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TECHNICAL PAPER

Mechanical properties, impact resistance and bond strength of green concrete incorporating waste glass powder and waste fine plastic aggregate

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Abstract

This research aims to reuse glass and plastic wastes by combining them in concrete to protect the environment and obtain green concrete with acceptable properties. A 15% of waste glass powder was used as a partial substitute for cement, and (10 and 20%) of crushed waste plastic was used as a partial substitute for fine aggregates. From the results, it was found that adding glass alone to concrete improved its properties such as compressive strength, splitting tensile strength, flexural strength, elastic modulus, energy capacity, and bond strength by 3.36%, 14.12%, 1.7%, 6.01%, 52.63%, and 57.32%, respectively compared to reference one. On the other hand, replacing sand with plastic for concrete with 15% glass powder led to some properties of concrete affected in a downwards especially for a 20% replacement like compressive strength, splitting tensile strength, flexural strength, elastic modulus, and bond strength by 38.44%, 5.61%, 22.22%, 18.26%, and 15.6%, respectively. Otherwise, the capability of energy absorption under impact load has been proved by 431.57% for 20% plastic aggregate.

Keywords Energy absorption · Glass powder · Impact resistance · Plastic aggregate · Strengths

Introduction

Cement, the primary component of concrete, emits significant amounts of global warming greenhouse gases during production. It was estimated that about 870 kg of CO_2 was released during the production of one ton of Portland cement. Cement production accounts for a significant 5% of the total 30 gyrations of CO_2 emitted globally [1]. In the paving blocks, waste glass was used as both fine aggregates and as a binder (i.e., as supplementary cementitious material) in the form of glass powder (GP). Despite the increasing amount of glass cullet (GC) used in the paving blocks, the strength of the paving blocks remained constant. The use of GC and fine's GP in combination reduced water absorption and drying shrinkage of the paving blocks to acceptable levels. The addition of GP could effectively resolve the concern of GC-induced Alkali-silica reaction (ASR) expansion [2]. A study in 2020 showed that by using waste glass as aggregate the mortar workability increases because of its lower water absorption than sand. As 100% sand was replaced with glass aggregate, the compressive strength at 90 days decreases from 77 to 73 MPa. Although porosity mounting by 1.5% to 13% for 25% to 100% of glass aggregate, reductions in drying shrinkage, absorption, and chloride permeability were observed. Lower permeability and irregular shape of glass aggregates are due to small variations in mortar properties. Comparison with natural sand after the exposition in temperature of 200 °C–800 °C, mortar using a glass aggregate had a similar trend of residual strength. Microstructural studies have shown that glass-aggregated mortars have fewer microcracks and improved bonds after high-temperature exposure in the Interfacial Transition Zone (ITZ). The results of this study further suggest that natural sand replacement using different percentages of waste glass cullet in alkaline-activated mortar offers comparable characteristics to those using natural sand [3]. The research was done to investigate the properties of concrete containing ground waste glass powder (GP) as a partial substitute for cement. Concerning a sustainable green environment and the added benefits of protecting natural resources as well as the production of more effective

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material, the use of wastes in concrete is now a global trend for efficient waste management. Laboratory tests were performed with (0, 15, 18, 21, 24, 27, and 30%) partial substitution of cement with the powder of the ground waste glass to determine the strength activity index, workability, splitting, and compression properties of the concrete. Based on the 28-day strength index for concrete containing 21% cement substitute, the composition oxide of the glass powder meets the requirements on pozzolanic material and shows a higher strength index above the recommended 75%. It was also discovered that as the percentage of glass content increased, the workability of the concrete decreased, while the compressive strength of the concrete significantly improved at 21 percent cement substitution, during which there was a decline in strength as the percentage glass content increased. However, as the glass content increased, the splitting tensile strength decreased. The results showed clearly that moderate resistance to sustainable concrete can be produced with 20% glass powder as a substitute for structural applications [4]. Another study worked to investigate fresh and hardened characteristics of concrete by using glass powder result from melted or broken windows as a partial cement replacement. Five mixes were created in this study with different percentages of waste glass powder used as cement substitute at 0%, 10%, 15%, 20%, and 25% by weight.

