those of the reference samples.

2.1 Materials and methods

2.1.1 Ground Granulated Blast Furnace Slag (GGBFS)

This study used GGBFS that satisfied the requirements of ASTM C9892010 [44] in terms of chemical composition, as listed in Table 1.

Table 1. Chemical analysis of GGBFS

Oxides	**Content** (%)	**Requirements of GGBFS (ASTM C 989- 10)**
SiO_2	35,9	--
Fe_2O_3	0,6	
Al_2O_3	8,4	
CaO	37,9	
MgO	8,9	
K_2O	0,7	
Na_2O	0,3	
SO_3	0,7	
L.O.I	0,9	
Sulfide sulfur (S)	0,5	max. 2,5 %

2.1.2 Aggregates

Natural sand (minimum size = 4,75 mm and maximum size = 20,00 mm) was used as the fine aggregates for the coarse aggregates obtained from Basra City, Southern Iraq. Table 2 and (Figure 1) present the grading and specifications of the fine aggregates that met the Iraqi Standard Specification No. 45/1984 Zone 2 [45].

Table 2. Sieve analysis of fine aggregate (sand) and PET

Sieve size (mm)	**Cumulative sand Percentage passing**	**Cumulative PET Percentage passing**	**Limits of Iraqi Standard IQS145- 1984, zone 2**
9,50	100,0	100,00	100
4,75	98,2	95,20	90-100
2,36	90,8	80,34	75-100
1,18	73,3	50,52	55-90
0,60	52,3	30,50	35-59
0,30	15,1	0,60	8-30
0,15	4,2	0,21	0-10

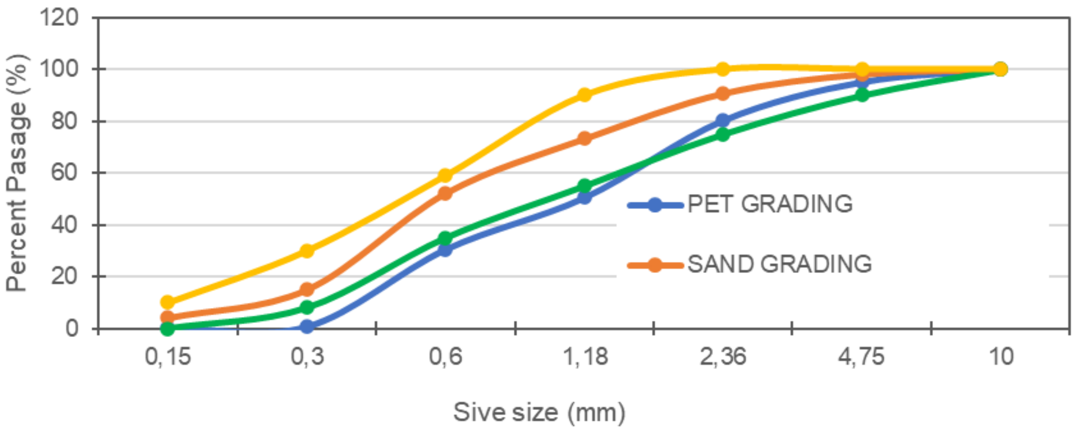


Figure 1. Grading Curve for Original Fine aggregate and PET waste

2.1.3 Alkaline liquid

This study used a combination of sodium hydroxide and sodium silicate solutions as the alkaline activator for geopolymerisation. NaOH is commercially available as flakes and pellets. Pure NaOH pellets (98 % pure) were dissolved in water to prepare a NaOH solution for the current investigation. The NaOH solution with a concentration of 10 M consisted of 10 × 40 = 400 g of NaOH solids (in pellet form) per litre of solution. Sodium silicate is commercially available in a liquid gel form; therefore, it can be used as such. The chemical composition of sodium silicate is as follows: SiO_2 = 32-33 %, Na_2O = 13,1-13,7 %, and water 54,9 % by mass. NaOH and sodium silicate solutions were combined before 24 h at the least before using the alkali liquid [46].

2.1.4 Admixture

TOPFLOW SP 603, consistent with ASTM C494 Types A, B, D, F, and G, was used in this study [47]. The dosage ranged from 0,5 to 3,0 L per 100 kg of the binder.

2.1.5 PET

PET bottles of various colours and sizes were used in this study. The PET bottles were crushed into small pieces that fit through a No. 4 sieve (Figure 2). Sieve analysis revealed that the PET particles satisfied the sand requirements of the Iraqi Specification No. 45/1984 Zone 2 [45]. Table 2 shows the results of particle analysis of PET particles.

