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Production of eco-friendly lightweight fibrous concrete by replacing half of the sand with PET waste

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Abstract:
This experiment examined the properties of concrete with relatively high proportions of polyethylene terephthalate (PET) plastic waste used as a substitute for sand. In addition to the reference mixture, two percentages of PET shredded-plastic waste from discarded PET bottles were used as sand replacements: 30 and 50 %. To improve the performance of concrete mixtures with a high PET percentage, the concrete was also reinforced by adding polypropylene fibers at a rate of 1,5 % of the concrete-mix volume. Several concrete-mix characteristics were studied, such as workability, dry density, compressive strength, flexural strength, modulus of elasticity, absorption, and ultrasonic pulse velocity test. The use of plastic waste as a half replacement of fine aggregate in concrete has several benefits. One of which is the ability to produce lightweight concrete, where the dry density of concrete with a higher percentage of PET plastic waste of 50 % was 1912,30 kg/m^3, and it had an acceptable compressive strength of approximately 25,3 MPa. The current study yielded important findings because recycling a high percentage of PET waste of half sand weight represents a structural advantage in reducing the weight of concrete. The proposed method also produces eco-friendly concrete due to the positive impact on the environment owing to the consumption of PET wastes within concrete mixtures.

Keywords:
recycled plastic aggregate; lightweight concrete; polypropylene fibers

1 Introduction

Modern society is confronted with the critical problem of reducing the amount of waste produced on a global scale. Reduced-waste development and recycling of items that must be generated are the two most commonly used conventional methods to achieve this. In 1950, 1,7 million tons of plastic was produced worldwide. This has increased by almost 170 times, reaching 288 MT by 2012 [1]. Polyethylene products account for approximately 29 % of the total plastic waste [2; 3]. These materials consist of high-density polyethylene, linear low-density polyethylene, and low-density polyethylene. Twenty percent of the world's plastic waste comprises polyethylene terephthalate (PET) and 18 % comprises polypropylene [2; 3], with the other 33% sourced from various polymer types. A considerable amount of plastic can be recycled into many different products [4; 5]; however, a substantial amount still goes to waste and must be disposed of. The construction industry is one possible application of this waste material; plastic waste has already been used in concrete, either as a shredded material or as part of a synthetic aggregate mix. Recycled waste in concrete mixtures has been the focus of many researchers [6-8].

Naturally occurring aggregates can be substituted by plastic-based lightweight aggregate because plastics have a lower density than most natural materials. Lightweight concrete aggregate made from recycled plastic bottles was the subject of an experimental study by Choi et al. [9]. The compressive strength, modulus of elasticity, slump, density, and splitting tensile strength of lightweight aggregate concrete made from recycled PET bottles were evaluated. Compared with regular concrete, the workability of this type of concrete was significantly enhanced [9]. Akçaözoğlu et al. [10] studied the incorporation of shredded waste into lightweight concrete by testing concrete cubes and cylinders. The effects of plastics in the aggregate and mortar on concrete shrinkage were explored [10]. According to Casanova-del-Angel et al. [11], PET aggregates may be used to produce high-quality mixes that have less weight, but have mechanical properties comparable to those of natural concrete. Because of their reduced weight and the minimal difference between the heat levels in concrete and PET, light concrete may be utilised as Class II concrete, making it suitable for diverse applications, such as light slabs for houses in hot climates.

Liguori and Iucolano [12] used synthetic aggregates manufactured from recycled plastics, namely, polyolefins and polyethylene terephthalate garbage. They used these materials as partial substitutes for natural aggregates used to fabricate hydraulic mortars. Water-vapour permeability was increased and open porosity was improved by using recycled plastic. However, plastic aggregates significantly reduced thermal conductivity, which increased the thermal-insulation properties of the mortar. Gurmel et al. [13] aimed to recycle plastic and red sand to create recycled plastic aggregate (RPA). A decrease in chloride penetration of approximately 13 % was observed when RPA was used as an alternative to conventional lightweight aggregate at a 100 % volume ratio. Although the compressive strength was lower, it was still within the practical range of 12-15 MPa, making RPA suitable for use in nonstructural components, including low-side buildings, cementitious backfills, and pavements.

Attanasio et al. [14] used three distinct types of plastic materials: polyurethane foam, tire rubber, and particles from recycled plastic separated from solid urban waste. These wastes were processed to make aggregates for nonstructural concrete. Using recycled plastic as an ingredient led to the creation of concrete with a lower density ranging from 1050 to 1300 kg/m^3. Optimal concrete mechanical qualities ranged from 2,6-9,3 MPa, but the addition of plastic significantly reduced their thermal conductivity, which was the most noticeable decrease (0,20-0-33 W/mK). In addition, the concretes showed a lower propensity to transmit ultrasonic pulses. In a study conducted by Jassim [15], a short reinforcement structure was created using waste polyethylene packaging, which included food crates and bottles, accounting for 10-80 % by volume. The results indicated that plastic cement can be made using 60% recycled polyethylene and 40 % Portland cement. This approach has led to the fabrication of lightweight materials with enhanced density, increased ductility, and improved workability. Similarly, Aslam et al. [16] investigated the effect of PET bottle fibres on the mechanical properties of concrete. PET fibres added at varying concentrations (0,25 %, 0,50 %, and 1,00 %) were shown to improve the workability of concrete when no recycled aggregates were used. However, their addition led to a reduction in the compressive and split tensile strengths. The study concluded that factors such as plastic fibres, curing time, and recycled aggregates interact synergistically to influence concrete strength, and proposed equations to predict these effects. In addition to what has been mentioned, many previous studies have addressed the topic of lightweight concrete and the use of alternative materials to improve its properties. These studies highlighted the role of these materials in enhancing mechanical performance and promoting environmental sustainability [17-23].

The overarching goal of the present study is to reduce the environmental impact of PET waste by recycling large percentages of PET as sand and using it in concrete with improved specifications and a lower density. To improve the performance of concrete mixtures with high percentages of PET, polypropylene fibers were added to the mixture at a rate of 1,5 % of the concrete-mix volume, which was considered a fibre-reinforced concrete mixture containing PET waste as a partial replacement for sand at percentages of 30 and 50 %.

2 Experimental work

2.1 Materials properties

The materials used in this study met all the requirements set forth by Iraqi standards. Ordinary Portland cement manufactured in Iraq was used. The physical parameters of the cement are summarised in Table 1 based on Iraqi Specification IQS 5/1984 [24]. The materials were selected based on compliance with Iraqi requirements, including IQS 5/1984 for cement and IQS 45/1984 for aggregates; their suitability for obtaining desired concrete qualities such as workability, strength, and durability; their availability in the local market, which ensures simple access to materials such as cement, sand, and PET; and environmental impact, as recycled PET bottles are used to encourage sustainability.

