AUT Journal of Civil Engineering

AUT J. Civil Eng., 6(3) (2022) 387-398
DOI: 10.22060/ajce.2023.21293.5799

Mechanical Properties of Concrete Containing Polyethylene Terephthalate, Rubber and Glass Wastes

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ABSTRACT: Reusing recycled materials is one of the most important issues in the world for achieving sustainable development. Polyethylene Terephthalate, rubber, and glass particles are used instead of sand or cement in the concrete industry in recent years. In this paper, three groups of concrete mix designs with different water-to-cement ratios are investigated. Experimental specimens of each group consist of PET, rubber, and glass particles partially replacing natural fine aggregates by 5, 10, and 15 percent. These waste materials are used separately and in combination with each to study the mechanical properties of the concrete. Compressive and flexural strengths of concrete under different freezing and thawing cycles are investigated. The compressive strain of the recycled concrete was studied too. Results show that PET and rubber particles have decreasing effect on both compressive and flexural strengths of concrete and an increasing effect on compressive ultimate strains compared to those of reference specimens. But, the glass particles often have increasing and decreasing effects on strengths and strains respectively compared to those of reference specimens. The compressive strength of frozen-thawed recycled specimens is about 5 % more than that of the frozen-thawed reference specimen. Moreover, In combined PET and glass specimens, the experimental compressive and flexural strengths increased compared to only PET specimens and in combined PET-glass and PET-rubber specimens, the ultimate strain increased compared to that of glass concrete.

Review History:

Received: Apr. 13, 2022
Revised: Jun. 12, 2023
Accepted: Jun. 13, 2023
Available Online: Jun. 17, 2023

Keywords:

Glass
PET
mechanical properties
rubber
strength

1- Introduction

Concrete is a highly versatile construction material that is well-suited for many structural members. Quality and type of aggregates have an important effect on the mechanical and durability properties of concrete. Generally, natural coarse and fine aggregates were used for constructing the concrete. On the other hand, different types of waste materials are increasing with time due to the modern lifestyle, industrialization, and new technologies. Most of these waste materials are non-disposal and remain for hundreds or thousands of years in the environment. The rapid growth of these non-biodegradable waste materials along with population growth has caused the environmental crisis all around the world. For decreasing the hazards of this environmental problem and eliminating the inappropriate effects of these non-disposal wastes, the recycling process of the waste materials has been developed.

Using solid waste materials such as PET, rubber, and glass as partial replacements for natural aggregates of concrete is a suitable strategy for reducing environmental pollution. Materials such as PET (Polyethylene Terephthalate), rubber, and glass are three groups of waste materials that are used in concrete to replace the aggregates. This recycling process can reduce the complete reliance on natural aggregate resources and subsequently, decrease the generated environmental pollution. These waste materials can be used as alternative resources for managing the demand for natural aggregates in the concrete industry. PET, rubber, and glass are usually used as fine and coarse aggregates and in the form of fibers too.

Many studies have been carried out to investigate the properties of concrete containing PET, rubber, and glass particles. The results depend on the size, type, and proportion of the waste materials. In general, the workability of recycled concrete containing PET, rubber, and glass particles is affected by some factors such as water-cement ratio, amount of plasticizers, and size, shape, and substitution level of these waste materials. The workability of concrete containing PET and rubber as a partial replacement of the natural aggregate, decreases as the amount of waste materials increases. Increased surface area, irregular shape, impervious nature, and high capacity of water absorption of PET and rubber conclude in low workability [1-3]. But, in the case of coarse PET particles, there are some studies with adverse results. In these researches, the workability increases as the content of the coarse PET increases, up to 50%. Beyond this level, workability decreases again [4].

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In the case of recycled glass concrete, there are conflicting results. The workability of concrete containing glass wastes is influenced by the size, content, and morphology of glass particles. For fine glass particles (less than 100 µm), the slump increases with the particle size. But, using coarse glass aggregates may reduce the workability [5, 6]. However, Yan and Liang concluded that the workability of coarse aggregate glass concrete increased with an increase in replacement percentage [7].

Previous investigations show that using PET, rubber, and glass particles as a partial replacement of natural aggregates concludes with a decrease in compressive, flexural, and split tensile strengths of concrete. Because of the poor bond strength between these waste particles and cement paste and the lower strength of the waste aggregates compared to natural ones, the reduction of these strengths seems to be logical. This reducing effect was measured about 13 to 90 percent, 6.3 to 76 percent, and 5 to 55 percent in the case of PET, rubber, and glass concrete compared to conventional concrete. Particle size and replacement percentage are two key factors for determining the strengths of these recycled concrete [8-12]. There are a few researches that conflict with the majority of investigations too. A low replacement percentage of fine aggregates with these waste materials increases the compressive strength of concrete. Waste particle grading and replacement percentage are two important factors for determining the different strengths of recycled concrete [13-15]. However, Du and Tan demonstrated that using fine glass instead of river sand (up to 100%) concluded in an increase in compressive strength, splitting tensile strength, and flexural strength [16]. But Serpa et al. concluded that a better performance was attained in concrete with coarse glass aggregates, followed by concrete with fine glass aggregates, and finally concrete with the simultaneous incorporation of coarse and fine glass aggregates [17].

The strain magnitude of recycled concrete with PET, rubber, and glass aggregates has been investigated by some researchers [18-20]. The results demonstrated that recycled PET and rubber concrete are more ductile than plain concrete. It can be concluded that the stress-strain behavior of recycled PET and rubber concrete is generally more nonlinear than that of normal concrete. The strain corresponding to peak strength and ultimate strain of this recycled concrete is more than that of conventional concrete and increases for larger particle content and smaller particle size [6]. Recycled concrete with glass aggregates has very similar stress–strain curves to conventional concrete. The values of ultimate strain and the strain corresponding to peak stress are lower for coarse glass aggregate concrete than that of conventional concrete [7].