They found that compressive strength with 10,15 and 20% of waste glass powder increased by 27.62, 41.46, and 20.18%, respectively at 28 days. While at 56 days compressive strength increased by 22.11, 41.75, and 21.36% at 56 days, and 27.05, 30.81, and 17.2% at 90 days for 10, 15, and 20% of waste glass powder, respectively, compared to reference specimens. Otherwise, 25% of waste glass powder caused a decrease in compressive strength by 14.34, 20.5, and 19.41 at 28, 56, and 90 days, respectively, compared to the reference mix. In addition, mechanical properties were improved by adding glass power [5], 6. Other research evaluated the pozzolanic behavior of glass powder with the content of (0, 5, 10, 15, 20, and 25%) by cement weight. The results showed that the compressive strength improved by an average of 16%, in addition, to improve other properties for modified concrete with glass powder by up to 15.0% [7]. Another study concluded that the use of 15% WGP would save 52.5 kg of cement for each cubic meter of concrete. The ultimate load of specimens with 10% and 15% GP showed an improvement of + 4 to 39% in all cases of reinforcement beams. This caused more brittle behavior due to the higher compressive strength of WGP concrete [8]. Waste plastic has been utilized in concrete in different sizes, some researchers used waste plastic as a low-cost fiber to improve the brittle nature of concrete. They found that adding waste plastic as fibers reduced the compressive strength and workability of mixes [9–12]. But it improved other properties like increasing tensile strength [9, 10] and decreased the dry shrinkage by about 35% compared to mix without plastic fibers [9]. Also, it’s improved resistance against abrasion [12]. The waste plastic has been used as fine or coarse aggregate replaced partially nature aggregate in concrete. Mohammadhosseini et al. [13] investigated the effect of waste polypropylene, which was used as short fibers of different sizes to place coarse aggregate, under elevated temperatures. Also, 20% POFA (palm oil fuel ash) was used as a substitution for cement. They found a reactive interaction among the fibers and POFA that led to increasing both compressive and tensile strengths of tested specimens at high temperatures. Besides using polypropylene with POFA was found delay time needs for heat transferring from surface to the middle of concrete specimens [14]. Another study waste PET (polyethylene terephthalate) as fine and coarse aggregate in the composition of polymer concrete. The results showed that coarse PET was more effective in case of improving fracture toughness and energy than fine PET. This was explained by the ability of coarse PET to bridge cracks [15]. Various types of waste plastic from different sources were used such as water drink bottles, their covers, and compact disk to substitute fine aggregate partially by (0, 10, 15, 20, and 25%). The results showed that fine plastic aggregate reduces compressive strength and modulus of elasticity, and the specimens were suffered from more deformations before failure. In addition, the bonding strength between concrete and steel reinforcement decreased with increasing plastic content. Results also illustrated that capacity of energy absorption under impact load was increased increasing plastic content [16]. Either most researches showed that using waste plastic as fibers or aggregate improved the impact resistance of concrete. Mohammadhosseini et al. showed that using a combination of WMP (waste metalized plastic) fibers and POFA improved impact resistance besides to tensile strength of the resulting concrete [17]. Also using 20-mm-long carpet fibers with 0 to 1.25% content with replacing cement with 20% POFA improved both tensile strength and impact strength effectively [18]. Saxena et al. utilized waste PET type as fine and coarse aggregates in concrete from 0 to 20%. They found no improvement in mechanical properties, increase in water absorption, but an improvement was a note in abrasion's resistance [19]. Jain et al. used plastic aggregate, from old waste bags, at a level from 0 to 5% with a 1% increment. They found that the impact resistance of specimens with plastic aggregate was higher than control one [20]. Another investigating also used plastic aggregate, from old waste bags, at a level from 0 to 20% with 5% increments. Moreover, the results illustrated that the strengths of concrete were decreased, while impact strength, abrasion resistance, and energy absorption were significantly improved [21]. In general, researches showed that utilizing waste plastic regardless of its type or size led to improve in the impact resistance of concrete and made its failure more ductile [22, 23].

The reasons behind investigated the combined effect of waste glass powder (WGP) and waste plastic (WP) as fine aggregate are:

- First it is illustrated from a review of existing researches that the effect of glass and plastic on concrete have been separately investigated. And there are researches that deal with the effect of waste plastic with a different type of pozzolanic material like POFA and fly ash but research was not found about the effect of combined WGP and WP.
- Second, the reuse of these waste materials would help to achieve the development goals by reusing the wastes in concrete and reducing the use of the raw materials.
- The third reason is that using glass powder alone increase concrete strength but for the same loading level, strains in specimens incorporating WGP were less than the one without WGP that refereed to the more brittle behavior of concrete [24]. While the effect of waste plastic decreases compressive strength but increased the ductility of concrete [23].

Therefore, this work aimed to use both wastes to take advantage of the effect of waste on concrete and to fill the gap regarding with effect of combined WGP and WP.

According to Yassin et al. [5], Mahmoud et al. [6], and Hama et al. [8], who replaced cement with different percentages of glass powder results from broken window glass, and it was the same as the glass used in the present study, stated that 15% of waste glass powder gave the best results. So a 15% was adopted as a partial replacement of cement in this study. Previous research focused on using plastic bottles, bags, and other forms of plastic in concrete as a replacement for aggregates or as fibers. A new source of waste plastic was adopted in this work to supply waste plastic. In this article, a new form of plastic, waste plastic from the manufacturing of valves for cooking gas bottles, was used for the first time. This work aims to reuse this form of plastic with waste glass powder. The main objective to achieve this aim is to investigate the fresh and hardened properties of concrete includes slump, density, mechanical properties, the amount of energy absorption through impact test, and bond strength between concrete and steel bar.