Table 1. Physical characteristics of cement

Physical properties	Tests results	Iraqi specification limits NO.5/1984 [34]
Fineness using Blain Air Permeability	382,00	≥ 230,00
Soundness using the autoclave method	0,25	< 0,80
Initial and final setting time using the Vicat method		
Initial h:min	2,08	≥ 45 min
Final h:min	4,27	≤ 10 h
Compressive strength of cement mortar		
3 days MPa	19,90	≥ 15
7 days MPa	30,40	≥ 23

The use of Iraqi natural sand as a fine aggregate is limited to particles not larger than 4.75 mm, and the sand utilised in this study lies in Zone No. 2. The gravel was composed of coarse aggregates that were not larger than 20 mm. Details of the fine aggregate and PET-particle grading are summarised in Tables 2 and 3, respectively, based on the limitations of the Iraqi standard specification IQS 45/1984 [25].

The superplasticiser employed was of varieties A and G, compliant with ASTMC494-99 [26]. The PET-crushing process involves collecting both large and small PET bottles and thoroughly washing them to remove contaminants. The bottles were then fed into a crushing machine, where they were mechanically ground into smaller particles. This process typically produces irregularly shaped particles resulting in a mixture of fine particles and large fragments. The particles were then passed through a sieve (such as sieve number 4) to refine their size distribution.

Table 2. Gradation of the fine aggregate

Standard sieve size [mm]	**Cumulative Passing** [%]	**Cumulative passing % Iraqi specifications limits No.45/1984 [25]**
10,00	100,00	100
4,75	96,60	90-100
2,36	88,05	75-100
1,18	65,20	55-90
0,60	40,75	35-59
0,30	15,02	8-30
0,15	4,50	0-10

Table 3. Gradation of the PET waste

Sieve size [mm]	**PET percent passing** [%]
10,00	100,00
4,75	95,60
2,36	97,64
1,18	18,72
0,60	2,55
0,30	0,50
0,15	0,19

The resulting particles generally had sharp edges and angular shapes, with some exhibiting flat surfaces due to the nature of the material and the crushing process, as shown in Figure 1, which illustrates the PET material used in the study. According to Iraqi Specification IQS 45/1984 [25], the PET particle-sieve analysis demonstrated an acceptable grade compared to sand-sieve analysis. The added polypropylene fibres had a length of 12 mm and a diameter of 0.018 mm, as shown in Figure 2. These fibres enhanced concrete properties by improving the compressive and tensile strengths, reducing cracks, and increasing durability and flexibility. They also helped to improve the ability of the concrete to withstand harsh environmental conditions and heavy loads.

Figure 1. PET waste-fibre shape

Figure 2. PP-fibre shape

A water-to-cement ratio of 0,4 and 0,5 % superplasticiser were used as the weight mixing ratio (1:1.5:3). Two different amounts of recycled PET bottles were used as partial sand replacements in addition to the reference mixture. The weight percentages of PET waste utilised for the sand were 30 and 50 % with the addition of polypropylene fibres at a ratio of 1,5 % of the concrete-mixture volume. The proportions of the concrete mixtures are listed in Table 4.

Table 4. Component ratios for concrete with varying amounts of PET replaced

PET/Sand [%]	Cement [kg/m^3]	Sand [kg/m^3]	Gravel [kg/m^3]	Water [kg/m^3]	PET [kg/m^3]	SP [%]	W/C	PP Fiber [kg/m^3]
0 (Ref)	450	675,0	1350	180	0,0	0,5	0,4	0,00
30	450	472,5	1350	180	202,5	0,5	0,4	13,65
50	450	337,5	1350	180	337,5	0,5	0,4	13,65

2.2 Specimen preparation for testing

Before mixing, the fine and coarse aggregates were washed and cleaned. Additionally, all moulds, whether cubes, cylinders, or prisms, were cleaned and oiled. Figure 3 shows the first stage, which involved preparing the PET-waste particles and mixing them with sand according to the quantities mentioned earlier. Gravel and other materials such as PET-waste alternatives were blended using a mechanical mixer. Subsequently, cement was added to the concrete, and while the mixture was still being mixed, water and a superplasticiser were added. Subsequently, the polypropylene fibres were carefully added to the concrete mixture by placing them in the mixing bowl while still rotating. The fibres were then mixed with the concrete materials for 5 min to ensure that they were equally distributed and to prevent them from clumping together. After mixing the materials, the concrete was poured into the prepared moulds (cubes, cylinders, or prisms) in layers. The concrete was then compacted using a tamping rod to remove air bubbles and ensure a uniform density distribution. After the concrete was poured, the specimens were cured by placing them in water-filled tanks to ensure adequate hydration and strength development. The proportions of the control mix (which did not include PET or fibres) were used to achieve a target strength of 35 MPa.

Figure 3. Process for pouring and curing concrete samples

2.3 Laboratory tests

In this study, specimens of different shapes were cast to evaluate the mechanical and physical properties of the hardened concrete. These properties include static and dynamic moduli of elasticity, compressive strength, split tensile strength, flexural strength, absorption and ultrasonic pulse speeds, dry density, and fracture energy. The samples used in this evaluation were cubes, cylinders (two sizes), and prisms. Moreover, the fresh operability of the concrete was evaluated using a slump test. The reference mixture was compared with the results of all the tests. conducted on replacement percentages. One side had six concrete cubes measuring 150 × 150 × 150 mm. Each replacement ratio was used to check the compressive strength at 7 and 28 days of age (three cubes were prepared for every age). Six additional cylinders measuring 100 × 200 mm were used to measure the tensile strength after 7 and 28 days. Two cylinders (150 × 300 mm) were used for elasticity testing at the age of 28 days. Flexural-strength testing was performed using six prisms (100 × 100 × 500 mm) (three prisms prepared for each age). After 28 days, one concrete cube measuring 150 x 150 × 150 mm was poured for each replacement ratio. It was used to evaluate the conductivity using the ultrasonic pulse velocity (UPV) and measure the absorbance. A total of 60 samples were cast for the various tests.