Figure 2. PET bottles waste particles

2.2 Mixture proportions

One of the most popular mixing weight ratios (1:1,5:3), which was used to obtain the target strength of 45 MPa for curing under ambient laboratory conditions. The masses of gravel, sand, and GGBFS in the mix were 1200; 650; and 400 kg per cubic meter, respectively. The ratio of water to GGBFS was 0:125 (with 0,3 % superplasticiser). Waste from PET bottles was added to the reference blend at five different percentages (i.e., 5; 10; 15; 20; and 30 %) as a partial replacement for sand based on the trial outcomes. The proportions of the GPC mixtures are listed in Table 3.

Table 3. Concrete mixture proportion for all PET replacement ratio (w_c = 0,125) (material kg/m^3)

Pet/Sand	GGBFS	Sand	Gravel	Water	PET	NaOH	S.S.	S.P.
0 %	400	650,0	1200	50	0,0	23	110	12
5 %	400	617,5	1200	50	32,5	23	110	12
10 %	400	585,0	1200	50	65,0	23	110	12
15 %	400	552,5	1200	50	97,5	23	110	12
20 %	400	520,0	1200	50	130,0	23	110	12
30 %	400	455,0	1200	50	195,0	23	100	12

2.3 Preparation of the test specimens

First, the fine and coarse aggregates were washed and cleaned before use. Second, cube, cylinder, and prism specimens were prepared, cleaned, and lubricated before casting (Figure 3). PET waste particles were mixed as a partial substitute for sand at the weight percentages indicated above. The aggregates, including gravel, sand, and PET waste substitutes, were mixed using an electric mixer. GGBFS was also included in the GPC. The mixing process involved several steps to ensure a homogeneous mix: The dry components, including gravel, sand, PET waste particles, and GGBFS, were first mixed thoroughly in an electric mixer for approximately 2 min to ensure uniform distribution. An alkaline activator solution consisting of sodium hydroxide and sodium silicate was gradually added to the dry mix while the mixer was running. This ensured that the alkaline liquid was uniformly distributed throughout the mixture. The superplasticiser and water were gradually added to the mixture. These components were added slowly to avoid sudden changes in the consistency of the mix.

The mixing process was continued for at least 2 min to achieve a uniform and workable consistency. The mixed concrete was poured into moulds with specified dimensions. The moulds were filled into layers, and each layer was compacted to remove air bubbles and ensure the proper filling of the moulds. Compaction was performed using a vibrating table or handheld vibrator to ensure that the concrete was well-compacted and free of voids. This step is crucial for achieving the desired density and strength of the concrete. After casting, the specimens were left in moulds for 24 hours to set. After demoulding, the specimens were cured at room temperature (39°). This curing process helps to achieve the desired mechanical properties of the geopolymer concrete. Following these detailed steps, the preparation of the test specimens ensured that the resulting concrete had consistent and reliable properties for further testing and analysis.
Compression strength tests were conducted at 7 and 28 days of age (three cubes for each age group). Similarly, cylindrical specimens (150 × 300 mm) were used for the splitting tensile strength test (three-cylinder specimens for each age). Energy absorption and elastic modulus tests were conducted on the specimens at 28 days of age. Six prism specimens (100 × 100 × 400 mm) were employed for the flexural strength tests at 7 and 28 days of age. Three prism specimens were tested at each age using the three-point load method in accordance with ASTM C1609-12 [48]. One cubic specimen (150 × 150 × 150 mm) was used for each replacement percentage to measure the absorption and ultrasonic pulse velocity (UPV) after 28 days. In accordance with ASTM C597 [49] the total number of samples casting for various tests was 120 samples, and the UPV test was performed with 0,1 μs accuracy using PUNDIT PC 1012.

Figure 3. Cast of test specimens for each replacement percentage

3 Discussion and results

3.1 Slump

In accordance with ASTM C143 [50], a slump test was conducted based on the finding that GPC exhibited reduced workability when the proportion of PET waste in the GPC mixture increased. A comparison of the 30 % replacement specimen with the reference sample showed a significant reduction (52,9 %) in GPC workability (Figure 4). This decrease in GPC workability was caused by the fact that the surface area of PET waste particles exceeded that of the sand particles; such a large surface area allowed for a considerable amount of water to be saturated on the surface. This behaviour is similar to that of OC, where a large decrease (62,5 %) in the workability of concrete is observed relative to the workability of the standard mix when a 20 % replacement rate is used [51]. At 25 % replacement, the reduction rate was 38,1 % compared to that of the control mix [52]. When the PET particle content was increased to 30 %, the slump decreased to 94 % of that of the reference mix [53].

