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The Combined Effect of Glass and Plastic Waste on Concrete Properties: Experimental Study

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Abstract

Industrial waste, including glass and plastic, has become widespread in recent years, harming the nature and environment in which we live. Recycling this waste in concrete appears to be one of the best solutions because of its economic and environmental benefits. In this study, the performance of concrete containing plastic waste in the form of fibers and glass waste as a partial replacement for cement was investigated. The effects of both wastes on workability and air content were studied for fresh concrete mixes, as well as their impact on the chloride penetration and carbonation resistance of hardened concrete. The effect of elevated temperature on the compressive strength, weight loss, and ultrasonic pulse velocity of the different mixes was also tested. The results showed that the combination of two wastes in the same mixture contributed to an improvement in the resistance to chloride penetration by 20.5% in the long term. The addition of glass powder to concrete increases the depth of carbonation, whereas the inclusion of plastic fibers reduces the depth of carbonation.

Keywords

glass waste, plastic waste, concrete, chloride, carbonation

1 Introduction

Concrete is widely used as a building material in the construction industry due to the affordability and availability of its main constituents, including aggregates, water, and Portland cement (PC) [1].

Plastics are one of the most important innovations of the 20th century. In the last few years, there has been a substantial increase in the consumption of plastics worldwide, which has also led to a strong growth in the production of plastic-based waste [2].

The classification of plastics present in municipal solid waste includes polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene/linear low-density polyethylene (LDPE/LLDPE), polylactic acid (PLA), polypropylene (PP), polystyrene (PS), and other resins [3].

Plastics have become an indispensable part of our lives; therefore, the only sustainable solution to reducing plastic pollution is to maximize recycling and reuse. There are many sectors in which plastic waste can be used or recycled for further applications in construction materials, such as concrete [4]. Many researchers have investigated the addition of fibers from waste plastics to concrete. Ghernouti et al. [5] examined the fresh and hardened properties of self-compacting concrete containing fibers from waste plastic bags. Their results showed that the incorporation of plastic fibers had no significant effect on the compressive and flexural strengths, but it had a positive effect on the split tensile strength value at 28 days.

Pesic et al. [6] studied the effect of incorporating high-density polyethylene extruded fibers (HFPE) into concrete. They concluded that water permeability and plastic shrinkage cracking decreased in concrete containing HFPE fibers, indicating that this concrete was more durable than conventional concrete.

Bhogayata and Arora [7] conducted an experimental study on the impact resistance and durability properties of concrete reinforced with post-consumer metalized plastic waste (MPW) generated from discarded food

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packaging plastics. They found that the optimum percentage of fibers from the metalized plastic waste is 1% by volume. Mohammadhosseini et al. [8] examined the effect of high temperatures on the properties of durable concrete composites incorporating metalized waste plastic fibers. They found that samples containing 0.5% WMP fibers exhibited a loss of compressive strength compared with the control samples at 800 °C.

Özasic and Eren [9] evaluated the mechanical properties of concrete reinforced with recycled polyethylene terephthalate fibers (RPFRC) at different proportions (0.5%, 1.0%, 1.5%, and 2.0%) by volume of concrete. They concluded that the addition of PET fibers improved the resistance of concrete to plastic shrinkage cracking up to 1 volume fraction of 1.5%.

Mohammed and Karim [10] studied the impact resistance and mechanical properties of high-strength concrete containing PET fiber waste. Plastic fibers of different lengths (10, 20, and 40 mm) were incorporated into the concrete at rates of 0.50, 0.75, 1.00, 1.25, and 1.50% (by volume). They observed a slight reduction in the speed of the ultrasonic pulses; however, the addition of 10 mm, 20 mm, and 40 mm PET fibers decreased the compressive strength by a maximum of 15.74%, 14.37%, and 10.28%, respectively, compared with the control concrete. Hama et al. [11] studied the behavior of concrete incorporating ring-shaped waste plastic fibers under different loading conditions. They concluded that under bending load, the modulus of rupture gave the best behavior in samples containing 0.5% waste ring plastic fibers.