Using PET, rubber, and glass particles improved the freezing-thawing resistance of concrete. Reducing glass particle size is effective in suppressing alkali-silica reaction expansion [5]. But in the case of recycled glass aggregates, there are some conflicting results. Abendeh et al. investigated the compressive strength, flexural strength, and indirect tension of glass wastes. Results showed that using glass particles decreased the deterioration of the concrete under the effect of frost action [21].

As stated, many researches have been performed on using waste materials in concrete separately and each of them has some advantages and disadvantages. But, there are few studies about the combined use of PET, rubber, and glass in concrete. Previously, most studies paid attention to the use of PET, rubber, or glass separately in concrete. There is a lack of information on the combined reuse of these waste materials. In this paper, these three recycled materials (replacement of fine aggregates) are used separately and in combination with each other for the production of concrete. Subsequently, workability, compressive and flexural strengths of concrete specimens after different cycles of freezing and thawing are investigated. Moreover, the strain magnitudes of the concrete specimens are studied.

2- Materials and Methods

Portland cement type II with chemical and physical characteristics according to Table 1 was used for this experimental program. Coarse aggregates with a maximum size of 19 mm and specific gravity of 2.61 were used for this experimental work. Natural river sand with a fineness modulus of 2.69 and specific gravity of 2.55 was used too. The grading size of the coarse and fine aggregates are shown in Fig.1 [22]. Drinking water was used for constructing the concrete. The grading size of waste materials was the same as that of fine aggregates and the specific gravity of PET, rubber, and glass particles was about 0.46, 0.63, and 2.6 respectively. The mixed proportion of concrete with water-to-cement ratios (w/c) of 0.45, 0.5, and 0.55 are given in Table 2. To examine the effect of PET, rubber, and glass particles on the mechanical properties of concrete, a mix containing different replacement percentage of these waste materials (by weight) as a partial replacement of fine aggregates were prepared.

Three groups of recycled concrete mixes having water-to-cement ratios of 0.45 (group 1), 0.5 (group 2), and 0.55 (group 3)_were designed. Experimental specimens of each group consisted of PET, rubber, and glass particles partially replacing natural fine aggregate by 5, 10, and 15 % having an incrementing range of 5%. In the whole specimens, the sand was replaced by the waste materials according to Table 3. To mix the substances, first, the gravel and half of the sand were mixed, then the waste materials were poured into the mixture so it could be mixed with the existing materials. After that, 25 % of the existing water was added to the mixer. Then remained sand and cement were poured into the mixer and finally the remained water was added to the materials.

To investigate the properties of fresh concrete, the Slump test was carried out following ASTM C143 [23]. To measure the compressive strength of hardened concrete, Cube samples of 150 * 150 * 150 mm were used in the standard test method BS 1881: PART 116 [24]. Moreover, for calculating the flexural strength of recycled specimens, samples of 150 * 150 * 600 mm were casted and tested according to ASTM C 293 [25]. For determining the strain characteristics of the recycled concrete, cylindrical specimens of 150 * 300 mm were tested. Concrete specimens were cast in plastic molds and then removed from the molds 24 hours after casting. The curing process was performed in saturated lime water at 23±2°C for