3 Results and discussion

3.1 Workability of fresh concrete (Slump test)

Slump testing was conducted in compliance with ASTM C143 [27]. As shown in Figure 4 and Table 5, the results demonstrate that the workability of the concrete decreases as the amount of PET waste in the mixture increases. The reference specimen (0 % PET+0 % PP) exhibited a slump of 162 mm. The specimens reinforced with polypropylene fibres and using (30 and 50 %) PET waste as sand had slumps of 68 and 40 mm, which produced reductions of 58,0 and 75,3 % relative to the reference ratio, respectively. Because the surface area of PET waste particles was higher than that of the sand particles, the workability of concrete was reduced. The elevated surface area enabled the accumulation of a substantial amount of water on its surface, which reduced the workability of the concrete. Furthermore, the incorporation of polypropylene fibres decreased the workability of the concrete by increasing the internal friction and reducing the fluidity. When combined with PET waste, the slump was significantly reduced owing to the high surface area of both materials, which trapped water and restricted movement within the mix.

Table 5. Result of slump for concrete specimens containing PET waste

PET/SAND	Slump (mm)	Variation in slump
0 % (R)	162	--
30,0 % PET + 1,5 % PP	68	58,0 %
50,0 % PET+ 1,5 % PP	40	75,3 %

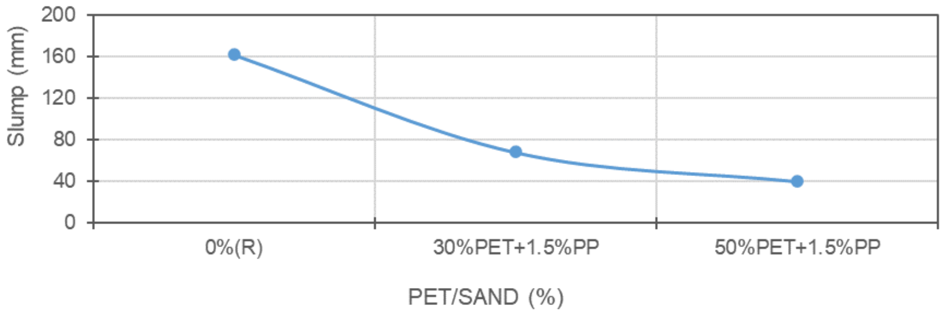

Figure 4. Slump curve for mixes of fibre and PET waste

3.2 Mechanical properties of lightweight mixture

3.2.1 Compression-strength results

Compressive-strength tests were conducted on concrete specimens reinforced with polypropylene fibre and containing PET waste to replace sand. The tests were conducted at 7 and 28 days of age in compliance with British Standard BS1881 part 116-89 [28]. The results are presented in Figure 5 and Table 6. After 7 days, the compressive strength of the reference specimens was 35,7 MPa. Then, the other concrete specimens with fibres and different ratios of PET waste (30 and 50 %) had compressive strengths of 33,1 and 22,9 MPa, which were lower than those of the reference mixture by -7,28 and -35,85 %, respectively. A noticeable change was observed in the compression-strength curve at 28 days of age, although it was not as notable as the change at 7 days when compared to the reference cube. The compressive strength of the reference specimens was 40,6 MPa after 28 days. Then, the other concrete specimens with fibres and different ratios of PET waste (30 and 50%) had compressive strengths of 36,3 and 25,3 MPa, which were lower than the reference mixture by -10,6 and -37,7 %, respectively. Thus, the lightweight fibrous concrete mixture with 50 % PET yielded an acceptable compressive strength of 25 MPa, which satisfied the main objective of the present study, which is to produce an eco-friendly lightweight fibrous concrete with a compressive strength suitable for structural applications.

Table 6. Result of compressive strength for concrete specimens containing PET waste

PET/SAND	Average compressive strength fcu [MPa]		Variation in compressive strength (28 days) [%]	7/28 ratio
	7 days	28 days		
0 % (R)	35,7	40,6	--	87,93
30 % PET + 1,5 % PP	33,1	36,3	-10,6	91,18
50 % PET + 1,5 % PP	22,9	25,3	-37,7	90,51

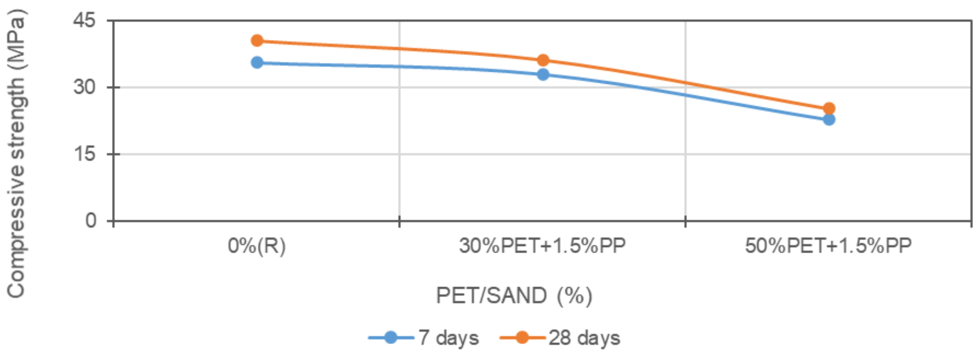

Figure 5. Compression-strength curve for mixes of fibre and PET waste

3.2.2 Splitting tensile results

Figure 6 and Table 7 show the results of the 7- and 28-day splitting tensile-strength tests performed on the reference specimen and concrete specimens reinforced with polypropylene fibre and containing PET waste as a substitute for sand. The test was performed in accordance with American Standard ASTM-C496 [29]. After 7 days, a split tensile strength of 2,1 MPa was attained for the reference specimen. However, when compared to the reference specimen, the other specimens that included PET waste in various ratios, 30 and 50 %, with polypropylene fibres had splitting tensile strengths of 2,20 and 1,52 MPa and showed a decrease of -4.76% and -27,62 %, respectively. At 28 days of age, a similar pattern of decreased tensile strength was observed. The reference specimen exhibited a tensile strength of 2,4 MPa. Then, the other concrete specimens with fibres and different ratios of PET waste, 30 and 50%, had tensile strengths of 2,3 and 1,9 MPa, which were lower than the reference mixture by -4,17 % and -20,83 %, respectively. Thus, the lightweight fibrous concrete mixture with 50 % PET yielded an acceptable splitting tensile strength compared with the other mixtures.