Table 1 Sieve analysis of glass powder

Sieve size (mm)	Cumulative passing %
0.300	100
0.150	99.8
0.075	93.4

Experimental Program

Materials

For all concrete mixes in this study, ordinary cement with 3.15 specific gravity, and 325 m^2/kg, fineness was used. This type of cement confirms Iraqi specification No.5 [24]. The waste glass, which used in this study was from broken windows. This waste was collected from a damaged building. Then the collected glass was washed to eliminate impurities and dust, then crushed with a crusher machine to a size of (0.1–10 mm), then ground by hand to produce a powder glass. Table 1 shows the size of this glass and its gradation. Table 2 and Fig. 1 explain the percentage of main components and the glass powder preparation stages, respectively.

Natural sand was used as a fine aggregate in this research, with a maximum size of 4.75 mm. its water absorption% sulfate content (SO_3) and specific gravity were 0.12%, 0.16%, and 2.62, respectively. Crushed gravel was also used as a coarse aggregate with a maximum size of 10 mm with a specific gravity of 2.65 and water absorption of 0.4%. Before to use, the fine and coarse aggregates were washed to remove any mud or defective particles. Table 3 shows the sieve analysis of aggregates, which are confirming the Iraqi specification No.45 [25].

The plastic that used in this study was polyethylene waste from the process of making the valve for cooking gas bottles, in which the plastic is dissolved and deformed into small white granules before being fed into a special injection and molding system to make the plastic part of

Table 2 Chemical components of glass powder

Chemical compounds	Glass Powder %	Cement %
Silicon dioxide (SiO_2)	97.488	20.11
Aluminum oxide (Al_2O_3)	0.795	6.42
Iron oxide (Fe_2O_3)	0.1404	3.37
Calcium oxide (CaO)	1.575	65.26

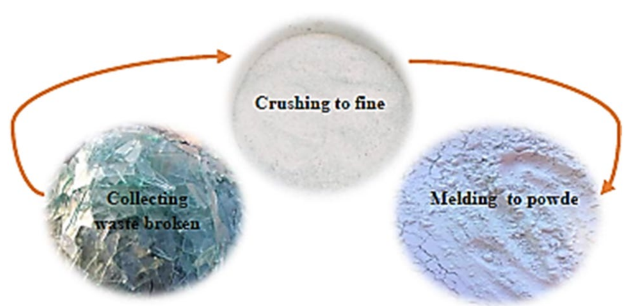

Fig. 1 Glass powder preparation stages

Table 3 Sieve analysis of used aggregate

Sieve size (mm)	Cumulative passing %		
	Sand	Plastic	Gravel
10	100	100	100
4.75	97.48	75.2	20.22
2.36	83.89	17.6	1.3
1.18	70.44	4	---
0.600	53.54	1.2	---
0.300	15.84	0.4	---
0.150	2.25	0.2	---

Table 4 Properties of superplasticizer

Property	Class
Commercial Name	Sika Visco Crete® -5930
Basis	Aqueous solution of modified polycarboxylate
Appearance	Turbid liquid
Transport	Non-hazardous
Density	1.08 kg/Lt ± 0.005
pH	8 ± 1

the safety valve. Figure 2 shows the steps of production of fine plastic aggregate from waste plastic. It was white color with a specific gravity of 1.366 and water absorption% equal to 0%. The plastic sieve analysis is listed in Table 3.

A 1% aqueous polycarboxylic superplasticizer, type F and G of (Sika ViscoCrete-5930), was used in this research. It complies with the ASTM C 494 [26] limitations. It has been used to improve the workability of waste glass powder and waste plastic aggregate concrete. Table 4 lists the properties of the superplasticizer. For all concrete mixtures and in the curing of specimens, tap water, without any salts or chemicals, was used.

Mix Proportion, Mixing procedure and Curing

Mixing ratio of (1:1.75:2.5) for cement, fine aggregate, and coarse aggregate was used in the casting of samples with 0.32 water to cement ratio (w/c), and 1% superplasticizer.

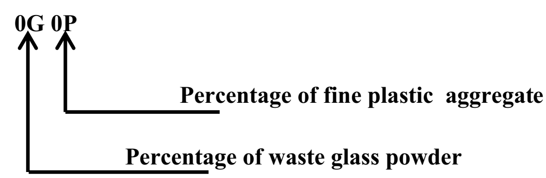

Fig. 3 Sample definition

The mixes ratios, per cubic meter (kg/m^3), are shown in Table 5. Figure 3 shows the sample definition in Table 5.

To achieve the homogeneous mix, the following steps were followed;

1. Before starting the casting process, the mixer and mold were cleaned to remove any or stuck materials and lubricate the molds well to facilitate the removal of the samples later.

Fig. 2 Production steps of fine waste plastic aggregate

Table 5 Mix proportions (kg/m^3)

Mix	w/c ratio	Cement	WGP	Fine Aggregate	Waste plastic	Coarse Aggregate	Water	Super plasticizer
0G0P	0.32	486	0	851	0	1215	155.52	4.86
15G0P	0.32	413	73	851	0	1215	155.52	4.86
15G 10P	0.32	413	73	765.9	44.71	1215	155.52	4.86
15G 20P	0.32	413	73	680.8	89.42	1215	155.52	4.86

WGP: Waste Glass Powder

Fig. 4 Slump test

2. All the amount of coarse aggregate + 50% (Cement + waste glass powder) + 50% of mixing water, all mix for (0.5–1) minutes.
3. All the amount of (fine aggregate + crushed waste plastic) + 50% (Cement + WGP) + 25% of mixing water + All Superplasticizer all mix for (2) minutes.
4. Then the remaining water is added and mixes completely for 3 min.
5. Ensure that the edges of the mixer base are free of any agglomerated materials.

