Physical and mechanical properties of concrete containing PET wastes as a partial replacement for fine aggregates

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ABSTRACT

In this study, the influence of using polyethylene terephthalate (PET) wastes as a partial replacement of natural sand is investigated to study the mechanical and physical properties of concrete. Fine aggregate (sand) is partially replaced by equivalent weight percentages of PET waste particles while maintaining all other proportions. Mechanical tests for compression, splitting, flexure, modulus of elasticity, toughness, and axial strain as well as physical tests for density, shrinkage, and absorption, are performed. In addition, the ultrasonic pulse velocity is presented. All specimens are observed for 7, 14, and 28 days. The tests results presented that the presence of PET particles changed the physical and mechanical properties of produced concretes. Physical properties (density and ultra sound velocity) gradually decreased as PET ratios increased, while an increase in absorption rate was observed. Furthermore, for strength-related properties, the results showed that the specimens containing partial substitution ratios rangingwithin5%–12.5% displayed 26.8%–43.64%, 18.6%–26.9%, and 18.1%–30.2%increments in the compressive, tensile, and flexural strengths, respectively, compared with the reference specimens. The findings also revealed an increase in toughness and axial strain of the specimens with 5%–20% replacement percentages, while the modulus of elasticity decreased as the PET content increased. The results further indicated that the strength parameters decrease when the PET content exceeds 15%. In conclusion, replacing sand with waste PET particles positively affects the strength-related values of concrete specimens as long as the replacement ratio is less than 15%.

1. Introduction

The population in the 21st century reached more than seven billion people, which requires many buildings and housing constructions all over the world. This lead toincrease the demand for concrete. Thus, the materials that constitute concrete may experience decline or depletion. Therefore, studies on the use of sustainable alternative materials as partial or full alternatives to some components of concrete have been conducted. One of the crucial considerations is the ratio of the additives to concrete and their influence on the concrete properties, as indicated in many studies [1-6]. Different materials can be added to concrete in order to changing its engineering properties. Some of these additives have appositive impact on concrete properties, while others may have negative impact [7]. Additive materials like fiber/rubber [8-13], plastics [5, 14], slag [15, 16], resin [17] are mixed with concrete components to improve its engineering properties. Plastics are remain in the environment for even hundreds of years due to it is very resistant to decomposition .It is become one of the environmental risks in the modern society because the long-lasting durability. Numerous researchers have explored the possibility of reusing PET wastes as a fiber in concrete mix with volumetric percentages ranging 0.25%–4%. The inclusion of PET fibers within concrete mixture showed an increasing in flexural strength[18,20,24], enhancing tensile and compression strengths [21,27,29,30], absorbed energy, ductility, and decreases workability and elastic modulus[1-12].The best fiber percentages obtained by previous studies in term of concrete mechanical properties were ranged from 1% to 1.5%[18,20,21,24]. Generally, there are limited researches related to use PET as fine aggregate. The mechanical properties of concrete included PET as fine aggregate yielded different results, due to the difference in size, shape, and percentages of PET that were used as a substitute for sand. Yun-Wang Choi et al. [5], found that using PETwith sizes ranged from 5 to15 mm as a partial replacement of fine aggregates by volumetric percentages of 25%, 50%, and 75% in concrete mixture, led to a decrease in the compressive strength and density of the samples when the replacement percentages increase. Similarly, Ismail et al. [31], showed that using PET with lengths ranging 0.15-12 mm and width ranging 0.15–4 mm by weight percentages of 0%, 10%, 15%, and20% as a partial replacement of fine aggregate in the concrete mixture produced decreasing in slump, density, and flexural and compressive strength of concrete. Likewise, Albano et al [32], used irregularly shaped PET particles with sizes ranged from 2.6-11.4 mm as a sand partial replacement by three volumetric percentages of 0%, 10%, and 20%. They found that using PET particles in plain concrete decreases tensile and compressive strength, and elastic modulus. Frigione et al. [33], displayed that substituted fine aggregate (natural siliceous sand from fluvial deposits with size 0.1–5 mm) partially by un-washed PET bottles waste aggregates with size 0.1 – 5 mm and by percent of 5% from weight in concrete led to decreasing in compressive and splitting tensile strength and increases ductility. Otherwise, Rahmani et al. [34] found that using PET bottle waste with a maximum size of 7 mm as a partial replacement for fine aggregate in the concrete mixture by percentage of 5%,