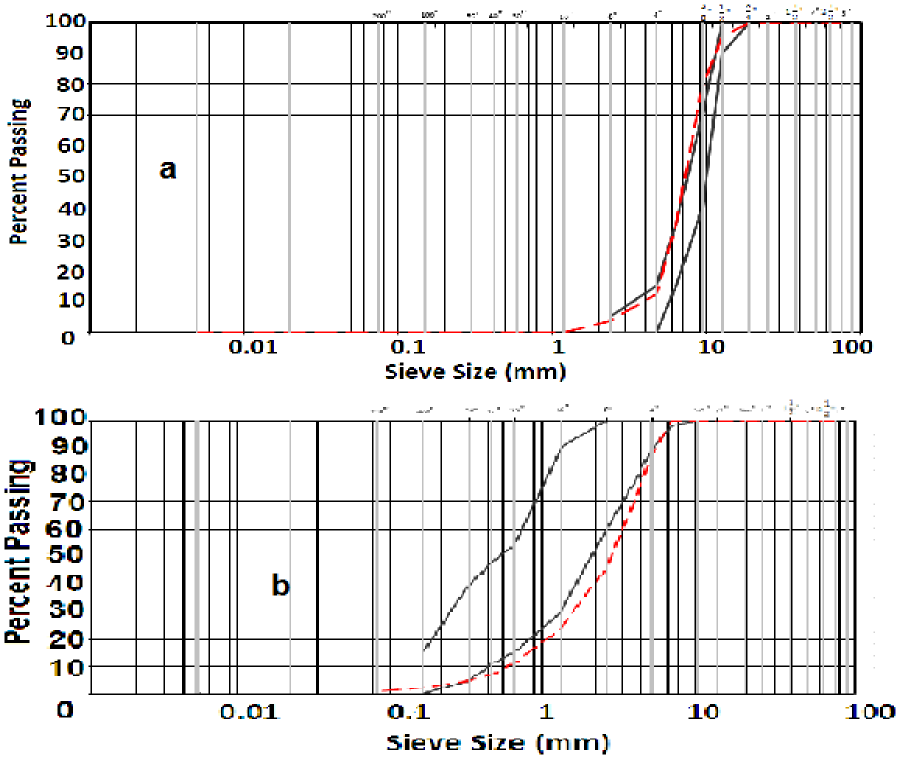

Fig. 1. Grading size of a) coarse and b) fine aggregates

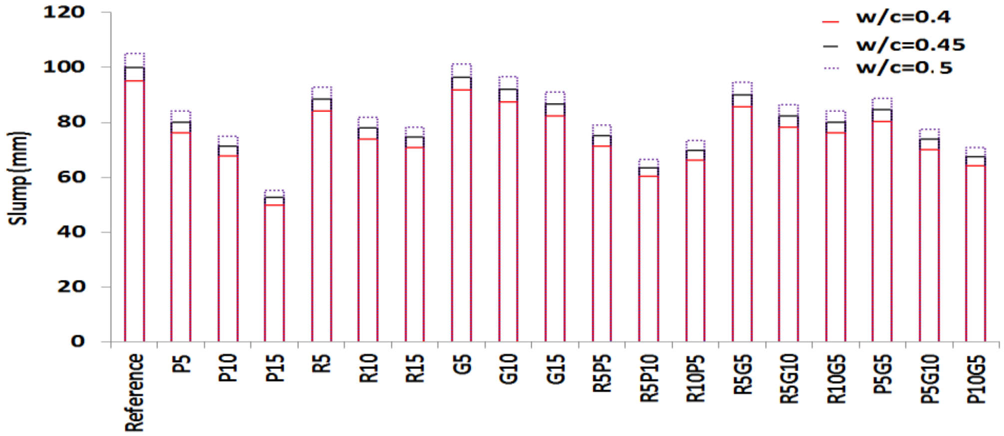

Fig. 2. Results of the slump test for the whole specimens

14 days according to ASTM C666 [26]. In this study, concrete specimens containing different amounts of waste particles were subjected to 0, 50, 100, and 150 cycles of freezing and thawing according to ASTM C666. Subsequently, these specimens were tested under the uni-axial compression and 3-point bending tests.

3- Results

Slump tests were carried out on the whole specimens and the results are presented in Fig. 2. As observed, using recycled particles concludes with less workability of concrete. As shown, increasing the number of waste particles results in decreasing the slump magnitude compared to the reference specimens. The minimum decrease belongs to G5 specimens (about 3.5 %) and the maximum decrease belongs to the P15 specimen (about 47.4 %). Increased surface area, irregular shape, and impervious nature of PET, rubber, and glass particles have an important effect on the workability of concrete and reduce the magnitude of slump which is in accordance with past researches [1-3].