After that, the concrete was cast into the molds and preserved in the laboratory for 24 h. The specimens were placed in a water pool until 7 or 28 days of water curing when they were tested.

Fig. 5 Ultrasonic pulse velocity test

Testing Program

The test was carried out according to ASTM C143 / C143M [27], as shown in Fig. 4.

Unit weight was measured according to ASTM C138 / C138M 01a [28]. Ultrasonic pulse velocity test was carried out following ASTM C597 [29], see Fig. 5. Ultrasonic pulse velocity was calculated using Eq. (1):

$$V = L/T \tag{1}$$

where: V = Velocity of pulse (m/s). L = Pulse length (m). T = Recorded time (s).

Based on BS EN: 12,390–3 [30], cubic specimens of (100 × 100 × 100 mm) size were tested. For tested both types of specimens a 2000 kN capacity machine are used. Cylindrical specimens with dimensions of (150 × 300 mm) were tested to find (f'_c), (i.e., the strength of concrete mixtures after 28 curing age), according to ASTM C39/C39M [31]], as shown in Fig. 6.

A splitting tensile strength test was carried out in the same compressive strength test machine on cylindrical samples (100 × 200) mm after 28 days of curing. This test was performed following ASTM C496/C496M [32]. By using Eq. (2) the splitting tensile strength was obtained;

$$f_t = 2P/\pi LD \tag{2}$$

f_t = Splitting tensile stress (MPa). P = maximum applied load recorded during the test (N). L = cylinder length (mm). D = cylinder depth (mm).

Fig. 6 Modulus of elasticity test

A flexural strength test was carried out with a hydraulic machine, on prismatic samples with a length of 500 mm and a Sect. (100 × 100 mm) according to ASTM C78/C78M [33]. The maximum load was recorded from the test, and flexural strength was determined using Eq. (3).

$$f_r = PL/\left(b * d^2\right) \quad (3)$$

f_r = flexural strength (MPa). P = maximum load (N). L = clear span length (mm). b = prism width (mm). d = prism depth (mm).

A compressive testing machine with a capacity of 2000 N, was used for modulus of elasticity (Young's) test, see Figure Cylindrical samples, with 150-mm diameter and 300-mm height, were used according to the ASTM C469[34]. The strains were recorded through the test, and the elastic modulus was calculated by Eq. (4).

$$E_c = \left(S_2 - S_1\right) / \left(\varepsilon_2 - 0.00005\right) \quad (4)$$

where: E_c = static modulus of elasticity (MPa). S_1 = stress corresponding to 0.00005 of longitudinal strain (MPa). S_2 = 40% of ultimate stress (MPa). ε_2 = produced longitudinal strain by S_2.

Figure 7 is illustrated the impact test, which was carried following ACI 544.2R [35], on a concrete disk, with a diameter of 150 mm and a height of 63.5 mm. A hammer weighing (4.536 kg) was dropping repeatedly from a height (0.4572 m) on an iron ball of 1182 g in the sample center. The test was carried out until each sample of concrete failed. The number of blows was recorded and the amount of the energy absorbed was calculated using Eq. (5);

$$EI = Nmgh \quad (5)$$

Fig. 7 Impact test

where: EI: Impact Energy (N.m). N: Blows number. m: Hammer mass (kg). g: Gravity acceleration (9.81 N/kg). h: Hammer Height (m).

According to RILEM-TC RC 6 [36], as shown in Fig. 8, a cubic sampler with dimensions of (100 × 100 × 100 mm) and a steel bar of φ10 mm were used. The rebar was 550 mm in length, 50 mm outside the cube and 100 mm was cast into the concrete cube. When the sample failure occurs, the maximum load shall be recorded and the bonding stress calculated from Eq. (7).

$$\tau_b = p/d\pi c \quad (7)$$

Fig. 8 Pull out test

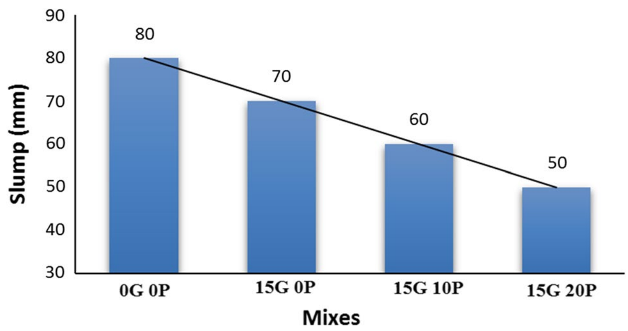

Fig. 9 Slump test for concrete mixes with different plastic content plus 15% glass powder

where; τ_b = Bond stress (MPa). p = maximum load (N). d = Diameter of the bar (mm). c = Length of the attached bond between steel bar and concrete (mm).