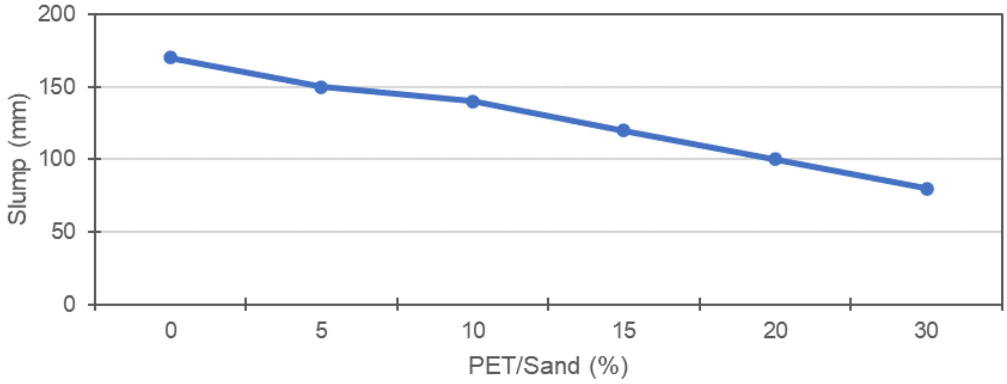


Figure 4. Effect of PET percentage replacement on Slump of a geopolymer mix

3.2 Density

The dry density measurements showed that the dry densities of the concrete specimens decreased when PET waste particles were added to the mixture (Figure 5). Given that the PET particles had a low density (1380 kg/m^3), increasing the PET proportion to 30 % resulted in a 17,25 % decrease in GPC density after 28 days in comparison with the reference mixture. In certain cases, such as in large concrete structures on unstable soil, this modest decrease may help reduce the dead load of GPC.

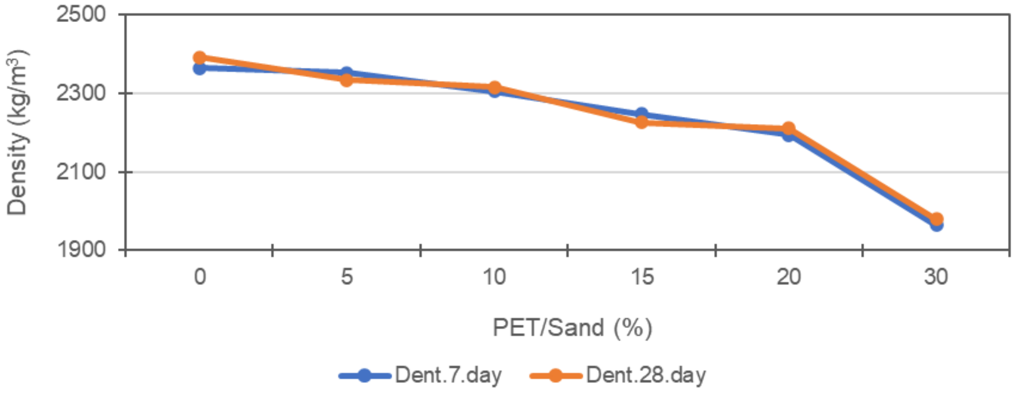


Figure 5. Effect of PET percentage replacement on density for 7 and 28 days

In Figure 5, the test results for GPC density and PET substitution are displayed as percentages. The densities of the specimen with a 10 % replacement percentage at 7 and 28 days (2305,15 and 2315,57 kg/m^3, respectively) were generally similar and showed a decrease of approximately 2,4 and 3,1 %, respectively, with respect to the reference mixture. When the quantity of PET waste in the concrete increased, the density decreased.

3.3 Compressive strength

The compressive strength test was conducted in accordance with B.S. 1881 Part 116 [54]. A 2000 kN compression machine was used. The compressive strength increased when the PET waste replacement rate was in the range of 5-15 % (Figure 6). Varying increases were observed across all ages. At 28 days, 10 % was determined to be the ideal percentage to achieve maximum improvement in compressive strength (12,70 %). Furthermore, when the ratios for replacing PET waste were 5 and 15 %, the compressive strength increased by 10,09 and 2,20 %, respectively. The compressive strengths of the cube specimens with a 15 % replacement percentage were similar to those of the cube specimens used as a reference. The strength of the cube specimens with a 30 % replacement rate of PET waste decreased by

29,09 % when the specimens were compressed. A small ratio of PET waste replacement increased in compressive strength. In specimens with 5; 10; and 15 % PET waste replacement, increases of 10,09 %; 12,70 %; and 2,20 %, respectively, were obtained after 28 days (Figure 6). When the applied load reached its maximum value, the failure mode manifested and influenced the PET particle structure (i.e., the concrete strength increased when the stress changed from shear to tensile). Moreover, sand particles elongate the plastic materials and change the loading before failure. Without these particles, GPC exhibited brittle behaviour. In contrast, the compressive strength decreased when the PET waste particles exceeded 15 % (Figure 6). The cementitious paste-to-PET particle bond strength was negatively affected by the PET particles' smooth surface. A notable zone was observed between the cementitious paste and PET residue fragments in the specimens with high percentages of PET waste (20 and 30 %). When compression was applied, the specimens weakened.