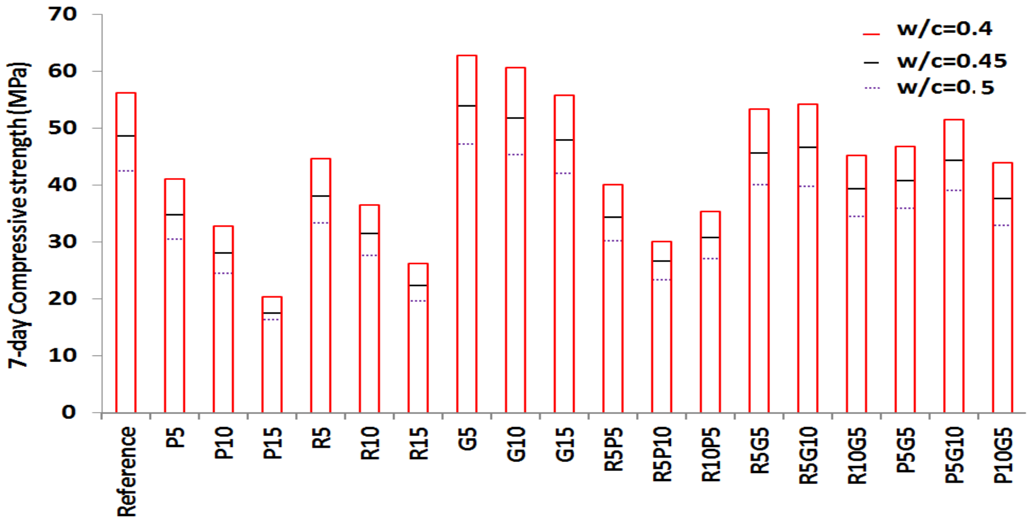

Fig. 3. 7-day compressive strength of the whole specimens

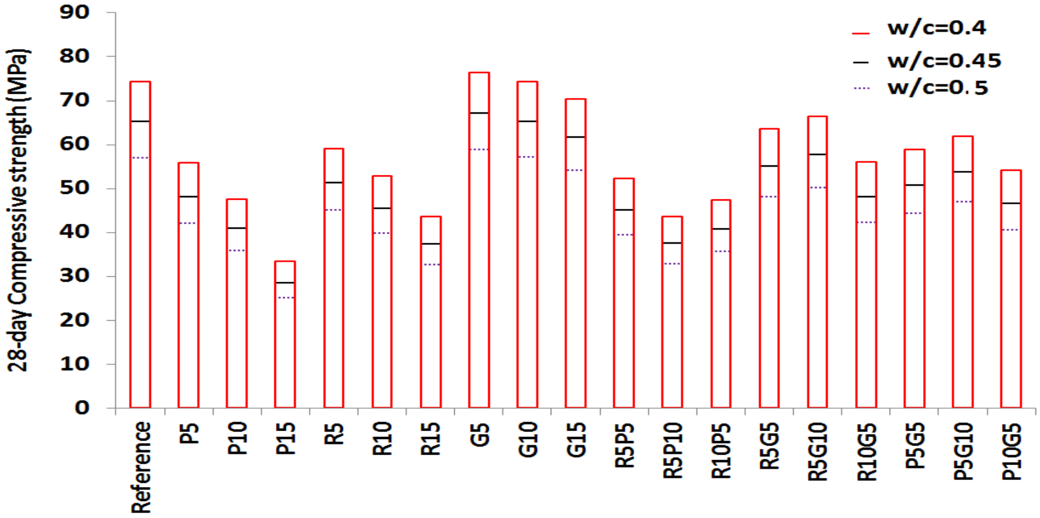

Fig. 4. 28-day compressive strength of the whole specimens

Compressive strength test was carried out on cube specimens at 7 and 28 days (f_{cu}) and the results are presented in Fig. 3 and Fig. 4 respectively. As observed, the Compressive strength of the whole specimens increases with decreasing the (w/c) ratio. The compressive strength of the specimens with w/c=0.4 and w/c=0.5 are about 1.17 and 0.88 times of the concrete specimens with w/c=0.45 respectively. As shown, the 28-day compressive strength of cube specimens on average is about 1.33 times more than that of the 7-day compressive strength. With increasing the magnitude of waste particles in concrete, the compressive strength of the specimens decreases. Using 15% PET, rubber, and glass as a replacement for and conclude an average decrease of about 57%, 43%, and 6% in the compressive strength of concrete compared to the reference specimen which is verified by some previous research [3, 5, 9, 10]. Moreover, the compressive strength of G5 specimens is about 2% more than that of reference concrete. PET particles are unconventional (flat and reactive) and subsequently, increase the holes and porosity of the concrete texture and have a negative effect on the mechanical properties of the concrete. Low stiffness and poor surface texture of the rubber aggregates lead to incompatibility between the different parts of concrete and the lack of bonding between the rubber and the surrounding cement paste reduces the compressive strength of concrete. The pozzolanic activity of fine glass particles improves the strength of the transition zone (interface between the paste and aggregate) in concrete

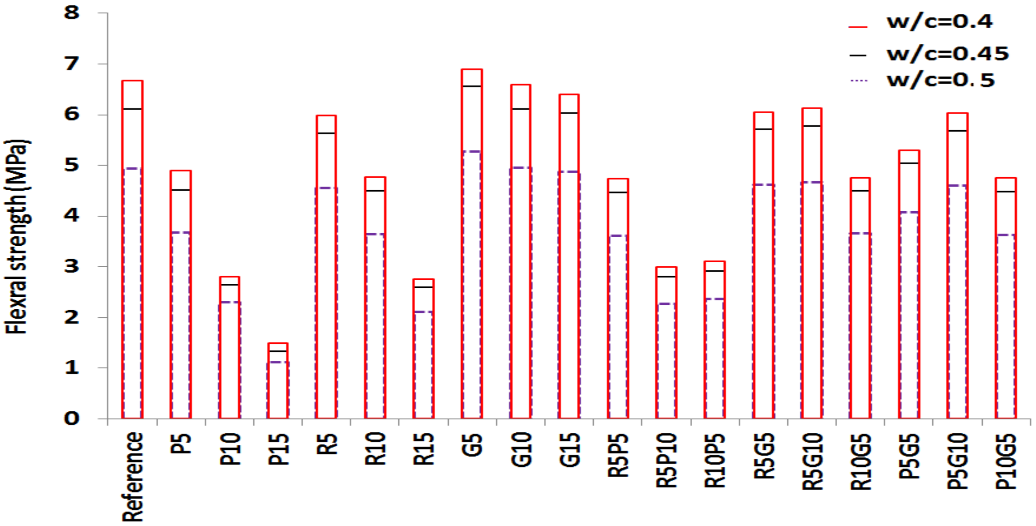

Fig. 5. Flexural strength of the whole specimens

and leads to higher strength. As observed, the rate of strength development for concrete (28-day/7-day) with glass particles is lower than that of the concrete with PET and rubber at the beginning days. Combined use of PET and rubber aggregates with glass particles concludes in an average decrease of about 20% compared to the reference specimen. The combined use of waste particles results in higher compressive strength compared to the separate use of PET and rubber aggregates. The maximum and minimum compressive strengths belong to G5 and P15 specimens and are about 1.02 and 0.43 times of the reference concrete respectively.

The dimensionless ratio of the 28-day compressive strength of the whole specimens to the 28-day compressive strength of the reference specimen is an important factor for determining the effect of waste particles on the structure of concrete. PET particles had the worst influence on the compressive strength of concrete and the minimum ratio on average is about 0.43 (P15). Using glass and rubber particles in combination with PET aggregates compensated for this decreasing effect of PET and resulted in better compressive strengths. This ratio in R10P5, R5P10, P5G10, and P10G5 specimens was on average about 0.62, 0.57, 0.82, and 0.71 respectively. It is obvious that the glass particles were more effective than rubber aggregates due to their pozzolanic activity in cement paste. In the case of the P10 specimen, this ratio is on average about 0.62, while using combined particles in R5P5 and P5G5 was concluded to be 0.69 and 0.77 respectively.

The flexural strength or modulus of rupture (MOR) of the material is defined as the maximum bending stress that can be applied to that material before it yields. Flexural strength is calculated with prismatic specimens that are subjected to a bending moment by the application of load through upper and lower rollers [2]. A flexural strength test was done on rectangular specimens at 28 days and the results are presented in Fig. 5. As observed the flexural strength (f_{ru}) of the whole specimens increase with decreasing the (w/c) ratio. The flexural strength of the specimens with w/c=0.4 and w/c=0.5 are about 1.06 and 0.808 times of the concrete specimens with w/c=0.45 respectively. The maximum and minimum flexural strengths belong to G5 and P15 specimens and are about 1.03 and 0.22 times of the reference specimen respectively.