Result and discussion

Slump and unite weight of concrete mixes

The slump test revealed that adding plastic aggregate and glass powder to the concrete mixture reduced the slump value by (12.5%, 25%, and 37.5%) for (15G0P, 15G10P, and 15G20P), respectively compared with the reference mixture (0G0P). One can see that slump was reduced linearly, as shown in Fig. 9. The reason behind the reduction in a slump with adding glass powder is because adding material with a higher surface area than cement increased the water dement of water and led to a denser and a stiffer matrix and lower workability as a state by Alyousef et al., Mohammadhosseini et al., and Hsie et al. [10, 17] and [37], respectively. While, the reduction in a slump with replacing sand with plastic aggregate was due to the sharp and irregular edges of plastic waste particles, which increased the friction between particles and caused a reduction in workability. A reduction in a slump was also found by other researchers who also used different types of waste plastic. Jain et al. found that the slump decreased from 81 mm for the control mix to 12 mm for mix with 20% fine plastic aggregate [21]. Hama and Hilal also found a reduction in a slump of concrete mixes after replacing natural aggregate with different types of plastic from a waste compact disk, water drink bottle, and cover of bottles [38].

According to the results, adding plastic changes the density downward, while adding glass changes the density upward, as shown in Fig. 10. The changes in unite weight were (+ 1.22%, − 0.2%, and − 1.83%) for 15G0P, 15G10P, and 15G20P, respectively, compared to the reference mix. Relatively high density with the inclusion of glass powder can be explained by the fact that it's the reaction of glass powder with calcium hydroxide, producing additional gel that led to a reducing amount of voids in the paste matrix [6]. While the reason behind the drop of density can be explained by the lower density of waste plastic compared to sand, resulting in a decrease in density [38]. Other researchers also noticed a reduction in concrete unite weight in case of replaced the natural aggregate with plastic aggregate regardless of its type [16, 23]. Jain et al. found the density of mixes incorporating waste plastic from old bags were 2408.82, 2279.41, 1900.00, 1691.18, and 1455.88 kg/m^3 at 0, 5, 10, 15, and 20% levels of replacement [21]. While the reduction in density 2.20% and 29.06% for 1% and 5% incorporation of waste plastic from old bags, respectively [12]. The average density obtained in this work was about 2440, there is a decrease in density but cannot consider the obtained concrete as lightweight concrete.

Compressive strength

As shown in Fig. 11 for cubic concrete samples, the compressive strength increased by 3.36% with 15% GP compared to control specimens. But with replacing sand with waste plastic, the compressive strength drops by (29.67% and 38.44%) for (10% and 20%) plastic ratios, respectively.