Glass is one of the oldest human-made materials. It is available in a variety of forms, including container glass, flat glass, and bulb glass, all of which have a limited life span and must be recycled or reused to avoid environmental problems that could arise if stacked or loaded [12]. In general, glass is a transparent material obtained by melting a combination of materials such as silica, soda ash, and calcium carbonate at high temperatures, followed by cooling, during which solidification occurs without crystallization [13].

Glass comprises up to 70% amorphous silica. When finely ground, glass exhibits pozzolanic properties that are beneficial for use as a cement replacement material [14].

Several researchers have studied the mechanical properties and durability of concrete containing glass powder as a partial replacement for cement.

Kamali and Qahramanizade [15] concluded that glass powder concrete improved chloride permeability and that the decrease in chloride permeability increased with an increase in glass powder replacement levels from 5% to 20%. Aliabdo et al. [16] concluded that the use of glass powder as a partial replacement for cement with a particle size of less than 75 μm up to 15% improved the properties of concrete. However, the use of glass powder as a cement additive improved the compressive strength by 4.7%, 14.6%, and 16.8% for concrete modified with 5.0%, 10.0%, and 15.0% glass powder, respectively, compared to the control mix. Kalakada et al. [17] examined the mechanical properties and durability of concrete by replacing cement with glass powder. The results showed that 30% was the ideal replacement level for better workability and high resistance to chloride-ion penetration compared to the control mix.

Elaqra et al. [18] showed that the compressive strength increased in mixes containing 10% and 20% glass powder as a partial replacement of cement after 90 days. This may be due to the pozzolanic reaction that affects the interfacial transition zone between the cement paste and aggregates, and the pores are more refined. Ibrahim [19] examined the feasibility and impact of using waste glass powder (WGP) as a partial replacement for cement in concrete. The replacement rates of the WGP with cement weight were 0%, 5%, 10%, 15%, and 20%. It was concluded that the workability increased with increasing WGP content for all types of concrete. This performance can be attributed to the smooth surface and low water absorption of the WGP, which increases the fluidity of the mixes.

Zeybek et al. [20] examined the effect of replacing cement with waste glass on the mechanical properties of concrete with a grain size between 0.1 mm and 0.2 mm. They found that substituting 20% WGP with cement was the optimal dose.

Jalalinejad et al. [21] found that self-placing concrete containing 22.5% glass powder had the greatest increase in compressive, tensile, and flexural strength (16.99, 23.53 and 17.65%, respectively).

Muhedin and Ibrahim [22] concluded that the sustainability of concrete increased considerably by replacing up to 15% of the cement with glass waste without any negative effect on the compressive strength of the concrete.

According to the bibliographical research on plastic waste and glass, we selected glass waste as a partial replacement for cement with a percentage of 15% and a particle size of less than 75 m, and plastic waste as a fiber incorporated in total volume by 1% and an aspect ratio AR = 2.5. This work aims to conduct an experimental study on the effect of combining glass and plastic waste on the properties of concrete containing plastic waste in the form of fibers and glass waste in the form of glass powder as a partial replacement for cement. In addition, it contributes to sustainable development by eliminating

environmental waste and to sustainable construction practices by reducing greenhouse gas emissions, extracting natural resources, and improving the energy performance and aesthetic properties of buildings built with this type of concrete.

2 Experimental programs

2.1 Materials

The cement used in this study was CEM I 42.5 R with a specific gravity of 3.12 g/cm^3. The physical properties and chemical composition of the cement are listed in Table 1 and 2, respectively. Two types of gravel with sizes of (4–8 mm) and (6–12 mm) with unit weights of 2.46 g/cm^3 and 2.61 g/cm^3, respectively, were used in this study. Sand was used with particles ranging from (0–4 mm) with a unit weight of 2.56 g/cm^3 and a fineness modulus of 3.26.

The fibers of the plastic waste used in this research were high-strength PET polyester, which is used in the form of packaging tape in the industry with AR = 2.5 (with a length of 150 mm and a width of 60 mm). These fibers were introduced into concrete with a volume fraction of 1%.