The dimensionless ratio of the flexural strength of the whole specimens to the flexural strength of the reference specimen is another effective parameter for determining the effect of waste particles on the quality of concrete. PET particles had the worst influence on the flexural strength of concrete and the minimum ratio on average is about 0.19 (P15). Using glass and rubber particles in combination with PET aggregates compensated for this decreasing effect and resulted in better flexural strengths. This ratio in R10P5, R5P10, P5G10, and P10G5 specimens was on average about 0.68, 0.37, 0.84, and 0.72 respectively. It is obvious that the glass particles were more effective than rubber. In the case of the P10 specimen, this ratio is on average about 0.4, while using combined particles in R5P5 and P5G5 was concluded to 0.7 and 0.77 respectively. It is concluded that the PET particles have a negative influence on both compressive and flexural strengths. But, this decreasing effect in the case of flexural strength is more than that of compressive strength and the maximum difference is about 23%. Rubber aggregates have decreasing effect on both strengths too. But, this decreasing effect in the case of compressive strength is more than that of flexural strength and the maximum difference is about 10%. Adversely, the glass particles often have an increasing effect on both strengths. But, this increasing effect in the case of flexural strength is more than that of compressive strength and the maximum difference is about 10%.

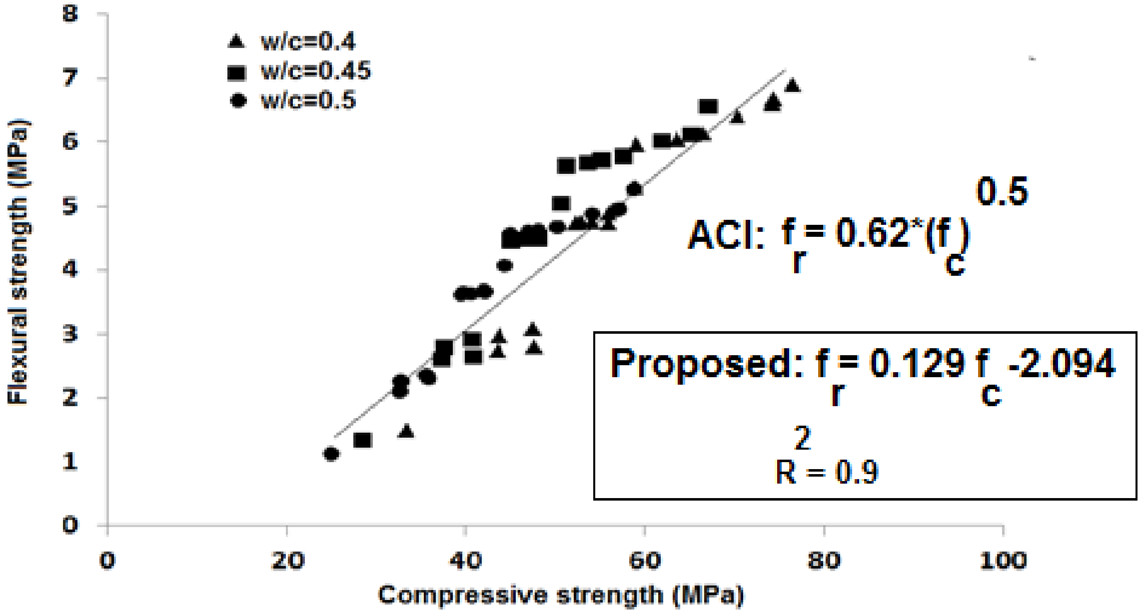

Fig. 6. Relation between compressive and flexural strength of the specimens

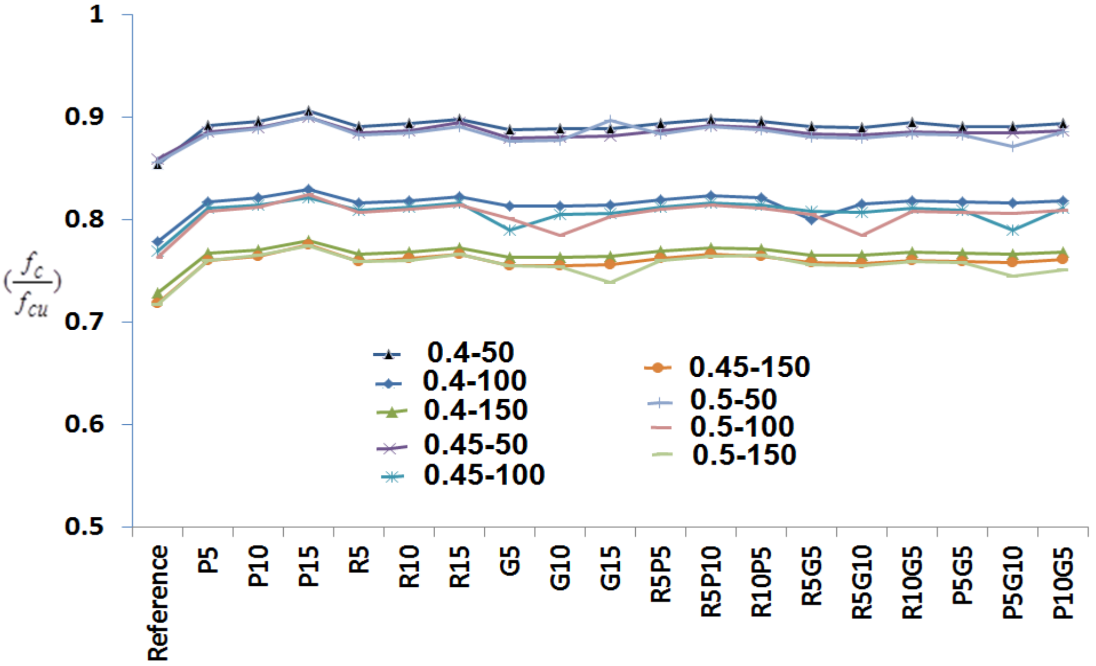

Fig. 7. Compressive strength of frozen thawed specimens

The relation between the compressive and Flexural strength of the whole specimens is shown in Fig. 6. The maximum difference between the proposed and the code equation is about 27.33% and the average difference between the proposed equation and the experimental results is about 14.5%. Hence, there is a good compatibility between the proposed values and the experimental flexural strengths.