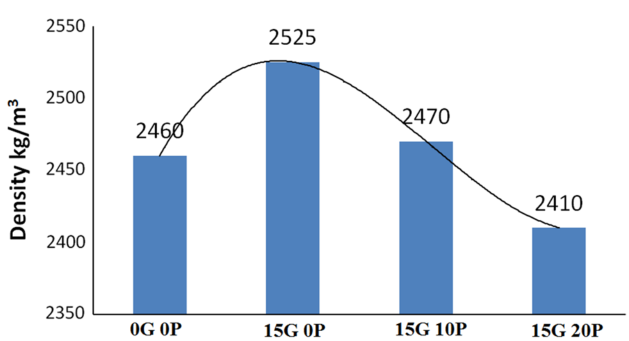

Fig. 10 Concrete density for different mixes

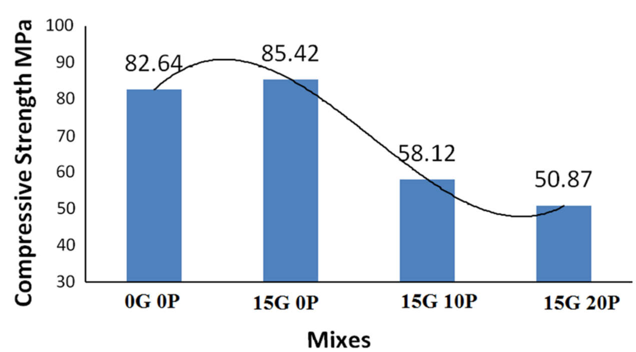

Fig. 11 Compressive strength cubic samples for different mixes

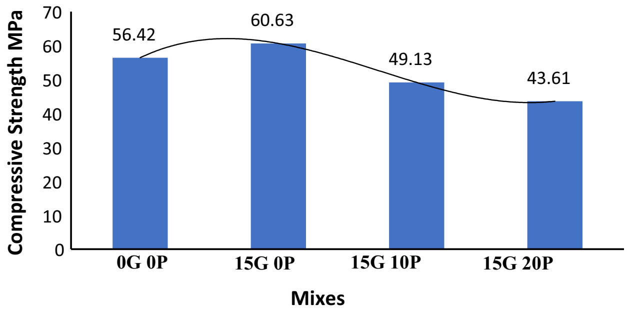

Fig. 12 Compressive strength cylindrical samples for different mixes

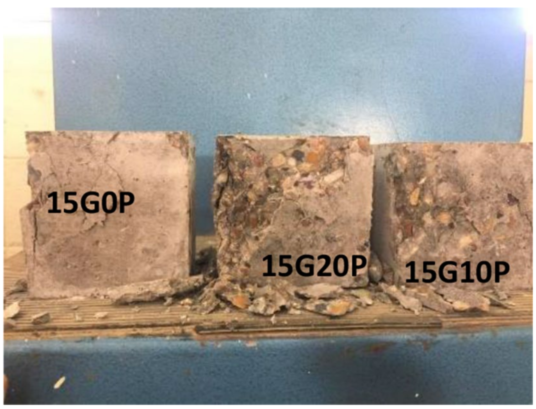

Fig. 13 Failure shape of cubes samples under compressive load

Fig. 14 Failure shape of cylindrical samples under compressive load

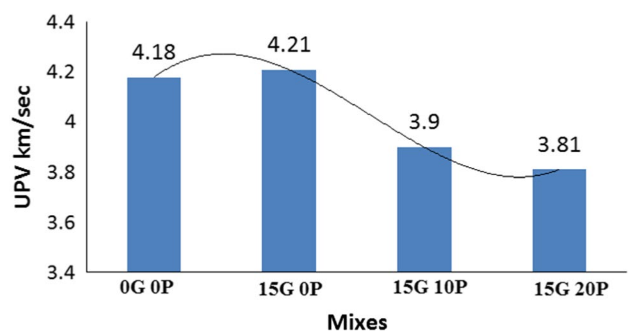

Fig. 15 Ultrasonic pulse velocity for different mixes

For cylindrical samples, the compressive strength increased by a rate of 7.46% for 15% WGP. For specimens 15G10P and 15G20P, the compressive strength decreased by 12.92% and 22.7%, respectively. See Fig. 12.

The reason behind the increasing strength in the case of replaced part of cement with glass powder can be explained as follow; Pozzolanic activity is the ability of pozzolan to react with Ca^{+2} or calcium hydroxide $Ca(OH)_2$ in the existence of water. Pozzolanic response is dependent on the pozzolan properties as chemical composition and the surface area. The glass contains a large quantity of silicon and calcium. Therefore, as soon as it is finely milled to particles sizes smaller than 75 microns, it can be used as a cement replacement in concrete. Cement paste shows pozzolanic properties when substituted with the glass powder at a replacement ratio of 10% and 20%. The formation of C–S–H with consumption of $Ca(OH)_2$ is higher for the (38 microns) glass replaced compare with (75–150 and 38–75) micron because of the activity of fine particle size [39, 40, 43].

And these results are close to that obtained by Yassin et al. [5], Mahmoud et al. [6]. The reduction in compressive strength due to adding plastic aggregate because of weak ITR (Interaction zone) among the surfaces of plastic particles and surrounding cement paste, in addition to the large particle size of plastic compared to sand particles size, which led to formations of pores in the concrete [12, [21]. A similar conclusion was investigated by other researchers who used different types of plastic as aggregate [9, 10, 12–16, 22, 23]. Figures 13 and 14 show shape of failure under compression load for cubes and cylinders samples, respectively.

Ultrasonic pulse velocity (UPV)

The results of the ultrasonic pulse velocity as illustrated in Fig. 15. The test showed an increase in UPV with the addition of 15% WGP to the reference mixture by 3.11% compared to reference specimens. This is because the glass milled led to reducing the voids and cavities in the inner structure of concrete, which led to an increase in density as mention before that made the velocity of waves was higher, and these results were close to that made by Yassin et al. [5]. But with the addition of plastic waste, the speed decreases by increasing the addition ratio as (6.7% and 8.85%) for (10% and 20%) respectively, compared to reference specimens. This is because UPV is affected by the material's unite weight, moisture content, and elasticity [42], and when the pulse is partially transmitted through

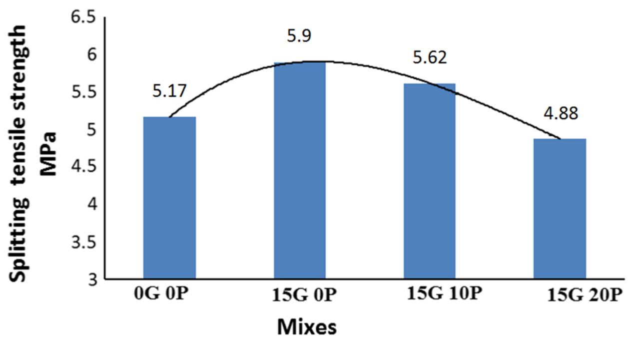

Fig. 16 Splitting tensile strength for different mixes

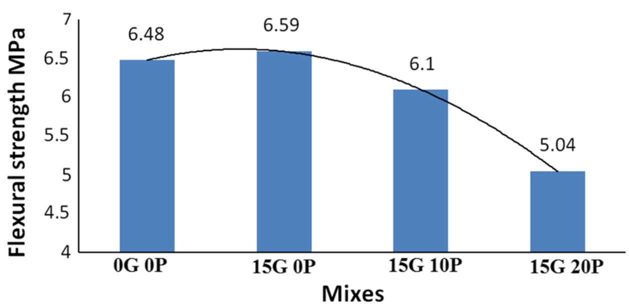

Fig. 17 Flexural strength for different mixes

various materials, the pulse velocity reduces [41] (Figs. 15 and 16).