Glass powder from green alcohol bottles was ground after washing with a ball mill, sieved to a fineness of less than 75 µm, and added as a partial replacement of cement at a percentage of 15%. The specific gravity of the glass powder was 2.59 g/cm^3, and its chemical composition is listed in Table 2. According to ASTM C618 [23], the sum of (SiO_2 + Al_2O_3 + Fe_2O_3) is higher than the minimum requirement of 70% for pozzolanic materials.

Fig. 1 shows the X-ray diffraction (XRD) of the glass powder and illustrates the amorphous nature of the glass without crystalline peaks, with a large peak at 25° (2), representing amorphous silica.

Table 1 Physical characteristics of cement.

Physical properties	Value
Specific gravity (g.cm^{-3})	3.12
Initial setting time (min)	166
Final setting time (min)	240
Sieve Residue (%) 45 µm	3.1
Water demand (%)	28.4
	3889
Surface spécifique de Blain (cm^{-2}.g)	1
Expansion (mm)	

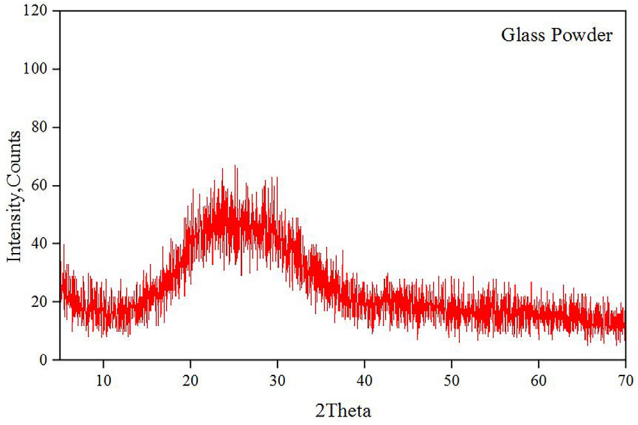

Fig. 1 XRD for glass waste

2.2 Mix proportion

Four types of concrete with a water-to-cement ratio of 0.49 were prepared in this study. The first mix contained plastic waste in the form of fibers with a volume fraction of 1% (CP), and the second mix contained glass powder as a partial replacement for cement at a percentage of 15% (CG). Plastic and glass wastes were combined in the third mixture using the same method as in the previous mixtures (CM). In addition, a mixture without waste was used as the control concrete (CR). Samples were prepared using the Faury method [24] and cured in water at 20 ± 1 °C in a tank for 14, 28, and 90 days. The compositions of the different mixes are listed in Table 3.

Table 3 Composition of concrete mixes

Materials kg/m^3	CR	CG	CP	CM
Cement	400	340	400	340
Water	197	197	197	197
Sand (0–4 mm)	872	872	872	872
Gravel (4–8 mm)	189	189	189	189
Gravel (6–12mm)	627	627	627	627
Volume contents of plastic waste fiber *V pwf* (%)	/	/	1	1
Glass waste	/	60	/	60
Superplasticizer	8 8	8	8	8

Table 2 Chemical composition of cement and waste glass

	Chemical compound								
Materials	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	Na_2O (%)	K_2O (%)	LOI (%)
Cement	20.26	4.41	3.09	62.78	2.09	3.00	0.26	0.88	2.86
Waste glass	70.90	1.93	0.40	13.30	0.18	0.06	12.40	0.33	0.50

2.3 Test method

2.3.1 Workability and Air content of concrete

The workability of the fresh concrete mixtures was assessed using the slump cone test following EN 12350-2 [25]. The air content was determined according to the standard EN 12350-7 [26].

2.3.2 Chloride penetration in concrete

The chloride diffusion coefficient was determined on cylinders 100 mm × 200 mm in length according to LNEC E 463 [27] at 28 and 90 days of curing.

This test was performed on 50 mm high samples obtained from 100 × 200 mm^2 cylindrical specimens after curing in water for 28 days. The specimens were placed in a vacuum chamber and subjected to a dry vacuum for 3 h at a pressure of less than 5 kPa. Under vacuum, a saturated solution of Ca $(OH)_2$ (prepared by dissolving excess calcium hydroxide in distilled water) was poured into the vessel to immerse all samples.