Table 7. Results of splitting tensile strength for concrete specimens containing PET waste

PET/SAND	Average splitting tensile strength ft [MPa]		Variation in tensile strength (28 days) [%]	7/28 ratio
	7 days	28 days		
0 % (R)	2,10	2,40	---	87,50
30 % PET + 1,5 % PP	2,20	2,30	-4,17	95,65
50 % PET + 1,5 % PP	1,52	1,90	-20,83	80,00

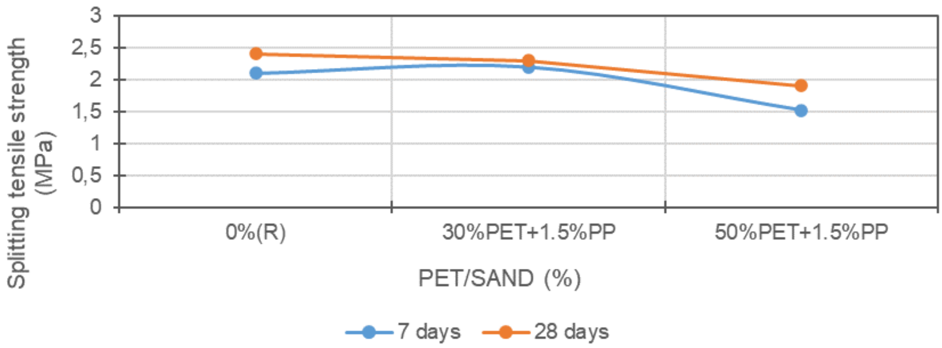

Figure 6. Tensile-strength curve for mixed fibre and PET waste

3.2.3 Flexural-strength results

Figure 7 and Table 8 show the results of the 7- and 28-day flexural-strength tests performed on the reference specimen and concrete specimens reinforced with polypropylene fibre containing PET waste as a substitute for sand. The test was performed in accordance with ASTM-C78 [30]. Prism samples with dimensions of 500 × 100 × 100 mm were subjected to flexural-strength tests. After 7 days, a flexural strength of 3,7 MPa was attained using the reference specimen. However, when compared to the reference specimen, the other specimens that included PET waste in various ratios, 30 and 50 %, with polypropylene fibres had flexural strengths of 3,6 and 3,1 MPa and showed a decrease of -2,70 % and -16.22%, respectively. At 28 days of age, a similar pattern of decreased flexural strength was observed. The reference specimens exhibited a flexural strength 4 MPa. Then, the other concrete specimens with fibres and different ratios of PET waste, 30 and 50%, had flexural strengths of 3,8 and 3,3 MPa, which were lower than those of the reference mixture by -5,0 and -17,5 %, respectively. The addition of polypropylene fibres helped improve the stress distribution within the concrete and reduced cracking, but its effect was limited in compensating for the decrease caused by PET waste. Despite improving the overall performance, its impact on flexural strength was less than that of PET.

Table 8. Flexural strengths for concrete specimens containing PET waste

PET/SAND	Average flexural strength ft [MPa]		Variation in tensile strength (28 days) [%]	7/28 ratio	fc' (MPa)	$f_r = 0{,}62\sqrt{fc'}$
	7 days	28 days				
0 % (R)	3,7	4,0	--	92,50	34,51	3,64
30 % PET + 1,5 % PP	3,6	3,8	-5,0	94,74	30,86	3,44
50 % PET + 1,5 % PP	3,1	3,3	-17,5	93,94	21,51	2,88

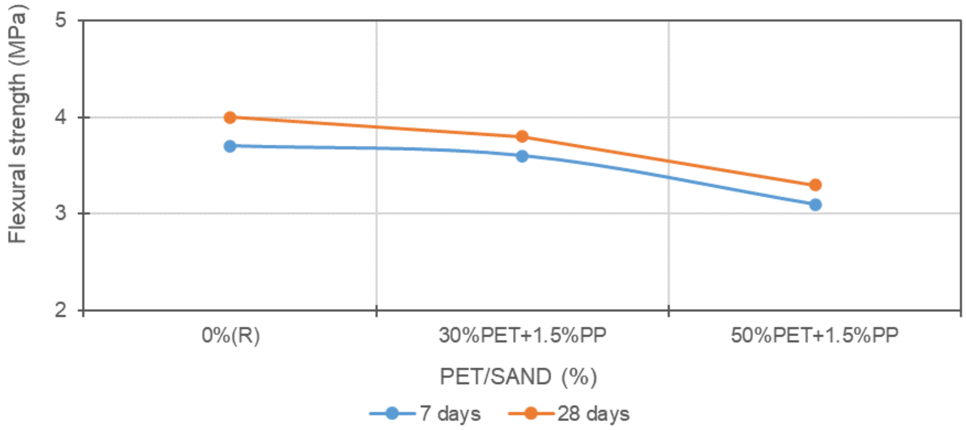

Figure 7. Flexural-strength curve for mixed fibre and PET waste

3.2.4 Static modulus of elasticity

According to ASTM-C 469-02, a stress–strain curve can be used to determine the modulus of elasticity [31]. Figure 8 shows the elastic-modulus data. The results and relationships demonstrate that the modulus of elasticity decreased significantly as the percentage of recycled PET plastic particles increased. First, the cylinder that did not include any PET waste (reference ratio) or fibre achieved the highest recorded modulus of elasticity of 30,51 GPa. Furthermore, as the strain values increased, the elastic-modulus values of concrete containing an increasing fraction of PET particles decreased. The specific strengths of the concrete specimens reinforced with polypropylene fibre and containing varying amounts of PET waste, 30 and 50 %, were 17,03 and 14,34 GPa, representing changes of -44,18 and -52,99 %, respectively. The lightweight fibrous concrete mixture with 50% PET yielded a closed modulus of elasticity of 30 % PET percentage, which is indicative of an eco-friendly lightweight mixture for structural applications.

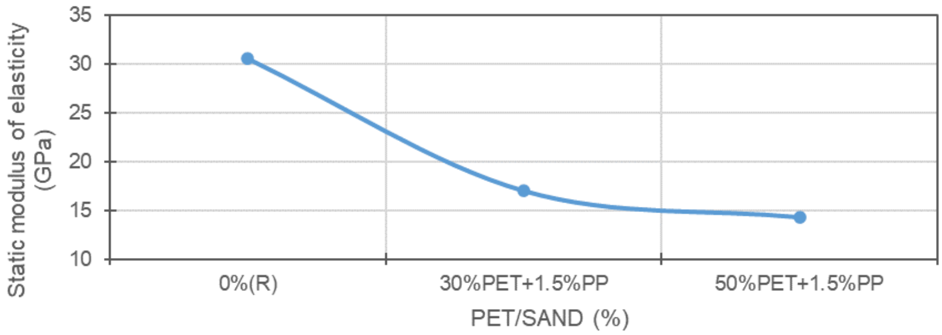

Figure 8. Static modulus of elasticity curve for mixed fibre and PET waste

3.2.5 Dynamic modulus of elasticity

To determine the dynamic modulus of elasticity, the ultrasonic pulse velocities of specimens (cubes) that were 28 days old were measured, and the results mainly depended on the density of the concrete. The dynamic modulus of elasticity was determined using the following equation:

$$Ed = \frac{\rho_{at\,28} UPV^2\,(1+\mu)(1-2\mu)}{(1-\mu)} \tag{1}$$

where *UPV* is the pulse velocity in Km/s, ρ is the concrete unit weight in kg/m^3, and μ denotes Poisson's ratio. Figure 9 shows the results of the dynamic modulus of the specimens. The dynamic modulus of elasticity of the reference specimen was 46,37 GPa. When PET waste was used as a sand replacement, the ratios, 30 and 50 %, had a dynamic modulus of elasticity of 27,67 and 19,56 GPa, which decreased by approximately -40,33 and -57,82 % compared to the reference specimen, respectively. A comparison between Figures 8 and 9 shows that both the dynamic and static moduli of elasticity for mixtures containing PET yielded relatively similar behaviours.

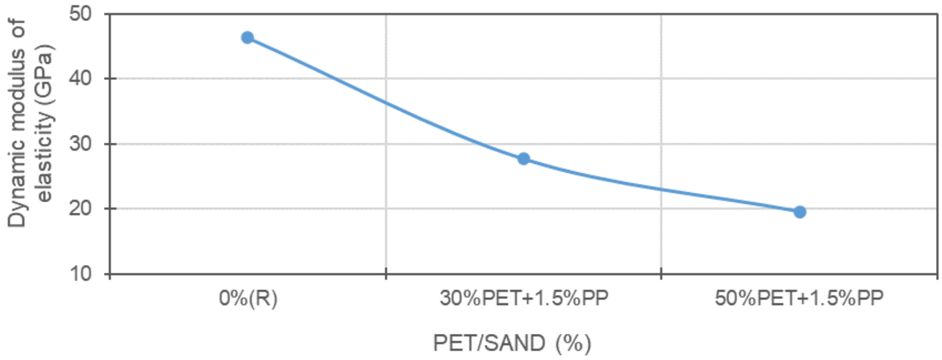

Figure 9. Dynamic modulus of elasticity for mixed fibre and PET waste

3.3 Physical properties of lightweight mixture

3.3.1 Dry density

The first step in the present experiment is to reduce the density of concrete by substituting as much sand as possible with PET waste so that the concrete mixture is homogenous and has acceptable strength for structural applications in which polypropylene fibres are added. The same cube specimens used for the compression-strength testing of concrete mixtures reinforced with polypropylene fibres and containing PET waste were used to measure the dry density in accordance with ASTM C642 [32]. At 7 and 28 days of age, compression tests and dry-density measurements were performed simultaneously. As shown in Figure 10, the density decreased with an increasing PET particle-to-concrete ratio. The density of the reference specimens was 2372,81 kg/m^3 at 28 days of age. In contrast, the sample with the PET replacement ratio of 50 % and containing polypropylene fibres had a density of 1912,30 kg/m^3, which was lower than 419,41 %.
The main factor contributing to the decrease in concrete density was the relatively low density of PET particles, which was 1380 kg/m^3. Thus, a fibrous concrete mixture containing 50 % PET as a replacement for fine aggregates yielded eco- friendly lightweight concrete.

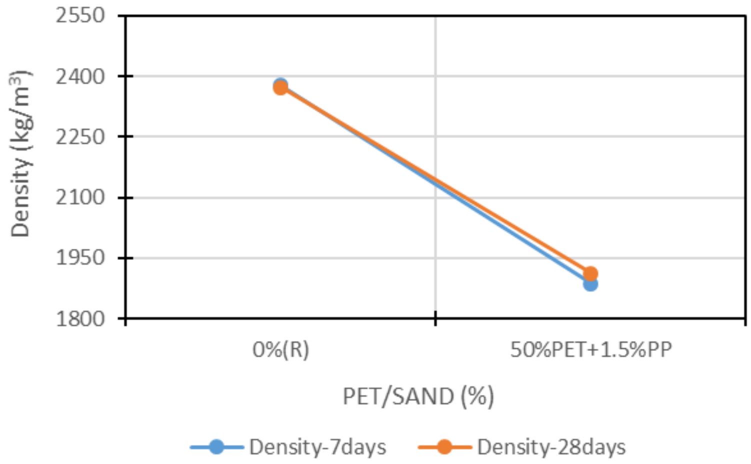

Figure 10. Dry-density curve for mixed fibre and PET waste

3.3.2 Absorption test

Three concrete cubes were used for the absorption test, and one cube was allotted for each percentage of PET particles. To determine the wet weight of the cubes, they were immersed in water for 24 h after being oven-dried for 72 h, based on ASTM C642 [32]. The results are presented in Figure 11. The absorption ratio increased in direct proportion to the PET waste/sand ratio. The reference cube had an absorption ratio of 1,55 %. The absorption ratios of the concrete specimens reinforced with polypropylene fibres and containing varying amounts of PET waste, 30 and 50 %, had absorptions of 2,79 and 3,41 %, which were higher than those of the reference mixture by 80 and 120 %, respectively. The absorption-test results showed that increasing the amount of PET waste in the mixture increased the water-absorption rate. This is attributed to the open pores left by the PET particles, which enabled greater water absorption than traditional sand. Additionally, the addition of polypropylene fibres may also affect the absorption properties owing to their interaction with other components in the concrete, resulting in an increased absorption capacity compared to that of the reference sample.