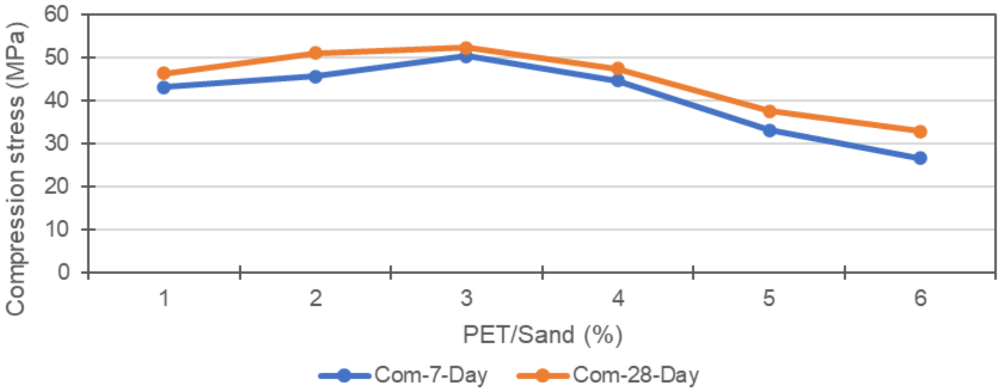


Figure 6. Effect of PET percentage replacement on compression for 7 and 28 days

The two classes were 5-15 % and 20-30 %. The compressive strength values increased considerably in the first class with 5-15 % substitution. Substitution in the second class (i.e., containing 15-30 % PET) showed a decline in compressive strength.

3.4 Splitting tensile

ASTM C496 [55] was used as a reference to perform the splitting tensile strength tests. The findings in (Figure 7) indicate that the splitting tensile strength increased when the percentage of substituted PET waste particles increased to 15 %. In contrast to the reference mix, the mix with 5 % PET waste replacement attained an optimal increase of 3,49 % in the splitting tensile strength at 28 days of age. However, the splitting tensile strength of the mix containing 30 % PET waste decreased by 12,23 % compared with the splitting tensile strength of the reference sample. When the ratio of recycled PET waste to the total waste exceeded 15 %, the opposite pattern was observed (Figure 7). Compared with sand particles, PET waste fragments exhibited reduced slipping because of their sharp edges and increased ductility, which increased the splitting tensile stress. The splitting tensile stress of the specimens was reduced by a 30 % PET replacement. The PET waste particles did not exhibit any water absorption that could reduce the hydration of GGBFS, indicating that the connection between the aggregates and the geopolymer paste was no longer present when bonding occurred. The test results are shown as percentages in Figure 7. The splitting tensile strength and PET substitution ratio were related. The 7-day tensile curve of 30 % PET replacement agreed with the 28-day curve, although it was more elevated. The effects of replacing sand with PET particles can be categorised into two main classes based on tensile strength: 5-15 % and 15-30 %. The tensile strength increased in the first class with substitution rates ranging from 5-15 %. In the second class, the tensile strength decreased by 15-30 %.