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10%, and 15%, produced higher compressive strength at 5% replacement. Also, they observed that the slump, modulus of elasticity, and pulse velocity decreases as a PET waste percentage increase. Azhdarpour et al. [35], presented PET waste fragments as a partial replacement for fine aggregate by percentages of 5%, 10%,15%, 20%, 25%, and 30% with two different sizes of PET fragments, the first has a diameter of 2–4.9mm and the second has a diameter of 0.05–2mm. They found that using PET particles till 10% percentages enhanced the compressive and flexural strength, while the best replacement percentage was 5%.This study aims to absorb some quantities of non-degradable PET waste that constitute a future threat to the ecosystem, to produce concrete with enhanced mechanical properties and relatively lightweight. It also aims to provide a sustainable material that contributes to replacing of concrete aggregates partly to maintain its continuity for the longest possible period and extend the shelf life of its sources. In this study, PET plastic wastewas cut to small particles close to natural sand gradation by special machine. The special machine is a shredder machine consists of a hopper with dimensions of 116 * 45 cm as input for plastic bottles, and rotating shaft consisting of nine moving blades and two installed for cutting plastic bottles, in addition to a filter in the bottom to sift the plastic parts to the required gradation. The machine is powered by a 30 kW electric motor see Fig. (2).It was used as a partial substitute for fine aggregates in various weight percentages (5%, 7.5%, 10%, 12.5%, 15%, and 20%) in addition to the reference mixture. The common mixing ratio (1:1.5:3) was used. The application of the obtained results in actual engineering works yields two benefits: ridding the environment of harmful wastes and improving the properties of concrete.

2. Methodology

The experiment involves studying the effect of using different percentages of PET wastes that have been cut and shredded by special machines as a partial substitute for fine aggregates in concrete. Several tests are performed on concrete samples with different weight percentages of PET wastes, which were then compared with reference samples containing fine aggregate to determine the optimum weight percentage.

2.1 Materials

2.1.1 Cement

Ordinary Portland cement Type I is used in this study. The physical properties and the chemical composition of the cement are satisfied the requirements of the Iraqi Specification No. 5/1984 [36] and ASTM C150-04[37].

2.1.2 Aggregates

Natural sand (maximum size = 4.75 mm) from Basra city in southern Iraqis used as the fine aggregates, whereas crushed natural stones (maximum size of 20 mm) are used as the coarse ones. The grading and specification for fine aggregates is presented in Table 1 and Fig.(1), which matches the Iraqi Standard Specification No.45/1984[38] and ASTM C33-03[39].

2.1.3 Admixture

Liquid super plasticizer (modified polycarboxylate polymer) conforming to ASTMC494-99 Types A and G is used in the experiment [40].

2.1.4 PET

Small and large PET bottles are used in this study.PET bottles with different sizes and colors are minced to achieve extremely small diameters and particles that can pass sieve No.4 (Fig. [3]). The PET bottles aggregate are purchased from local recycling factories and Choppers. The PET particles are subjected to sieve analysis, and the results satisfied the requirements for sand under Iraqi Specification No.45/1984 [38]. The difference in the fine sieves is shown in Fig. (1). Specific gravity and absorption rate for PET particles are shown in Table 1 [31].

2.2 Mixture proportions

One of the most common weight ratios for mixing (1:1.5:3) with a target strength of 35 MPa at 28 days is adopted to achieve the closest approximation to reality. The weights of the cement, sand, and gravel, per cubic meter in the mixture are 444.75, 667, and 1334 kg, respectively. The water–cement ratio 0.41 (with 0.4% superplasticizer). According to pre-experiments work, PET bottle wastes are added to the reference mixture in six different percentages (5%, 7.5%, 10%, 12.5%, 15%, and 20%) as partial substitute for sand. Table 2 lists the concrete mixture proportions.

2.3 Preparation of the test specimens

The fine and coarse aggregates are washed and cleaned before using in the mixtures. All molds (cubes, cylinders, and prisms) are prepared, cleaned, and lubricated before casting (Fig. [4]). At first the PET waste particles are prepared and mixed as a partial substitute for sand with the weight percentages indicated above. An electric mixer is used to mix the aggregates (including the PET waste replacements and gravel). Afterward, cement was added to the concrete mixture. Finally, the water and superplasticizer were appended to the mixture gradually with continuous mixing. The mixing process lasted for at least 2 min.