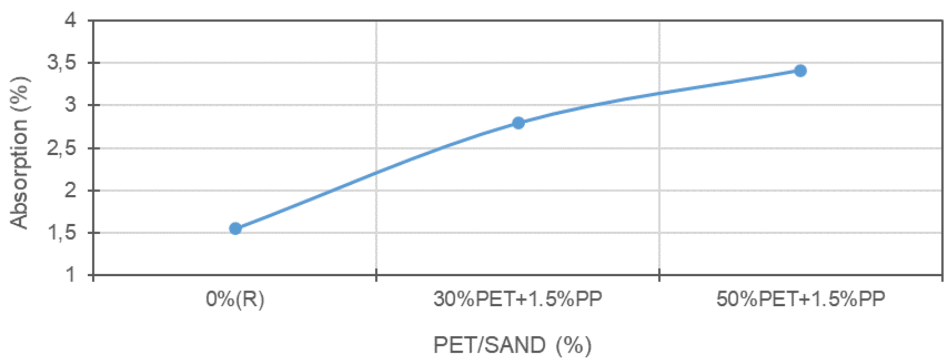

Figure 11. Absorption curve for mixed fibre and PET waste

3.3.3 Ultrasonic pulse-velocity tests

Figure 12 shows the results of ultrasonic pulse-velocity tests conducted on concrete specimens (cubes) reinforced with polypropylene fibre and with varying ratios of PET waste relative to the reference specimen. A cube was tested for each proportion of PET waste. A linear procedure was employed for each test. The results of this test match the requirements of BS 1881 Part 116 [33]. The results showed that the pulse velocity decreased gradually as the proportion of PET particles increased, which was a result of the very low-velocity characteristics of PET. The reference specimens had a pulse velocity of 4,660 km/s, whereas the concrete specimens with fibres and different ratios of PET waste, 30 and 50%, had pulse velocities of 3,692 and 3,371 km/s, which were 20,77 and 27,66 % lower than those of the reference mixture, respectively. The addition of polypropylene fibres to the concrete improved the stress distribution within the mix, but its effect on ultrasonic pulse velocity was limited. Although the fibres may improve the overall durability of the concrete, their impact on the pulse velocity was not sufficient to offset the negative effects of PET waste. Thus, the pulse velocity remained low because of the properties of PET, whereas the fibres played a greater role in improving the mechanical performance of the concrete, rather than affecting the acoustic properties.

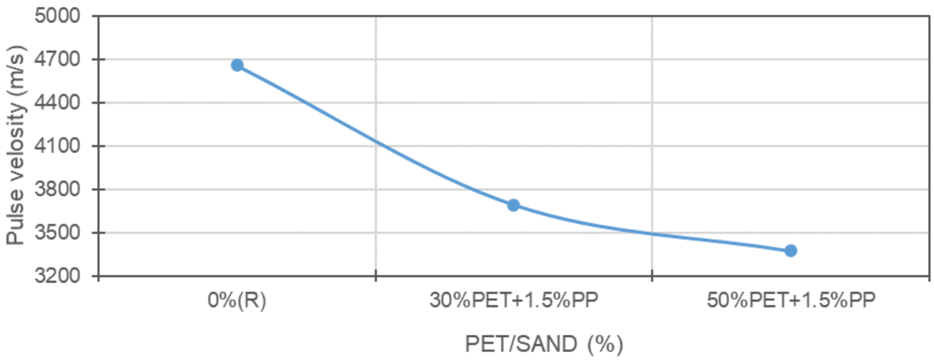

Figure 12. Pulse-velocity curve for mixed fibre and PET waste

3.4 Compressive fracture energy

A fundamental property of concrete required for a logical forecast of brittle failure in concrete structures is its fracture energy. The most crucial mechanical properties of concrete structures for assessing and forecasting changes in structural performance are the compressive strength and compressive-fracture energy. Two methods were used in the present study to determine the compressive-fracture energy and evaluate the performance of a lightweight concrete mixture with a relatively high percentage of PET waste as a sand replacement: the Bazant and CEB-FIP methods.

3.4.1 Bazant model

Bazant presented an empirical formula in his model that included factors such as compressive strength, aggregate size, and the water-to-cement ratio. To study the fracture energy, all known data were entered into the equation. This experiment employed angular aggregates with respect to the aggregate-factor form. The formula for Bazant's model is as follows:

$$G_F = 2{,}5\alpha_0 \left(\frac{f_c}{0{,}058}\right)^{0.4} \left(1 + \frac{D_{\max}}{1{,}94}\right)^{0{,}43} \left(\frac{W}{C}\right)^{-0{,}18} \quad (2)$$

with α_0 = 1,00 for spherical aggregates and α_0 = 1,12 for angular aggregates, where α_0 is the aggregate form factor. Dmax is the maximum aggregate size, w/c is the water-to-cement ratio, and fc is the compressive strength of the concrete. The fracture energy of the reference specimen was 126,21 N/mm. Then, the concrete specimens with fibres and different ratios of PET waste, 30 and 50 %, had fracture energies of 120,68 and 104,46 N/mm, which were lower than those of the reference mixture by -4,38 and -17,23 %, respectively.

3.4.2 Construction of references

CEB-FIP offered a formulation that accounted for the mixture design in the same manner as the Bazant equation. Equation (3) can be used to obtain the fracture energy:

$$G_F = 0{,}0143\ a_0(D_{max})^{0{,}2} - (0{,}5D_{max} + 26) \cdot \left(\frac{f_c}{10}\right)^{0{,}7} \quad (3)$$

with α_0 = 1,00 for spherical aggregates and α_0 = 1,12 for angular aggregates, where α_0 is the aggregate form factor. Dmax is the maximum aggregate size, w/c is the water-to-cement ratio, and fc is the compressive strength of the concrete. The fracture energy of the reference specimen using this method was -94,63 N/mm. Then, the concrete specimens with fibres and different ratios of PET waste, 30 and 50 %, had fracture energies of -87.50 and -67.96 N/mm, which were lower than those of the reference mixture by -7,53 and -28,18 %, respectively. Thus, both mixtures with 30 and 50 % PET waste as a sand replacement yielded acceptable compressive-fracture energies from a structural-application point of view using both the Bazant and CEB-FIP methods.

3.5 Estimation the elastic modulus of polypropylene fibrous concrete with PET wastes

The equation of Aslani and Smalley [34] provides the best prediction of the modulus of elasticity when the experimental modulus of elasticity for plain concrete is given. The equation of Aslani and Samali [44] was used to determine the modulus of elasticity of concrete with discrete fibres, as follows:

$$E_c = E_{cp} - 31.177\ V_f \quad (4)$$

where E_c is the elastic modulus of the fibre-reinforced concrete (MPa), E_{cp} is the elastic modulus for plain concrete (MPa), and Vf is the volume fraction of the fibre (%). Based on the experimental results for the static modulus of elasticity in Section 3.3.4, the elastic moduli of the reference, 30 % PET, and 50 % PET mixtures were 30509, 17030, and 14340 MPa, respectively. Thus, based on the results of the present study, the following equation is proposed to estimate the elastic modulus of polypropylene fibrous concrete containing relatively high percentages of PET waste as a sand replacement, as a modification of the Aslani and Smalley [34] equation:

$$\mathrm{Ec} = 0{,}8 \cdot (1 - PET)E_{cp} - 31{,}177\ V_f \quad (5)$$

where PET is the ratio of PET to sand (for example, for a 30 % PET replacement, PET in Equation 5 is 0,3). Equation 5 yields the elastic moduli for 30 and 50 % PET-to-sand replacement ratios of 17038 MPa and 12157 MPa, respectively. Thus, for 30 % PET as a sand replacement, the elastic moduli obtained by both experimental findings and Equation 5 are close, whereas for 50 % PET, Equation 5 yields an elastic modulus of approximately 84,8 % of the experimental findings, which may be considered acceptable for structural applications.