The vacuum was maintained for an additional hour before air could enter the vessel, and the samples were kept in the solution for 18 ± 2 h. Two solutions were prepared: a cathodic solution containing 1667 g NaCl in 15 liters of water (100 g NaCl + 900 g H_2O) and a cathodic solution containing 24 g NaOH in 2 liters of water (12 g NaOH + 1000 g H_2O). The plastic container was filled with the cathodic solution, and a rubber sleeve was placed in the specimen, as shown in Fig. 2 and secured with two stainless-steel clamps.

Each sample was filled with 300 ml of the anode solution using a sleeve. The anode was immersed in the anode solution, and the cathode was connected to the negative pole of the electrical sample and the anode to the positive pole.

The electric current was connected to a voltage of 30 V, and the recording and initial current intensities flowing through each test sample were recorded. The initial temperature was recorded for each anode solution, and the appropriate test duration was selected based on the initial current intensity. The final current intensity and temperature were recorded before the completion of the test.

After the sleeve samples were removed, the specimens were cleaned with tap water and cut into two sections by diametral compression. The newly separated section was sprayed with a 0.1 M $AgNO_3$ solution, as shown in Fig. 2. When the white silver chloride precipitate was visible on the separated surface, the penetration depth was measured every 10 mm for up to seven depths.

Fig. 2 Image of sample preparation for chloride penetration resistance test

2.3.3 Effect of high temperature on concrete mixes

Cubes of 100 × 100 × 100 mm^3 were cast for the four types of mixes and hardened in water for 28 days. Some samples were air-dried in the laboratory for six days and in an oven at 105 °C for 24 hours [28]. The samples were then placed in an oven at 200 °C and 400 °C. The temperature was increased by 13 °C/min, and the cubes were maintained at the maximum temperature for 2 h. To avoid thermal shock, the samples were cooled in a furnace, as shown in Fig. 3. The samples were stored at 20 °C for 24 hours before testing. Ultrasonic pulse velocity (UPV), compressive strength, and weight loss tests were conducted, and some specimens were tested at a normal temperature of 25 °C. The compressive strength was determined according to EN 12390-3 [29], and the ultrasonic pulse velocity of cubic samples of different mixtures was measured before testing the compressive strength as per EN 12504-4 [30].

Fig. 3 Concrete samples in the electric oven

2.3.4 Carbonatation resistance

Carbonation tests were performed according to the European standard EN 12390-12 [31].

The 100 × 100 × 400 mm^3 prisms were cast and cured for 28 days. After conditioning the prisms in a laboratory air environment for 14 days and sealing all but two longitudinal faces with paraffin wax, the prisms were placed in a storage chamber with a carbon dioxide level of (4.0 ± 0.5)%, temperature (20 ± 2) °C, and relative humidity (55 ± 5)% for 70 and 85 days. After each exposure period, a 50 mm slice was broken from each prism and sprayed with phenolphthalein to determine the carbonation depth, as shown in Fig. 4.

3 Results and discussion

3.1 Fresh property

3.1.1 Slump

The slump values of the concrete mixes are shown in Fig. 5, and the W/C ratio for all mixtures was 0.49.