2.4. Laboratory tests

Different specimen shapes are prepared in this work, including cubes, cylinders(two sizes), and prisms (two sizes), to evaluate the mechanical properties of hardened concrete, such as compression strength, elastic modulus, dry density measurement, splitting tensile, flexural strength, shrinkage, absorption, and energy absorption. In addition, slump test is performed to evaluate the workability of fresh concrete see Fig. 3. All tests are performed on each substitution percentages, which are then compared with the reference mixture. Nine concrete cubes (150 × 150 × 150) mm are prepared for each substitution ratio to conduct the compression strength test at ages 7, 14, and 28 days (i.e., three cubes for each age).Similarly, nine cylinders (100 × 200) mm are prepared for the splitting tensile strength at the same ages, with three cylinders for each age. Another three cylinders (150 × 300) mm are used in the experiment two of which are used for the modulus of elasticity test and one is used energy absorption test; both variables are tested at the age of 28 days. Six prisms (100 × 100 × 500) mm are utilized for the flexural strength test at the ages of 7 and 28 days, with three prisms for each age tested using the single-point method following ASTM C293 [41]. In addition, two prisms (75 × 75 × 300) mm are used for the expansion and shrinkage tests after the age of 28 days using a shrinkage apparatus. Conductivity measurements through ultrasonic pulse velocity (UPV) and absorption tests are performed using one concrete cube (150 × 150 × 150) mm for each replacement percentages after the age of 28 days. The UPV test is performed according to ASTM C597 using PUNDIT PC 1012 with an accuracy of 0.1 μs.

3. Results and discussion

3.1 Slump

The slump test is performed according to ASTM C143 [42]. The results show that the workability of the concrete decreases as the percentage of PET waste in the concrete mixture increases. The same conclusion has been presented in previous studies [31, 32, 34, 35, 43]. The 20% replacement rate yields a larger reduction in concrete workability (62.5%) compared with the reference mix (Fig. [5]). This reduction is due to the larger surface area of the PET waste particles than the sand particles, which allows the saturation of a large amount of water in its surface and therefore reduces the workability of concrete.

3.2 Density

The dry density measurement results indicate that the addition of PET waste particles to concrete mixture reduced the dry densities of concrete Fig. (6-A). These results are compatible and supported by other studies [5, 31, 34, 35, 43, 44]. Increasing the PET percentage to 20% decreased the density of concrete compared with the reference mix due to low density of PET particles (1380 kg/m^3). This relatively small reduction may be useful in decreasing the dead load of concrete in some applications, such as massive concrete structures on weak soils. The test results are plotted against the relationship between concrete density and PET replacement as percentages in Fig. (6-A) and the results are summarized. Figure (6-A) shows that the densities of the specimens with 7.5% replacement percentage at ages of 7, 14, and 28 days are close to each other. Meanwhile, those with 10% and 15% replacement percentages are almost identical at 14 and 28 days. The density curve generally decreases with the increase in the PET waste content in concrete**.**