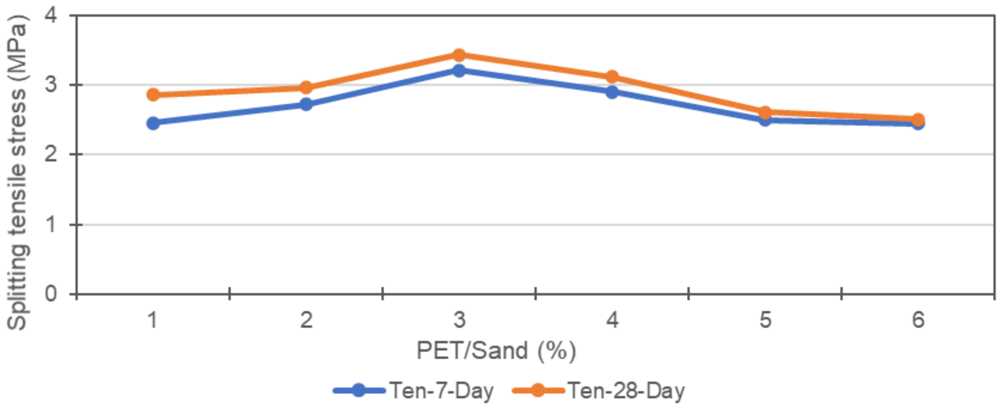


Figure 7. Effect of PET percentage replacement on tensile for 7 and 28 days

3.5 Flexural strength

Flexural strength tests were performed based on the ASTM C293 standard [56]. Test prism specimens measuring (100 × 100 × 400 mm) were used. Specimens with PET replacement ratios between 5 and 15 % exhibited high strengths. The 10 % replacement percentage had the largest increment (14,28 %) among all replacement percentages. Reference specimens with 15 % PET waste replacement also exhibited an increase in flexural strength. The flexural strengths of the specimens decreased by 0,60 and 1,8 1% when 20 and 30 % PET waste replacements were used, respectively. Figure 8 displays the test results as percentages and the relationship between the flexural strength and PET waste replacement. GPC was inherently brittle, resulting in low tensile strength. Employing PET waste particles improved the flexural strength by increasing ductility. Compared with fine aggregates, these particles were more malleable. Before reaching the maximum load, the prism samples with PET waste substitution exhibited considerable flexural deformation. The specimens with 5; 10; and 15 % PET waste replacement exhibited increases of 10,26; 14,28, and 8,45 % in flexural strength, respectively. The GPC specimens began to deform because the number of waste particles made of PET decreased the elastic modulus. This reduction in sand increased the possibility of a notable build-up of PET particles at a specific location. These specimens can be considered as points of initial failure because they create vulnerabilities in GPC. Figure 8 shows that the samples with 10 % PET replacement achieved satisfactory strength at 7 and 28 days. The PET particles that affected the strength values could be categorised into 5-15 % and 15-30 % classes. The fibre strength values in the first class increased considerably with 5-15 % replacement. In the second class (15-30 %), the flexural strength decreased marginally by 0,60 and 1,81 % when the substitution rates were 20 and 30 %, respectively.

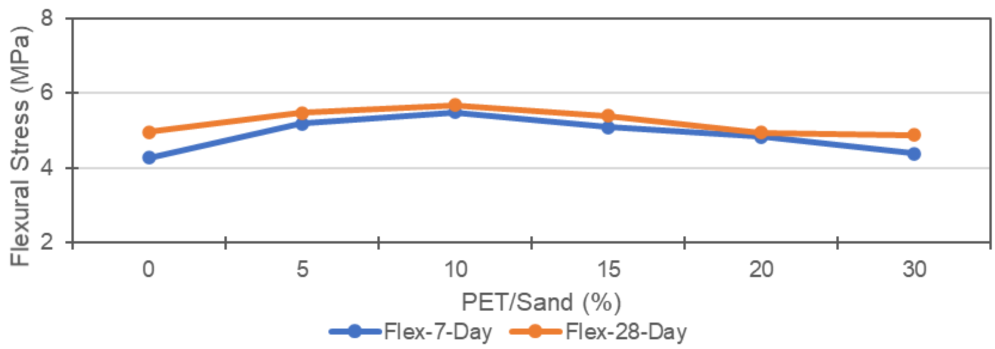


Figure 8. Effect of PET percentage replacement on flexural for 7 and 28 days

3.6 Absorption test

Absorption tests were conducted in compliance with the ASTM C642 standard [57]. Cubic specimens measuring 150 × 150 × 150 mm were used in this test. The specimens were examined at 28 days of age. According to the test results, the absorption rate increases as the proportion of PET increases. The absorption rate of the reference mixture was 0,76 % and the test specimens achieved an absorption rate of 1,2 % when the PET replacement rate was 30 %. The absorption rates of the test specimens were 0,78 % higher than those of the reference specimens (Figure 9). This is because the sharp edges and irregular shapes of the PET particles increased the number of pores and voids in the GPC structure. The absorption rate increases in the presence of numerous holes and voids.