Concrete specimens after exposure to 50, 100, and 150 cycles were tested under compressive and flexural tests [6]. Normalized compressive (f_c / f_{cu}) and flexural (f_r / f_{ru}) strengths of the specimens after different freezing and thawing cycles are presented in Fig. 7 and Fig. 8 respectively. Where, f_c and f_r are the measured compressive and flexural strengths of the specimens with different freezing

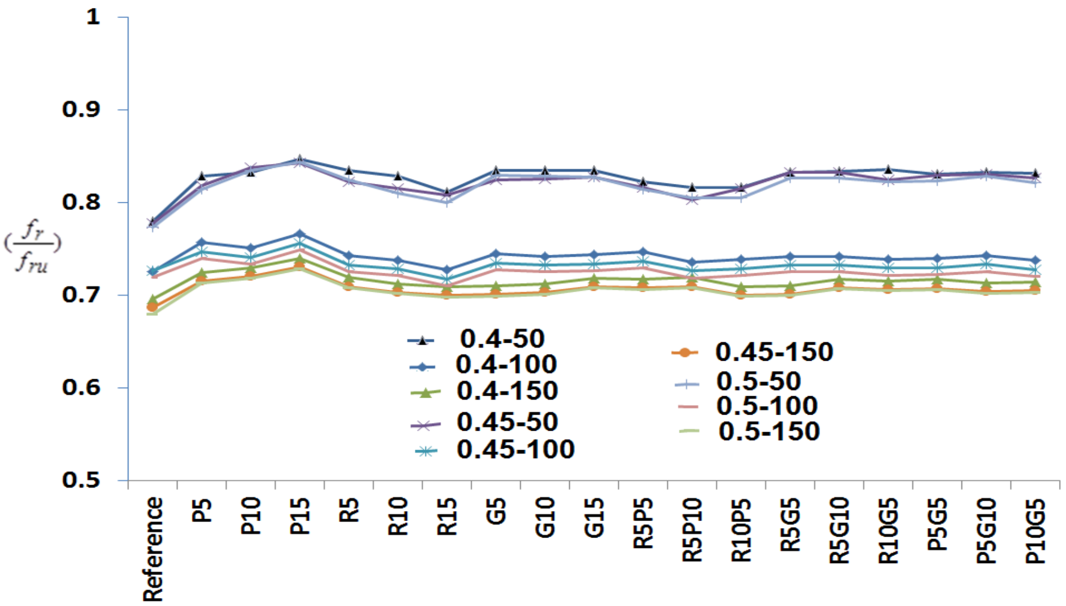

Fig. 8. Flexural strength of frozen-thawed specimens

Fig. 9. Compression test set up [27]

and thawing cycles. As observed, the (f_c / f_{cu}) of the whole specimens after exposing to 50, 100, and 150 cycles of freezing and thawing are in average about 0.887, 0.81, and 0.761 respectively. The maximum decrease in compressive strength of frozen-thawed concrete belongs to reference specimens and is about 0.85, 0.76, and 0.72. The minimum decrease in compressive strength belongs to P15 specimens and is on average about 0.9, 0.82, and 0.78. Moreover, the (f_r / f_{ru}) of the whole specimens after exposure to 50, 100, and 150 cycles of freezing and thawing are on average about 0.82, 0.73, and 0.71 respectively. The maximum decrease in compressive strength of frozen-thawed concrete belongs to reference specimens and is about 0.77, 0.72, and 0.68. The minimum decrease in compressive strength belongs to P15 specimens and is in average about 0.84, 0.75, and 0.73.

Cylindrical specimens (150 mm diameter and 300 mm length) were tested under the uni-axial compression according to Fig. 9. As it shown, one displacement transducer was installed on the face of the specimen for measuring the displacement over a central 200 mm length. Uni-axial compressive displacement with a constant rate of 1.3 mm/min was applied on cylindrical specimens to record the stress–strain data of the concrete. Experimental data including load and displacement values were recorded every 0.5 second through the test and saved on the data logger [18, 19, 20].

The strain at the peak stress (ε_0) and ultimate compressive strain (ε_{cu}) of the cylindrical specimens are determined according to Fig. 10 and presented in Table 4. Strain at the peak stress, ultimate strain, and the relation between these two parameters are presented in Fig. 11, Fig. 12, and Fig. 13

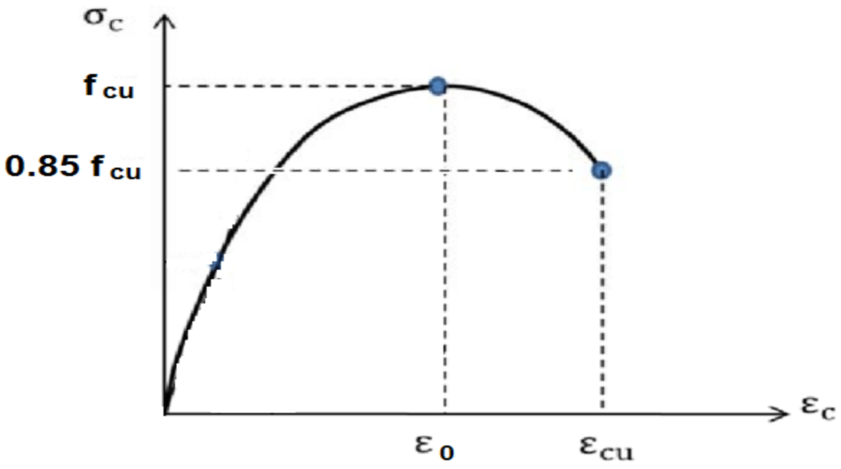

Fig. 10. The strain at the peak stress and ultimate compressive strain of the cylindrical specimens [27]