3.3 Compressive strength

This test was done according toB.S.1881, Part 116[45] using a compression machine with a capacity of 2000kN.The compressive strength increases when the PET waste replacement percentages range from 5% to 12.5% (Fig. [6-B]).Varying increments are observed at the three ages. The optimum percentage for the highest increase in compression strength (43.64%) at 28 days is 7.5%. In addition, the compressive strength increased by 34.03% when the PET waste replacement ratio is 5 %. The compressive strength increased by 29.56% and 26.8% when the replacements ratio is 10% and 12.5%, respectively. The compressive strength of cubes with 15% replacement percentage is close to that of the reference cubes. The cubes with 20% PET waste replacement exhibit a 5.3% reduction in compressive strength. The compressive strength increases when the PET waste replacement ratio is low. Increments of 34.03%, 42.16%, and 28.31% are observed in the specimens with PET waste percentages of 5%, 7.5%, and 10%, respectively, at 28 days (Fig. [6-B]). The structure of the PET particles is affected by the mode of failure when the applied load reaches the ultimate load (i.e., the internal stresses are converted from shear stresses to tensile stresses, which boosts the strength of the concrete). In addition, the plastic materials are elongated by the aggregate particles (sand), thereby transforming the loading before the failure point. The concrete without PET waste particles is brittle; the failure point of the specimens with PET wastes occurs at low applied load. By contrast, the compressive strength decreases when the percentage of PET waste particles is more than 10% (Fig. [6-B]). The smooth surface of the PET particles exerts negative influence on the bond strength between the cement paste and the particles. Specimens with high PET waste percentages (12.5%, 15%, and 20%) have a large interfacial transition zone between cement paste and PET waste particles (i.e., the specimens are weak under compression loads).The test results are plotted against the relationship between the compressive strength and PET replacement percentages (Fig. [6-B]). Fig. (6-B) depicts that the compressive strength curve at the ages of 7 and 14 days is similar in form. A slight increase in resistance is observed in the latter but both curves meet at the replacement percentage of 20%. Compared with the 14-day compression curve, the compression curve at 28 days exhibits a large increase at replacement percentages of 5% and 7.5%, matching at 10% and 12.5%, and converges at 15%. Based on the findings of this research, the effect of substituted PET particles on the compressive strength values could be divided into three main classes based on PET amount as sand replacement, namely 0–10%, 10–15%, and 15–20%. In the first class, with 0–10% of substitution, compressive strength values considerably increased. This conclusion may contradict the results reported by Choi et al. [5], Ismail et al. [31], Albano et al [32], Frigione et al. [33], and Almeshal et al. [43], while it agreed with other researchers [34, 35]. These discrepancies between the results of previous and present studies may be related to the grading, shape, and size of PET particles, type of cement, water-cement ratio, and so on. Concerning the second class (i.e. substitution of 10–15% of PET), the addition of PET particles still positively affects the compressive values of strength. This conclusion contradicts the results reported by all other studies that show a decrease in compressive strength when the replacement percentage exceeds 10% [5, 31, 32, 33, 34, 35, 43]. Finally, the third class of substitution (i.e. using 15–20% of PET) showed reduction in compressive strength.

3.4 Splitting tensile

This test was performed according to ASTM C496 [46].The results presented in Fig. (6-C) suggest that the splitting tensile strength increases as the replacement percentage of the PET waste particles increases upto 15%. At the age of 28 days, the 7.5% PET waste replacement achieved an optimum splitting tensile strength increase of 26.9% compared with the reference mix. Conversely, the splitting tensile strength of the mixes containing 20% PET waste decreases by 3.7% with respect to the reference. These findings reveal that the splitting tensile stresses of specimens with 5%, 7.5%, and 10% PET waste replacement increase to 7.88%, 26.97%, an 19.08%, respectively, at 28 days. An opposing behavior is observed when the PET waste replacement ratio is higher than 10% (Fig. [6-C]).The increase in the splitting tensile stress due to the increased ductility and sharp edges of the PET waste particles results in reduced slipping in comparison with sand particles. The specimens with 20% PET replacement exhibit a decrease in the splitting tensile stress. This behavior can be attributed to the large numbers of particles that accumulated in one place and stuck together. In this study, the PET waste content is matched with the weight proportion of sand, that is, the amount of PET particles is more than that of sand particles at the same percentage. No water absorption in the smooth surfaces of the PET waste particles that can reduce the hydration of cement is observed. Hence, the interaction zone between the cement paste and the aggregates is lost during bonding. The test results are plotted against the relationship between the splitting tensile strength and PET replacement ratio as percentages in Fig.(6-C). The 14-day tensile curve slightly resembles the 7-day curve; the latter is slightly higher than the former by an average difference of 11%, but both curves meet at replacement percentages of 12.5% and 20%. The tensile curve at 28 days is similar to that at 14 days; the former is higher than the latter by an average difference of 12%, but both curves meet at the replacement percentage of 5%. The effect of the PET particles as sand replacement on the tensile strength values could be divided into two main classes, namely 0–15% and 15–20%. In the first class, with 0–15% of the substitution showed an increasing in the tensile strength. This conclusion conflicted with the results reported by Choi et al. [5], Ismail et al. [31], Albano et al [32], Frigione et al. [33], Rahmani et al. [34], and Almeshal et al. [43], which showed a decreasing in splitting strength, while it agreed with Azhdarpour et al. [35]. For the second class (i.e. 15–20%), a slight reduction in tensile strength, while its effect still positive on tensile values according to the study of Azhdarpour et al. [35] . These discrepancies among the results of various studies are due to the different gradations and sizes of PET particles, which resulted in a difference in the bonding strength between the concrete components and PET particles.