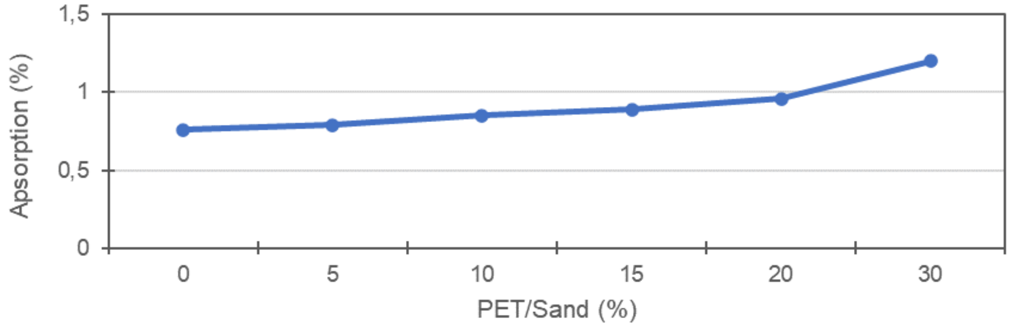


Figure 9. Effect of PET percentage replacement on absorption test curve

3.7 Ultrasonic Pulse Velocity (UPV)

The ultrasonic tests were conducted in compliance with the ASTM C597 standard [58]. An apparatus was used to measure the pulse velocities of ultrasonic and cubic specimens (150 × 150 × 150 mm) that had been aged for 28 days. This test aimed to assess how PET particles, which replace sand in concrete, affect the quality of the material (density and absorption) using pulse rates. GPC containing these particles has a low density because of the low density of PET particles (Section 3.2). When the proportion of PET particles in the cubic specimens increased, the ultrasonic test showed a decrease in pulse velocity (Figure 10). The reference cubic specimen reached a pulse velocity of 4697 mm/μs, and the cubic specimen with 30% PET replacement reached a pulse velocity of 4317 mm/μs, which is 8,09 % lower than the former. These values were appropriate when GPC density was considered. The densities of the specimens in Figure 5 exceeded those of the specimens with 30 % PET replacement. The agreement between the low pulse velocity and density at all substitution ratios and the comparable trends of the pulse velocity and density curves suggested that the PET waste particles were responsible for the decrease in velocity. Furthermore, the pulse velocity decreases when the PET content increases, indicating an increase in the number of voids. This finding was consistent with the absorption test results, which showed that the absorption increased when the PET content increased in GPC (Section 3.6). The effects of using PET as a partial replacement for sand on the pulse velocities of GPC mixtures can be divided into two categories. In the first category (5-10 %), the pulse velocity values decreased slightly with the PET replacement percentage. In the second category (15-30 %), the pulse velocity decreased substantially. For instance, with 20 and 30 % PET replacement, the reductions in pulse velocity were 7,89 and 8,09 %, respectively.

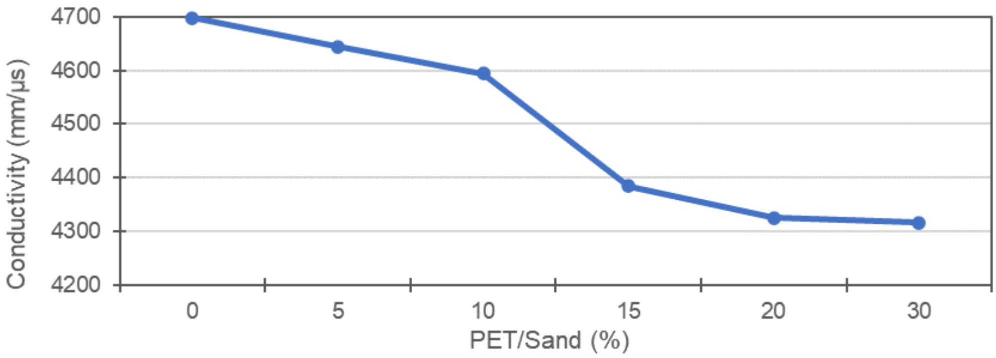


Figure 10. Effect of PET percentage replacement on pulse velocity for geopolymer mix

3.8 Axial strain–stress curve

The strain of the failure load increased as the volume of PET waste increased (Figure 11). The strain of the reference sample was $1{,}39E^{-3}$. The values increased progressively in proportion to the waste content of PET in GPC. The sample with 30% PET replacement exhibited a strain of $2{,}59E^{-3}$, indicating an increment of 55,71 % relative to the strain of the reference samples. This behaviour was attributed to the high flexibility of the PET waste particles.

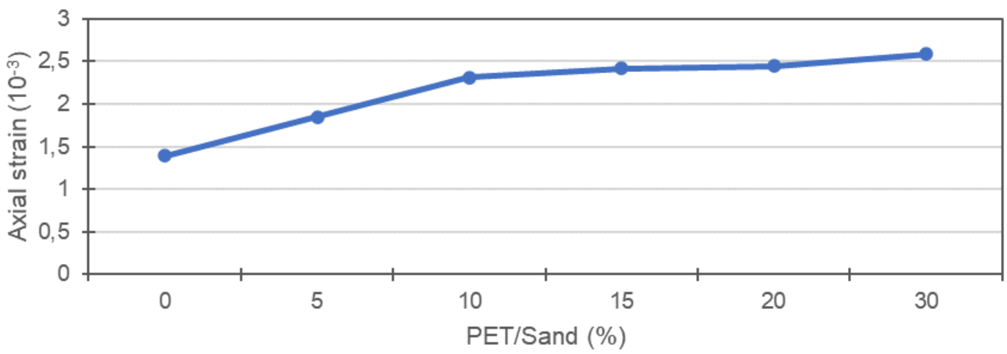
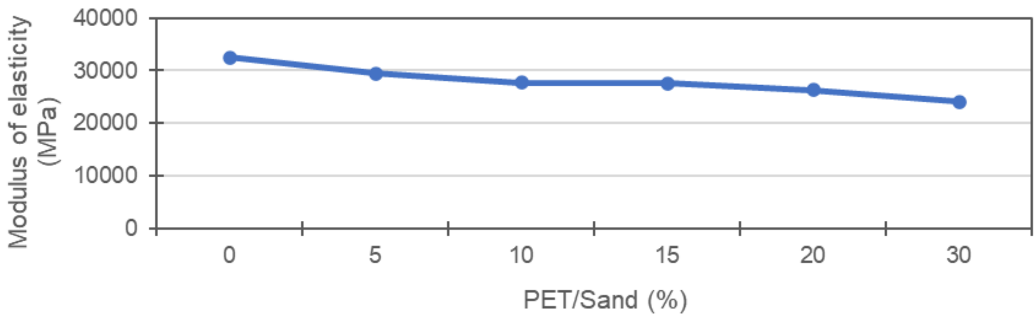