Table 4. (ε_0) and (ε_{cu}) of cylindrical specimens

Reference	P5	P10	P15	R5	R10	R15	G5	G10	G15
0.0021	0.00221	0.00224	0.00228	0.00218	0.00222	0.00227	0.002	0.002	0.002
0.00316	0.00363	0.00369	0.00376	0.0036	0.00367	0.00373	0.003	0.003	0.00297
0.00218	0.00229	0.00233	0.00237	0.00227	0.00231	0.00236	0.0021	0.0021	0.0021
0.0033	0.0038	0.00384	0.00391	0.00374	0.00382	0.00388	0.00312	0.00312	0.0031
0.00222	0.00236	0.00239	0.00244	0.00233	0.00237	0.00243	0.00214	0.00213	0.00213
0.00338	0.00388	0.00395	0.004	0.00385	0.00393	.00399	0.00321	0.0032	0.00318
Reference	R5P5	R5P10	R10P5	R5G5	R5G10	R10G5	P5G5	P5G10	P10G5
0.0021	0.00219	0.00221	0.0022	0.0021	0.0021	0.0021	0.0021	0.0021	0.00211
0.00316	0.00362	0.00365	0.00364	0.0033	.0033	0.00334	0.00332	0.00331	0.00334
0.00218	0.00227	0.0023	0.0023	0.00218	0.00218	0.0022	0.00219	0.00219	0.0022
0.0033	0.00378	0.00379	0.0038	0.00341	.0034	0.00345	0.00345	0.00345	0.00347
0.00222	0.00234	0.00236	0.00236	0.0023	0.0023	0.0025	0.0025	0.00224	0.00226

respectively. The ultimate strain corresponds to 15% decrease in compressive strength of the concrete [27].

As observed, the Compressive strains of the whole specimens increase with increasing the (w/c) ratio. The compressive strains of the specimens with w/c=0.4 and w/c=0.5 are about 0.96 and 1.02 times of the concrete specimens with w/c=0.45 respectively. As shown, the compressive strain at the peak stress and the ultimate strain of cylindrical specimens with glass particles on average is about 0.96 and 0.94 times of the reference specimen. Using 15% PET and rubber aggregates as a replacement for sand conclude in an average increase of about 9% and 17.5% in the (ε_0) and (ε_{cu}) of concrete compared to the reference specimen. It is concluded that using PET, rubber, and combining these particles with each other and with glass aggregates leads to more compressive strains compared to normal concrete. The maximum difference between the proposed ultimate strains and those of experimental data is about 4.7% and the average difference is about 2.4%. Hence, there is good compatibility between the proposed values and the experimental ultimate strains. It must be noted that the grading size of the whole waste particles was the same as that of the fine aggregates (sand). Variations in the grading size could be concluded to different results.