3.5 Flexural strength

The flexural strength test was conducted following the ASTM C293 [41]. Prism specimens with dimensions of (100 × 100 × 500) mm are used for the test. The flexural strength of specimens with PET replacement ratio ranging within 5%–12.5% increases. The highest increment (30.2%) is observed at the 7.5% replacement percentage. Specimens with 15% PET waste replacement also demonstrate an increase in flexural strength compared with the reference specimens. By contrast, the flexural strength of specimens with 20% PET waste replacement declines by 3.9%. The test results are plotted against the relationship between the flexural strength and PET waste replacement as percentages in Fig. (6-D).Concrete is brittle, and brittle materials possess low tensile strength. Therefore, using PET waste particles, which increases ductility, enhances the flexural strength. These particles are more flexible than fine aggregates. With regard to the flexural deformation, prism specimens with PET waste replacement exhibited large deformation before reaching the ultimate load. The flexural strength of the specimens with 5%, 7.5%, and 10% PET waste replacement increased to 27.15%, 30.24%, and 26.26 %, respectively. Given that the modulus of elasticity decreases with the amount PET waste particles, the concrete specimens become highly deformable and flexural materials before failure loading. However, the flexural strength decreases when the replacement ratio exceeds 10%. This decline causes the PET particles to form groups within the concrete specimens, thereby increasing the possibility of accumulating a large number of particles in one region. These groups produce weakness zones in the concrete and are therefore considered as starting failure points. Fig. (6-D) shows that the specimens with PET replacement percentages higher than 15% achieve a flexural strength at 7 days that is close to that at 28 days. The effect of the substituted PET particles on the flexural strength values can be divided into three main categories, namely 0-5%, 5-15% and 15-20%. In the first class, with 0-5% replacement, the flexural strength values increased significantly. This conclusion conflicted with the results reported by Choi et al. [5], Ismail et al. [31], Albano et al [32], Frigione et al. [33], and Almeshal et al. [43], while it agreed other researchers [34, 35]. Concerning the second category (i.e. the replacement of 5-15%), addition of PET particles still positively affects the values of flexural strength. Similarly, same conclusion was approved by Azhdarpour et al. [35] that, but with higher rates. Regarding the third category (15-20), the values of flexural strength showed a slight reduction in flexural strength of 4% when the replacement rate was 20%, while Azhdarpour et al. [35] recorded a decrease of 8% for the same replacement rate. This inconsistency among different studies may due to the total percentage of PET substitution with regard to concrete's total weight, as well as the different gradations and sizes of PET particles.

3.6 Shrinkage

This test was executed according to IOS 54/1970 [47] using a shrinkage device consisting of a base and two length stands 400 mm that are 100 mm apart and carrying a 15mm-iron beam with a dial gauge (0.01 mm accuracy, Fig. [7]). Prism specimens with dimensions of (75 × 75 × 150) mm are used in this test. The results show that an increasing in size of the concrete specimens after being immersed in water for 28 days. The amount of these increasing decreases as the percentage of PET particles increases (Fig. [9-A]). The largest increasing in size was for the reference samples with ratio of 0.000385, which gradually decreased as the percentage of PET particles increase. For specimens containing 20% PET replacement, size increasing reduction by 74.75% compared to the reference mixture is observed. These results are considered normal if Iraqi sand is considered to contain a percentage of SO_3 apart from the PET particles. SO_3 increases the size of the hardened cement paste after interacting with cement components. The products of this reaction fill the pores and reduce the voids, and thus increase the volume. For shrinkage measurement, the same specimens were used and put in an oven at 50 °C for 44h, then left in the air under normal conditions, while continuing to record the readings periodically till readings being stable. After 140 days, stabilization of the shrinkage readings was observed for all specimens. Results showed that the shrinkage decreases as the PET replacement percentage increases (Fig. [9-B]). During the test, only the specimens containing a PET replacement percentage ranging from 0%–7.5% experience shrinkage. The reference specimens exhibit a maximum shrinkage value of −0.00035, whereas the specimens with 7.5% PET replacement display a minimum shrinkage of −0.00011, which is 68.57% lower than that of the latter. This phenomenon can be ascribed to the size increase stage after curing; the size increase rate of the specimens is high after the immersion in water. By contrast, the shrinkage rate after drying increases. When the PET replacement percentage is increased to more than 7.5%, the results show a different trend, which is represented by volumetric change while drying. A slight and uniform increase in volume is observed as the replacement percentage increases. The recorded volumetric change at replacement percentages of 10%,12.5%, 15%, and 20% are 8E−05, 0.000222, 0.000304, and 0.000325, respectively. These rates may be due to the expansion of the plastic particles when exposed to heat.