Splitting and flexural tensile strength

As shown in Fig. 16, the splitting tensile strength increases with replaced cement by 15% WGP by 14.12%. When replacing fine aggregate with 10% plastic, splitting strength increase by 8.7%. But when 20% of plastic replacement, the splitting strength decreased by 5.61%. The results of the flexural strength test are shown in Fig. 17. Flexural strength increased by 1.7% when adding 15% WGP to the reference mixture and decreased by (5.86% and 22.22%) when adding (10% and 20%) of plastic waste, respectively with 15% glass to the mixture.

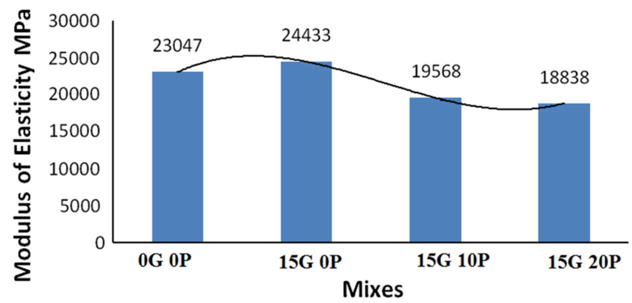

Fig. 19 Static modulus of elasticity for different mixes

The increase in splitting and flexural strengths due to incorporating glass powder is mostly attributed to the same factors that causing an increase in compressive strength [5, 6]. These results are close to those obtained by Yassin et al. [5] and Mahmoud et al. [6]. And also incorporating plastic aggregate into the concrete matrix led to a decrease in splitting and flexural strengths due to weak bonds between the aggregates and paste matrix, and specimens failed by debonding from the cement paste [39]. Figure 18 shows the specimen's failure under splitting and flexural stress. Jain et al. [21] observed a reduction in flexural strength from 3.55 to 0.78 MPa for replacing fine aggregate by 0 to 20% plastic, respectively. Hama also noticed that both flexural and splitting strength of samples decreases by incorporating plastic aggregate [23].

Static modulus of elasticity

The results of the elastic modulus test as in Fig. 19 showed increasing of 6.01% over the reference mixture by adding 15% WGP and decreasing of (15.1% and 18.26%) when adding (10% and 20%) of crushed waste plastic, respectively.

The increase in modulus of elasticity due to replaced cement by glass powder is because the compressive strength of concrete increased, and modulus of elasticity is a function of compressive strength. And this is close to that obtained by Mahmoud et al. [6]. The decrease in modulus of elasticity due to incorporating plastic aggregate was similar to the decrease in compressive strength. And the same behavior

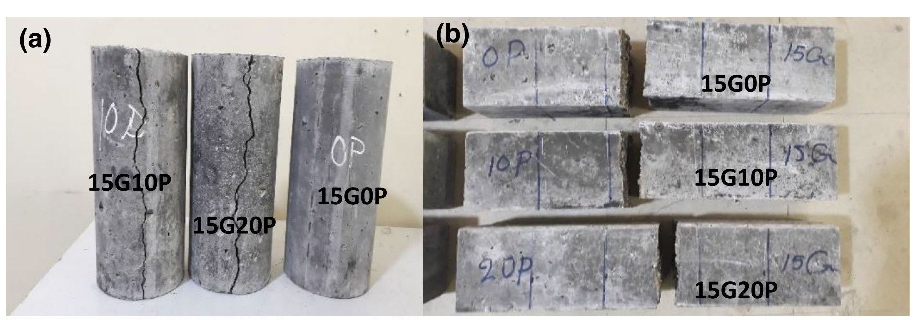

Fig. 18 Failure shape of samples under **a** splitting stress **b** flexural stress

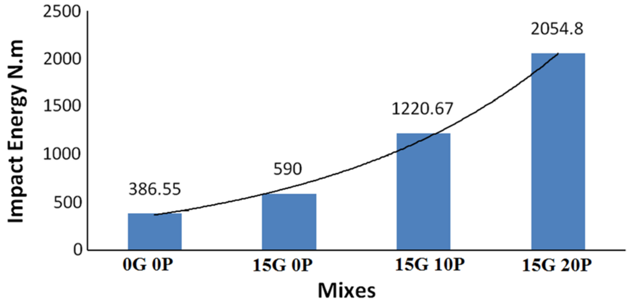

Fig. 20 Impact energy for different mixes

Fig. 21 Specimens failure shape under impact load

Table 6 Number of blows and associated impact energy of impact test

Mix	Number of blows causing the first crack	Number of blows causing the final crack	Impact Energy N.m
0G0P	17	19	386.55
15G0P	26	29	590
115G0P	54	60	1220.67
215G0P	99	101	2054.8