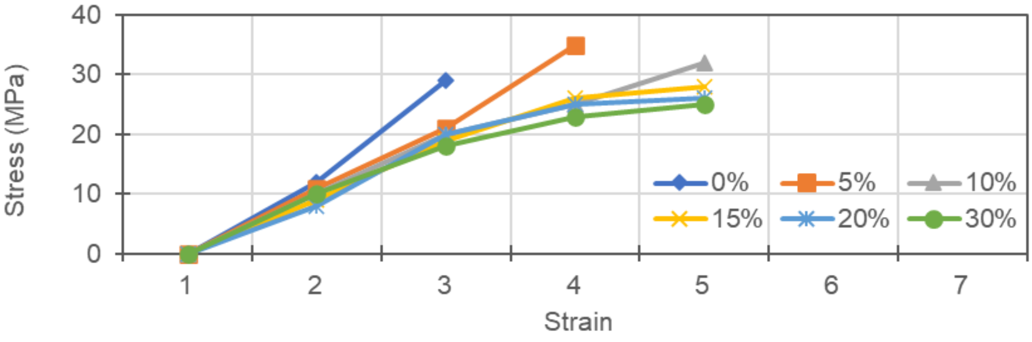
Figure 11. Effect of PET percentage replacement on axial strain for the mix

3.9 Modulus of elasticity

The modulus of elasticity was computed from the stress–strain curve shown in Figure 12b) in compliance with ASTM C-469 [59]. A test of the modulus of elasticity was also performed by gluing a strain gauge at the mid-depth of the cylindrical specimen and connecting the gauge to a data acquisition device. A 200-ton compression machine was used, as shown in Figure 12c).



a)



b)

c)

Figure 12. a) effect of PET percentage replacement on elastic modulus for the mix; b) stress to strain relation; c) the method and materials used for testing the energy absorption and modulus of elasticity

3.10 Energy absorption

The area under the stress–strain curve was used to compute the energy absorption. These findings indicate that when the percentage of PET replacement increases, energy absorption also increases (Figure 13).

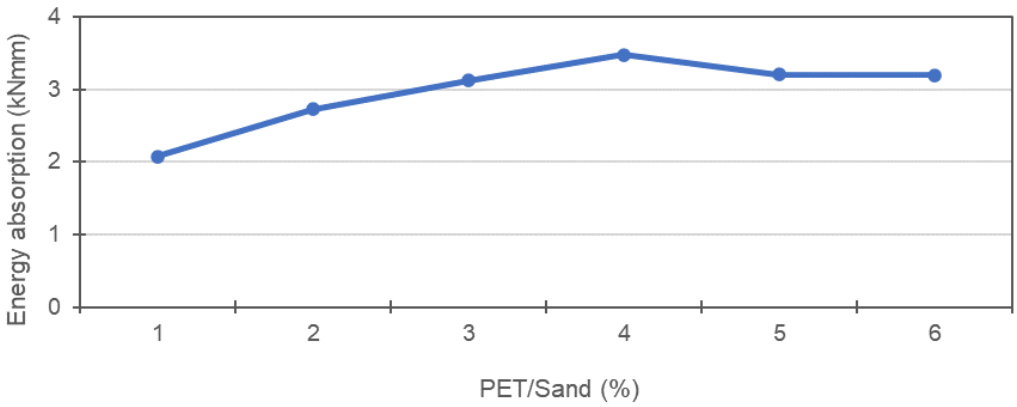


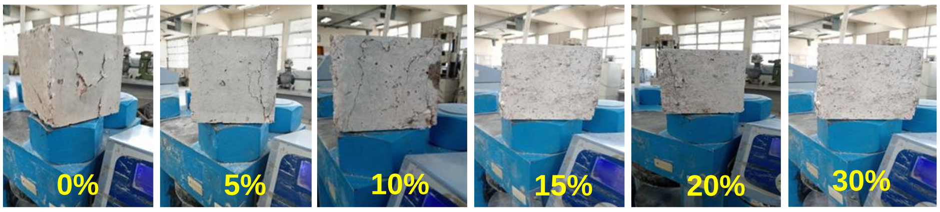
Figure 13. Effect of PET percentage replacement on energy absorption for the mix

The reference specimens absorbed 0,02076 kNmm of energy, which increased gradually in proportion to the replacement percentage. The energy absorption achieved by the samples with 5 and 10 % PET replacement was 0,02727 and 0,03124 kNmm, respectively. These values are 31,35 and 50,48 % higher than those of the reference mixtures, respectively. The samples with 15; 20; and 30 % PET replacement had energy absorption values of 0,03473; 0,03202; and 0,3193 kNmm, respectively, which are 67,29; 54,23; and 35,80 % higher than the energy absorption value of the reference sample, respectively. These findings show that when the replacement percentage increased, the area under the stress–strain curve also increased. The presence of PET particle waste caused GPC to change from brittle to flexible and ductile.