3.7 Absorption test

This test was performed according to ASTM C642 [48].Cubic specimens with dimension of (150 × 150 × 150) mm are used in this test. Specimens were tested at age of 28 days. The results showed that the absorption rate increases as the PET percentage increases. This conclusion has been proven in previous studies [32,44]. The reference mixture shows an absorption rate of 1.55%, and the specimens with 20% PET replacement achieve an absorption rate of 2.41%, which is 55.48% higher than that of the former (Fig. [10-A]). This phenomenon might be due to the irregular shape and sharp edges of the PET particles, which increased the voids and pores in the concrete structure; the absorption rate increases as the number of voids and pores increase.

3.8 Ultrasonic pulse velocities

Ultrasonic test was performed in accordance to ASTM C597 [47]. Cubic specimens (150 × 150 × 150) mm with age of 28 days and an ultrasonic pulse velocity apparatus are used in this test (Fig. [8]). The objective of this test is to evaluate the effect of PET particles as sand replacement on the quality of concrete (e.g. density and absorption) via pulse velocities. PET particles possess low density and this characteristic reduced the density of the concrete that contain these particles see sec.3.2. The ultrasonic test result shows that the pulse velocity decreases as the percentage of PET particles in the cube increases (Fig. [10-B]). The results are in accordance with the findings of other researchers [32, 34, 35, 43]. The reference cube achieves a pulse velocity of 3906 mm/μs, and the cube with 20% PET replacement obtains3397 mm/μs, which is 13% lower than that of the former. These values are acceptable considering the density of the concrete. Fig. (6-A) shows that the specimens with 7.5% PET replacement have higher densities than those with a 20% replacement. The similar trend of the density and pulse velocity curves, in addition to the convergence of the reduced density and pulse velocity for all substitution ratios compared with the reference samples, indicates that the decrease in velocity is due to the PET waste particles. Moreover, the decreasing of pulse velocity with increasing the PET content indicates an increase in the voids, and this confirms the results of the absorption test, namely, the absorption increases as the PET content increases in the concrete, see section 3.7.

3.9 Modulus of elasticity

The modulus of elasticity is calculated from the stress–strain curve shown in Fig. (12-C). in accordance to ASTM C-469 [50].

$E = (\sigma_2 - \sigma_1)/(e_2 - 50\times10^{-6})$

Where

σ_2: is the stress corresponding to 40% of the ultimate load;

σ_1: is the stress corresponding to the longitudinal strain (50×10^{-6}); and

e_2: is the longitudinal strain produced by σ_2.

Results displayed that the modulus of elasticity and the PET particle replacement percentage are inversely related. The modulus of elasticity decreases as the percentage of PET substitution in the fine aggregate increases. This conclusion is agreed with previous studies [31, 32, 34]. The reference specimens obtain an elastic modulus of 27.206 GPa, whereas the specimens with PET replacement percentages demonstrate a gradual decrease in the elastic modulus Fig. (12-A).The specimens with 20% PET replacement achieve an elastic modulus of 21.088GPa, which is 22.48% lower than that of the reference. The modulus of elasticity of the specimens with 5%, 7.5%, 10%, 12.5%, and 15% PET replacement are 24.437, 22.767, 22.577, 22.343, and 22.108 GPa, i.e. less than the reference specimen by 10.17%, 16.31%, 17.01%, 17.87%, and 18.73%, respectively. This finding is anticipated because of the inverse relation of modulus of elasticity and strain; the strain increases and the modulus of elasticity decreases with the increase in PET particle ratio (Fig. [12-D]) Fig. (11) shows the test method and the specimens.