4 Sustainable development goals

The results of this study contribute to several sustainable development goals (SDGs) through the use of PET waste as a partial sand replacement in concrete. First, it promotes innovation in the concrete industry by utilising recycled materials, which supports Goal 9 (industry, innovation, and infrastructure) and enhances the development of sustainable and resilient infrastructure. Additionally, the lightweight concrete produced in this study helps to reduce the weight of buildings, contributing to the creation of more sustainable urban communities with lower resource consumption, thereby supporting Goal 11 (sustainable cities and communities). The use of PET waste also reduces plastic waste and promotes sustainable production practices, contributing to Goal 12 (responsible consumption and production) by reducing waste and fostering a circular economy. Finally, the use of recycled materials helps reduce the emissions associated with the extraction of conventional sand, thereby mitigating the impacts of climate change and supporting Goal 13 (climate action).

5 Environmental and economic impacts

The extensive use of sand in concrete production has significant environmental and economic consequences. The extraction of sand from rivers and beaches causes habitat destruction, biodiversity loss, soil erosion, and ecosystem disruption. In addition, transporting sand over long distances increases carbon emissions and contributes to climate change. Economically, the rising demand for sand has led to shortages and price increases that affect construction costs and availability. The illegal extraction of sand harms the environment and reduces the economic benefits of sustainable sand production. Therefore, sustainable practices are required in the construction industry to address these issues. The use of alternative materials, such as recycled PET plastic-waste aggregates, offers an opportunity to reduce the reliance on natural sand while addressing waste management and environmental preservation. Sustainable practices, including material recycling and the adoption of eco-friendly construction methods, can help mitigate the negative impacts of sand usage, conserve resources, and promote a more sustainable future for the industry. Thus, the results of this study, which produced lightweight structural concrete by replacing a relatively large percentage of sand, reaching 50 %, with PET waste, show that the present study satisfied the SDGs.

6 Mode of failure

Increasing the PET-replacement percentage in concrete led to a reduction in fracture size and crack length, thereby enhancing the ductility of the material. The specimens containing PET were less brittle and had fewer cracks than the reference specimen. Moreover, the addition of polypropylene fibres further improved the ductility and toughness of the concrete. The fibres helped distribute stresses more evenly across the material, reducing crack propagation, and improving the ability of concrete to absorb energy before failure. The combination of PET and fibres resulted in a more resilient concrete with better crack control and overall durability.

0 % (R) | 30 % PET + 1,5 % PP | 50 % PET + 1,5 % PP

Figure 13. Mode failure of compressive specimens

0 % (R) | 30 % PET + 1,5 % PP | 50 % PET + 1,5 % PP

Figure 14. Mode failure of splitting tensile specimens

0 % (R) | 30 % PET + 1,5 % PP | 50 % PET + 1,5 % PP

Figure 15. Mode failure of flexural specimens

7 Conclusions

- This study highlights the importance of using recycled PET and polypropylene fibres in lightweight concrete, contributing to improving sustainability and reducing the environmental impact of the construction industry. Notably, increasing the PET ratio reduced the weight of the concrete but negatively affected some properties of the concrete, such as workability and mechanical strength.
- The results of the present study open the door for future research to improve the bonding between recycled materials and fibres to enhance the mechanical and physical properties of concrete, leading to more efficient and lighter concrete while maintaining its strength.
- Because the particles in recycled plastic are not homogeneous in shape, the workability of the concrete is reduced. Therefore, the workability of the blends was significantly affected. The specimens with 50 % PET + 1,5 % PP had a workability of 40 mm, which was 75,3 % less than that of the reference specimens.
- Increasing the ratio of replacement PET caused a decrease in dry density. Accordingly, specimens with 50 % PET + 1,5 % PP had their unit weights reduced by 19,41 % compared with the reference concrete mixture, that is, the fibrous concrete mixture containing 50 % PET as a replacement for the fine aggregate yielded eco-friendly lightweight concrete.
- As the percentage of PET waste reinforced with polypropylene fibres increased up to 50 %, the compressive strength, splitting tensile strength, and flexural strength all noticeably decreased. Therefore, the specimen with 50 % PET + 1,5 % PP exhibited a decrease of 37,7 % in compressive strength, 20,83 % in tensile strength, and 17,5 % in flexural strength compared with the reference specimens.
- The UPV test and static and dynamic moduli of elasticity decreased as the proportion of recycled PET increased. The UPV test and static and dynamic Young's moduli for the specimen with 50 % PET + 1,5 % PP were 27,66, 52,99, and 57,82 % lower than those of the reference specimen, respectively.
- The absorption ratio increased as the proportion of recycled PET increased. The specimen with 50 % PET + 1,5 % PP exhibited an absorption rate of 3,41 %, which was 120 % higher than that of the reference specimens.
- The specimen with 50 % PET + 1,5 % PP can be categorised as lightweight concrete based on its density and compressive strength.

References

[1] Plastics Europe. Plastics – the Facts 2014/15: An analysis of European latest plastics production, demand and waste data. Accessed: April 29, 2025. Available at: https://plasticseurope.org/wp-content/uploads/2021/10/2014-Plastics-the-facts.pdf

[2] United States Environmental Protection Agency EPA. Economic Impact Analysis of the Plastic Parts and Products NESHAP. Accessed: April 29, 2025. Available at: https://www.epa.gov/sites/default/files/2020-07/documents/plastic-parts_eia_neshap_proposal_08-2003.pdf

[3] European Commission DG ENV. Plastic waste in the environment. Accessed: April 29, 2025. Available at: https://ceeii.org/environment/waste/studies/pdf/plastics.pdf