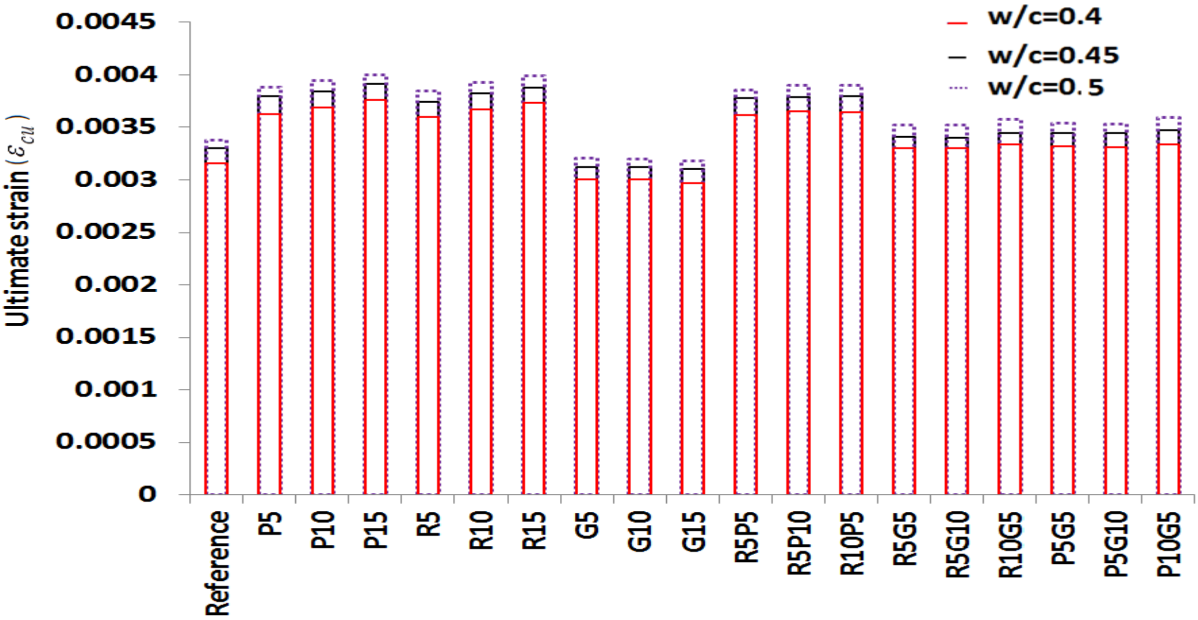

Fig. 11. Strain at the peak stress of the cylindrical specimens

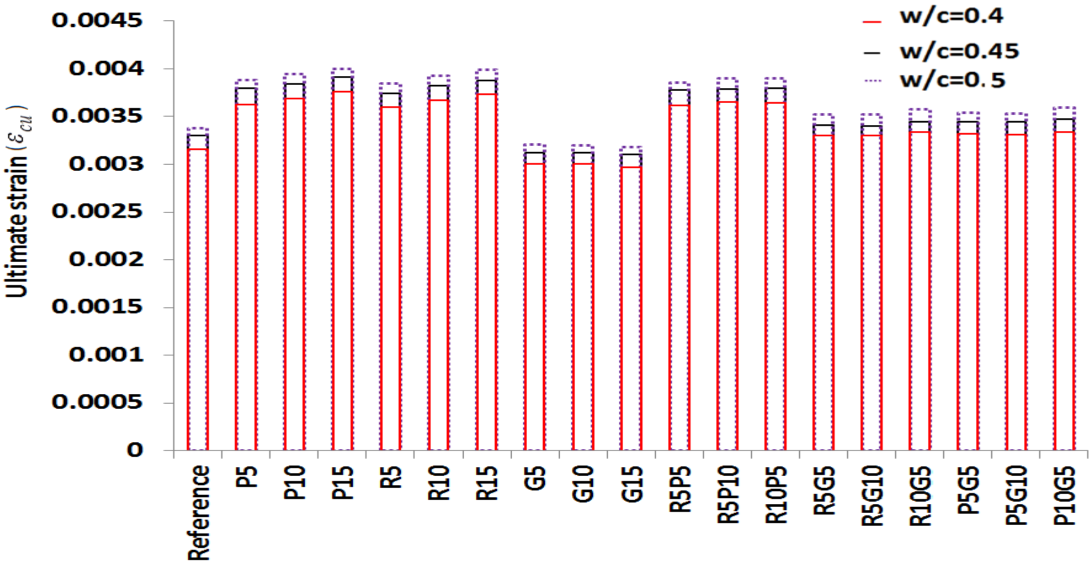

Fig. 12. Ultimate strain of the cylindrical specimens

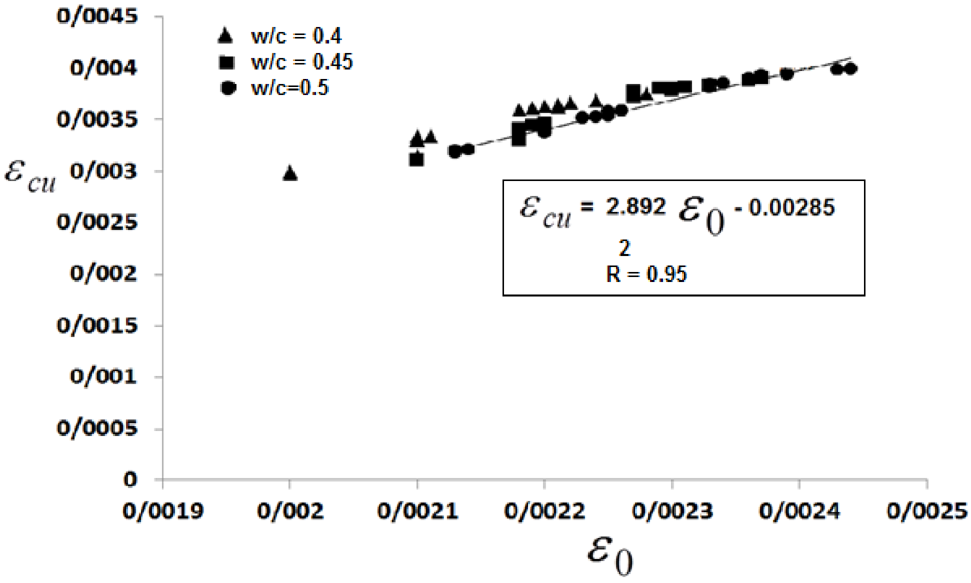

Fig. 13. Relation between the ultimate strain and strain at the peak stress of the specimens

4- Conclusions

Based on the experimental work, the following conclusions can be drawn:

1. Increasing the number of waste particles results in decreasing the slump magnitude compared to that of the reference specimen. The minimum and maximum decrease belongs to G5 and P15 specimens (about 3.5 % and 47.4 %) respectively.

2. The maximum and minimum compressive strengths belong to G5 and P15 specimens and are about 1.02 and 0.43 times the reference specimen respectively. Combined use of PET and rubber aggregates with glass particles concludes in an average decrease of about 20% compared to that of the reference specimen. Therefore, using glass wastes with other waste materials concludes with an average increase (about 40%) in compressive strength of concrete.

3- The maximum decrease in compressive strength of frozen-thawed concrete belongs to reference specimens and the concrete specimens with waste materials shows more compressive strengths compared to that of plain concrete.

4- The compressive strain at the peak stress and the ultimate strain of specimens with glass particles on average is about 0.96 and 0.94 times of the reference specimen respectively. There is good compatibility between the proposed values and the experimental ultimate strains.

5- Using dual waste materials instead of fine aggregates in this concrete concludes to improve the mechanical properties. In combined PET and glass specimens, the experimental compressive and flexural strengths increased compared to only PET specimens and in combined PET-glass and PET-rubber specimens, the ultimate strain increased compared to that of glass concrete.

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HOW TO CITE THIS ARTICLE

A. Hemmati, N. Afzalifar, Mechanical Properties of Concrete Containing Polyethylene Terephthalate, Rubber and Glass Wastes, AUT J. Civil Eng., 6(3) (2022) 387-398.

DOI: 10.22060/ajce.2023.21293.5799