3.10 Energy absorption and axial strain

The energy absorption is calculated as the area under the stress–strain curve which measured until post-peak region. The results show that energy absorption increases with the increases in PET replacement percentage Fig. (12-B). The reference specimens obtain energy absorption of 0.01374 kN.mm, which gradually increases as the replacement percentage increases. The specimens with 5% and 7.5% PET replacement achieve energy absorptions of 0.0206 and 0.0274 kN.mm, respectively. These rates are 50% and 99.8% higher than that of the reference mixture, respectively. The highest energy absorption value is 0.0286 kN.mm (108% higher than that of the reference mixture), which is obtained by the specimens with 10% and 12.5% PET replacements. The specimens with 15% and 20% PET replacement obtain energy absorption of 0.0261 kN.mm, which is 90% higher than that of the reference. The results reflect the increase in the area under the stress–strain curve due to the increase in the replacement percentages. This behavior is desirable for many applications that require high toughness. The test procedure and specimens are displayed in Fig. (11).The behaviour of concrete changes from brittle to flexible and ductile due to the presence of the PET waste particles. The strain at the failure load increase with the increase in PET waste content (Fig. [12-D]). The reference specimens achieve a strain of 0.92E−3 .This values gradually increase as the amount of PET waste in the concrete increases, where the specimens with 20% PET replacement recorded a strain of 1.63E-3, with an increase of (76.7%) compared to the reference specimens. This behavior is due to high flexibility of PET waste particles.

3.11Failure mode

The destruction tests conducted on the different specimens (cubes, cylinders, and prisms) produced a clear variation in the failure modes. The shape and crushing ratio, as well as the size and length of cracks, decrease as the PET replacement percentage increases. The various reference specimens tend to break down as a result of the brittleness of the concrete. The failure mode of the specimens containing PET wastes is manifested in the form of cracks with sizes and lengths that decrease as the replacement percentage increases. This behavior indicates that ductility, which is a crucial characteristic that increases the flexibility of concrete, increases with the increase in replacement percentages. Fig. (13) shows the failure modes of the different specimens.

B

A

C

D

A

B

C

D

4. Conclusion

The following conclusions are drawn from the results of the experiment.

1. The workability of concrete gradually decreases as the PET waste percentage increases. The slumps of the specimens with 5% and 20% PET replacements decreased by 12.5% and 62% with respect to the reference mix.

2. The absorption rate increases with the increase inPET waste content.The absorption rate at 20% replacement percentage is greater than that of the reference specimens by 55.4%.

3. The compression, splitting tensile, and flexural strengths increase with the increase in PET waste percentage up to 12.5%. The optimum replacement percentage is 7.5%, in which the compression, splitting tensile, and flexural strengths increased by 43.64%, 26.9%, and 30.2%, respectively, compared with the reference mix.

4. The increase in the concrete size after treatment decreases as the percentage of partial PET waste replacement increases. The specimens with 20% replacement percentage obtained the lowest size increasing rate, which is 74.75% lower than that of the reference specimens. Similarly, the shrinkage decreases as the replacement percentage increases. The lowest shrinkage (68.57% lower than that of the reference specimens) is observed at 7.5% replacement percentage. When the PET content is increased to more than 7.5%, the volume of the concrete increases.

5. The density and pulse velocity of concrete decrease with the increase in PET waste percentage. The concrete with 20% PET percentage recorded density and pulse velocity reductions of 7.11% and 13%, respectively, with respect to the reference mix. The specimens with 15% replacement percentage obtained reductions of 6% and 6.4%, respectively.

6. The modulus of elasticity decreases as the PET replacement ratio increases. The lowest elastic modulus (22.48% lower than that of the reference specimens) is obtained at 20% replacement percentage.

7. The energy absorption increases by increasing the replacement percentages at different rates. The lowest energy absorption is exhibited by the reference specimens, whereas the optimum one (108.28% higher than that of the reference specimens) is obtained at 12.5% replacement rate. The specimens with 5% replacement percentage achieved an energy absorption that is 50% higher than that of the reference specimens.

8. The ductility increases as the ratio of PET particles in the concrete increases. This was concluded from the failure mode of different specimens.

9. Using PET plastic wastes in concrete rids the environment of non-degradable harmful wastes and prevents future environmental pollution.

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