[4] Siddique, R.; Khatib, J.; Kaur, I. Use of recycled plastic in concrete: A review. *Waste Management*, 2008, 28 (10), pp. 1835-1852. https://doi.org/10.1016/j.wasman.2007.09.011
[5] Pappu, A.; Saxena, M.; Asolekar, S. R. Solid wastes generation in India and their recycling potential in building materials. *Building and Environment*, 2007, 42 (6), pp. 2311-2320. https://doi.org/10.1016/j.buildenv.2006.04.015
[6] Falih R. S.; Dawood A. O.; Al-Khazraji H. Structural behaviour of concrete beams reinforced with polyethylene terephthalate (PET) bottles wastes bars. *IOP Conference Series: Materials Science and Engineering*, 2020, 928 (2), 022033. https://doi.org/10.1088/1757-899X/928/2/022033
[7] Falih, R. S.; Dawood, A. O.; Al-Khazraji, H. Structural behavior of reinforced concrete beams containing pet waste particles as sand replacement. *Civil and Environmental Engineering*, 2022, 18 (1), pp. 209-220. https://doi.org/10.2478/cee-2022-0020
[8] Sabar, Z. A.; Dawood A. O. Flexural Investigation of Fibrous Concrete Slabs Incorporating Pet Wastes as Sand Replacement. *Civil and Environmental Engineering*, 2024, 20 (2), pp. 1040-1054. https://doi.org/10.2478/cee-2024-0075
[9] Choi, Y.-W.; Moon, D.-J.; Chung, J.-S.; Cho, S.-K. Effects of waste PET bottles aggregate on the properties of concrete. *Cement and Concrete Research*, 2005, 35 (4), pp. 776-781. https://doi.org/10.1016/j.cemconres.2004.05.014
[10] Akçaözoğlu, S.; Atiş, C. D.; Akçaözoğlu, K. An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete. *Waste Management*, 2010, 30 (2), pp. 285-290. https://doi.org/10.1016/j.wasman.2009.09.033
[11] Casanova-del-Angel, F.; Vázquez-Ruiz, J. L. Manufacturing light concrete with PET aggregate. *International Scholarly Research Notices*, 2012, 2012 (1), 287323. https://doi.org/10.5402/2012/287323
[12] Liguori, B.; Iucolano, F. Recycled plastic aggregates in manufacturing of insulating mortars. *CSE Journal - City Safety Energy*, 2014, (1), pp. 93-99. http://dx.doi.org/10.12896/cse2014001009
[13] Alqahtani Fahad, K. et al. Lightweight concrete containing recycled plastic aggregates. In: *Proceedings of the 2015 International Conference on Electromechanical Control Technology and Transportation*, Shyu, Y.-H.; Zhang, Y. (eds.). October 31-November 1, 2015, Zhuhai City, Guangdong Province, China, Atlantis Press, 2015, pp. 527-533. https://doi.org/10.2991/icectt-15.2015.101
[14] Attanasio, A. et al. Sustainable aggregates from secondary materials for innovative lightweight concrete products. *Heron*, 2015, 60 (1/2), pp. 5-26.
[15] Jassim, A. K. Recycling of polyethylene waste to produce plastic cement. *Procedia Manufacturing*, 2017, 8, pp. 635-642. https://doi.org/10.1016/j.promfg.2017.02.081
[16] Aslam, H. M. et al. Effect of waste polyethylene terephthalate bottle fibers on the mechanical properties of recycled concrete. *Advances in Civil and Architectural Engineering*, 2023, 14 (27), pp.1-13. https://doi.org/10.13167/2023.27.1
[17] Aslam, H. M. et al. Evaluating the mechanical and durability properties of sustainable lightweight concrete incorporating the various proportions of waste pumice aggregate. *Results in Engineering*, 2024, 24, 103496. https://doi.org/10.1016/j.rineng.2024.103496
[18] Noshin, S. et al. Evaluating the compressive strength of concrete containing recycled aggregate in different curing conditions. *Journal of Applied Engineering Sciences*, 2021, 11 (2), pp. 127-136. https://doi.org/10.2478/jaes-2021-0017
[19] Noshin, S. et al. Effects on compressive and tensile strength of concrete by replacement of natural aggregates with various percentages of recycled aggregates. *Mehran University Research Journal of Engineering and Technology*, 2022, 41 (1), pp. 195-201. https://doi.org/10.22581/muet1982.2201.19
[20] Noshin, S. et al. Effect of Quarry Dust on Mechanical Properties of Rice Husk Ash-Based Concrete for Sustainable Environment. *International Journal of Nanoelectronics*

and Materials (IJNeaM), 2024, 17 (2), pp. 194-203. https://doi.org/10.58915/ijneam.v17i2.683
[21] Kanwal, H. et al. Human hair as fiber reinforced concrete for enhancement of tensile strength of concrete. *Mehran University Research Journal of Engineering and Technology*, 2020, 29 (1), pp. 63-70. https://doi.org/10.22581/muet1982.2001.07
[22] Rehman, A. U. et al. Experimental study on the behavior of damaged CFRP and steel rebars RC columns retrofitted with externally bonded composite material. *Advanced Composite Materials*, 2024, 34 (1), pp. 93-139. https://doi.org/10.1080/09243046.2024.2358262
[23] Yasin, M. et al. Innovative early age mechanical properties of 3D printable mortar enhanced with SBR latex and kaolin. *European Journal of Environmental and Civil Engineering*, 2024, 29 (6), pp. 1053-1075. https://doi.org/10.1080/19648189.2024.2425974
[24] Central Organization for Standardization and Quality Control Iraq. IQS 5/1984. *Portland cement*. Iraq: IQS; 1984. [in Arabic]
[25] Central Organization for Standardization and Quality Control Iraq. IQS 45-(1984). Aggregates from Natural Sources for Concrete and Building Construction. Iraq: IQS; 1984.
[26] American Society for Testing and Materials. ASTM C494-99. *Standard specification for chemical admixtures for concrete, Annual Book of ASTM Standards*. USA: ASTM; 2005.
[27] American Society for Testing and Materials. ASTM C143. *Standard Test Method for Slump of Hydraulic-Cement Concrete 1*. USA: ASTM; 2000.
[28] British Standards Institution. BS1881/PART116 (1989). *Method for Determination of Compressive Strength of Concrete Cubes*. London: BS; 1989.
[29] American Society for Testing and Materials. ASTM C496-04. *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. USA: ASTM; 2008.
[30] American Society for Testing and Materials. ASTMC78/C78M-18. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*. USA: ASTM; 2002.
[31] American Society for Testing and Materials. ASTM C469. *Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression*. USA: ASTM; 2002.
[32] American Society for Testing and Materials. ASTM C642. *Standard test method for density, absorption, and voids in hardened concrete*. USA: ASTM; 2013.
[33] British Standard Institute. BSI 1881- PART 116 (1983). *Method for Determination of Compressive Strength of Concrete Cubes, Testing Concrete*. London: BS; 1983.
[34] Aslani, F.; Samali, B. High strength polypropylene fibre reinforcement concrete at high temperature. *Fire Technology*, 2014, 50, pp. 1229-1247. https://doi.org/10.1007/s10694-013-0332-y