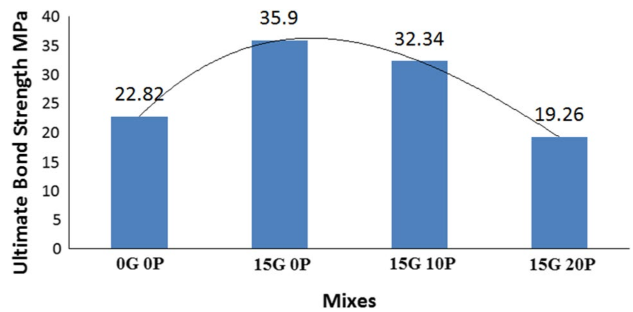

Fig. 22 Ultimate bond strength for different mixes

was noticed by Jain et al. [12, 21], and Saxena et al. [19]. The reason behind the reduction in modulus of elasticity, when sand is replaced by plastic, the low elastic modulus [44], and according to the theory of composite materials, the elastic properties for any composite materials depend mainly on the elastic properties of its constituents and their relative amounts [45].

Impact strength

The results showed, as in Fig. 20, a significant rise in the ability of energy absorption of the concrete samples with replacing cement by WGP, and a higher rise was observed by replacing sand with plastic aggregate. The increase was (52.63%, 215.79%, and 431.57%) for (15G0P, 15G10P, and 15G20P), respectively compared to 0G0P. Table 6 shows the number of blows causing the first and final cracks and corresponding impact strength for different mixes. Figure 21 shows the failure of specimens under the impact force. Replacing cement with glass powder led to an increase in impact resistance and this is similar to that obtained by Ubeid et al. [46]. This is because of the pozzolanic behavior of glass powder, and similar results were obtained by Mohammadhosseini et al. [17, 18], but they used 20% palm oil fuel ash as pozzolanic material. Additional improvement was noticed by replacing sand partially with plastic aggregate and that can be observed by increasing the number of blows needs to case failure. Energy absorption of concrete was noticed to increase as plastic aggregate contain increase due to the high elastic properties and flexibility of plastic compared to natural aggregate, which led to enhancing the ductility of concrete and as results increase the energy absorption ability of specimens. Similar results were obtained by other researchers, who used different types of plastic but all results refereed to improve in impact resistance by adding plastic in concrete[16–18, 20–23].

Bond strength

Figure 22 indicates that the bond strength between concrete and steel reinforcement increases with the addition of glass and decreases with the addition of plastic. This change was (+57.32%, +41.72%, and −15.6%) for (15G0P, 15G10P and 15G0P), respectively. This behavior can be explained by the fact that the glass partials, especially the fine which are smaller than 75 microns, act as pozzolanic material that interacts with sodium hydroxide to form a cement gel (C–S–H), which fills the voids, capillary pores, and transition zones, which increases the strength of cohesion between the concrete and the reinforcement steel bars. These results are similar to those obtained by Ubeid et al. [46].

The reason for reducing the bond strength by incorporating plastic is due to a lack of the chemical reaction between plastic aggregate and the cement paste, the other reason is the smooth surface of the plastic that used in this study, which results in a weak bond between the cement matrix and the steel bar [47]. Another cause is that high quantities of plastic are difficult to cover with concrete paste, causing a decrease in bond strength [16, 34]. And these results are close to that obtained by Hama [16]].

Conclusions

1. Workability and unite weight of specimens containing waste plastic decreased with increase in plastic content due to unregularly shape and low density of plastic compressive, flexural, and splitting strengths of plastic mixtures reduced with the increase in plastic content. This is due to the weaker interface among plastic particles and surrounding paste.
2. Compressive strength drops by (29.67% and 38.44%) for (10% and 20%) plastic ratios, respectively. Splitting strength increase by 8.7%. But for 20% of plastic replacement, the splitting strength decreased by 5.61%. While Flexural strength decreased by (5.86% and 22.22%) for (10% and 20%) of plastic waste, respectively. Improvement in the concrete strengths of the mixture containing waste glass powder was noticed compared to that of control concrete mixes. This is due to the high SiO2 content of glass powder, which made it acts like pozzolanic material.
3. Modulus of elasticity of concrete incorporating fine plastic aggregate decreased with an increase in the plastic content. This is due to the higher deformation capacity of concrete containing plastic aggregate. Modulus of elasticity decreased by (15.1% and 18.26%) for (10% and 20%) plastic ratios, respectively.
4. Significant a rise in the capacity of energy absorption of the concrete samples with replacing cement with glass powder was observed. The additional rise was observed by replacing sand with plastic aggregate. The rising percentages were (52.63%, 215.79%, and 431.57%) for (15G0P, 15G10P, and 15G20P), respectively, compared to 0G0P.
5. The bond strength between concrete and steel reinforcement improved for 15G0P, 15G10P compared with control specimens 0G0P. But it decreased for mix contain 20% plastics.

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