3.11 Failure mode

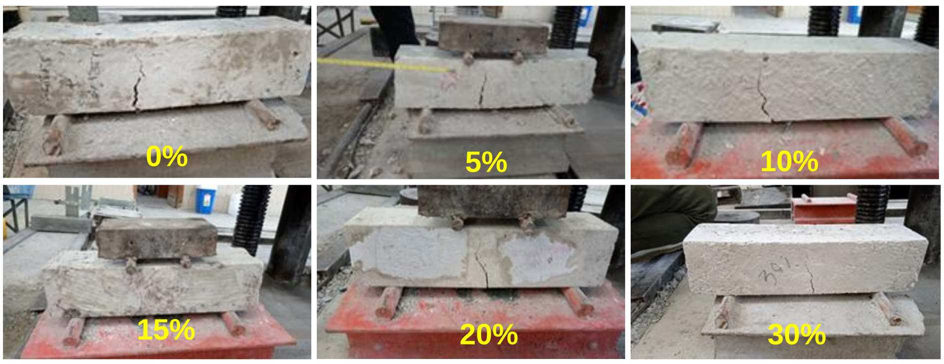
A noticeable difference was observed in the failure modes of the cubic, cylindrical, and prism specimens that were tested for destruction. When the percentage of PET replacement increased, the shape-crushing ratio, length, and width of the cracks decreased. The brittleness of GPC led to the disintegration of the reference specimens. The specimens containing PET waste exhibited a failure mode in which cracks with decreasing sizes and lengths emerged in proportion to the replacement percentage. This behaviour suggests that when the replacement percentage increases, ductility, a critical property that enhances the flexibility of GPC, also increases. Figure 14 illustrates the failure modes of the various specimens.

This study aligns with several key objectives from the perspective of SDGs. By incorporating PET waste into geopolymer concrete, this study addresses SDG 12, Responsible Consumption and Production by promoting the recycling and reuse of plastic waste. Additionally, the enhanced durability and mechanical properties of PET-incorporated GPC contribute to SDG 9 (Industry, Innovation, and Infrastructure) by fostering the development of sustainable and resilient infrastructure. Furthermore, the reduction in the use of natural sand and Portland cement aligns with SDG 13: Climate Action, as it helps reduce the carbon footprint associated with traditional concrete production. Overall, this study supports the advancement of sustainable construction practices and the achievement of multiple SDGs.



a)

b)



c)

Figure 14. Failure modes: a) compression samples; b) splitting tensile samples; c) flexural strength samples

4 Conclusion

This study investigated the mechanical and physical properties of geopolymer concrete and fine aggregates (sand) that were partially replaced at 5; 10; 15; 20; and 30 %. Equivalent weight percentages of PET waste particles, while maintaining the quantities of all other proportions. The experimental findings led to the following conclusions:

- Geopolymer concrete gradually decreased as the polyethylene terephthalate waste percentage increased. In the reference specimens, the slumps decreased by 11,7 % and 52,9 % when 5 and 30 % of polyethylene terephthalate, were replaced.
- The absorption rate increased with an increase in polyethylene terephthalate waste quantity. At 30 % replacement percentage, the absorption rate was 58,04 % higher than that of the reference specimens.
- When the quantity of polyethylene terephthalate waste increased to 15 %, compressive, tensile splitting, and flexural strengths increased. The ideal substitution proportion was 10 %, under which compressive, tensile splitting and flexural strengths increased by 12,07; 20,27; and 14,28 %, respectively, relative to the reference mixture.
- When the polyethylene terephthalate waste percentage increased, geopolymer concrete pulse velocity and density decreased. A comparison of geopolymer concrete containing 30 % polyethylene terephthalate with the reference mixture showed 8,04 and 16,49 % reductions in pulse velocity and density, respectively.
- A large polyethylene terephthalate replacement ratio results in a decreased modulus of elasticity. The 30 % replacement ratio had the smallest elastic modulus among all the replacement ratios; its value was 25,78 % lower than that of the benchmark sample.
- The energy absorption increased when the polyethylene terephthalate replacement rate increased. Among the tested specimens, the reference specimen exhibits the lowest energy absorption. The energy absorption of the reference specimen was 67,29 % lower than that of the specimens with 15 % polyethylene terephthalate replacement.
- Ductility increased as the proportion of geopolymer concrete containing polyethylene terephthalate particles increased. This result was inferred from the failure modes of various specimens.
- The use of geopolymer concrete is highly advantageous for producing concrete products required for the restoration and retrofitting of structures after disasters because of geopolymer concrete's exceptional properties. The results and discussions in the preceding sections demonstrate that geopolymers can be successfully produced and used as building materials in various engineering fields.

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