Fig. 4 Spray samples with phenolphthalein to determine carbonation depth

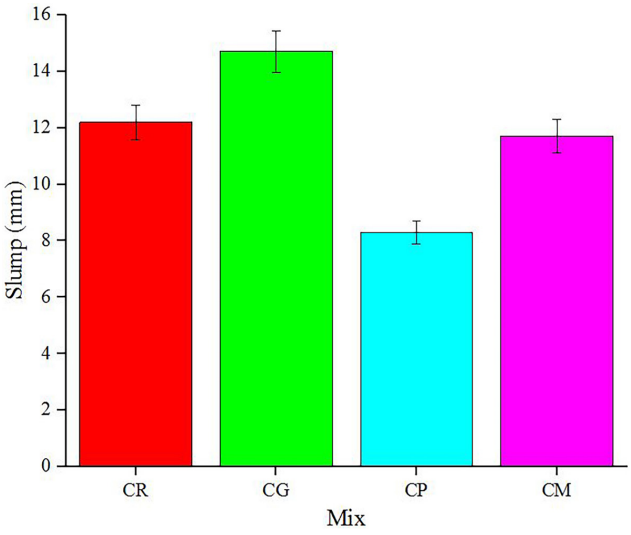

Fig. 5 The slump value in the different concrete mixes

The results indicated an increase in the slump value of the CG mix. This may be due to the presence of more water in this mix because of the low water absorption of the glass powder. A decrease in the slump in the CP mixture was observed, which was attributed to the presence of PET fibers in the concrete, which caused greater friction between the particles [32].

In the CM mix, a slight decrease was observed, which can be explained by the effective effect of the glass powder compared with the plastic fibers in this mix.

3.1.2 Air content

The air content results for the different concrete mixes are shown in Fig. 6. The air content of the reference mixture was 1.3%. This value increased to 1.4% for the CP mixture. This is related to the reduction in compaction owing to the presence of fibers that make the fresh concrete harder and therefore present more voids in the mix [33]. The decrease in air content in both CG mixes was due to the presence of glass powder, which filled the voids between the particles, thus reducing porosity.

The air content of the CM mixture was lower than that of the PF mixture. This is because of the more effective effect of the glass powder compared with that of the plastic fibers in this mixture, which leads to a reduction in pores.

3.2 Hardened property

3.2.1 Chloride penetration

The penetration of chloride ions into reinforced concrete is one of the causes of the corrosion of reinforcing steel. There are three main mechanisms through which chloride ions penetrate a concrete mass: hydrostatic pressure, diffusion, and

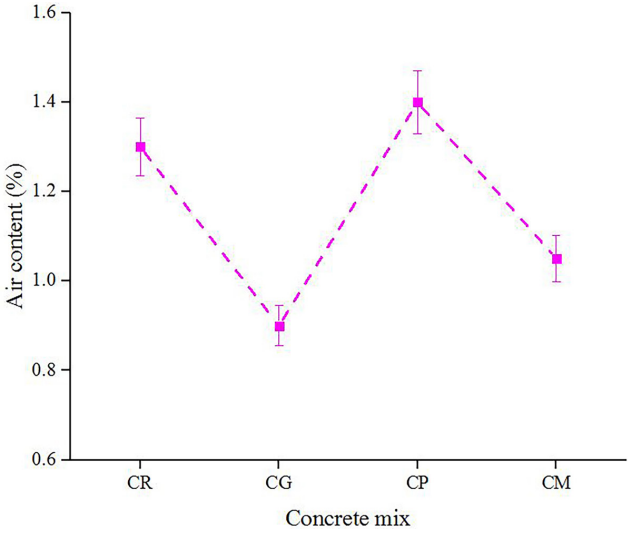

Fig. 6 The air content of concrete mixes

capillary absorption. Two elements are required for the diffusion of chloride ions in concrete: an ionic concentration gradient and a continuous interstitial fluid medium [34].

Fig. 7 shows the results of the determination of the chloride diffusion coefficient by migration after 28 and 90 days of curing. The chloride diffusivity values were greater than 15×10^{-12} (m^2 s^{-1}) at 28 days, indicating that the resistance to chloride penetration of different concrete mixtures was low, as shown in Table 4 [35].

At 90 days, these values were between $(10 – 15) \times 10^{-12}$ (m^2 s^{-1}), which indicates that the resistance was moderate and that there was an improvement in the resistance of different mixtures to chloride penetration. There was an increase in the chloride diffusivity in the CG mixture at 28 days, and this value was reduced after 90 days of hardening. This was due to the reduction in pores and the denser microstructure resulting from the pozzolanic reaction of the glass powder [36]. The chloride diffusivity decreased in the CP mixture compared with that in the control mixture at 28 and 90 days. This can be explained by the reduced internal conductivity of the pores, lower capillary porosity, and improved fiber dispersion [37].

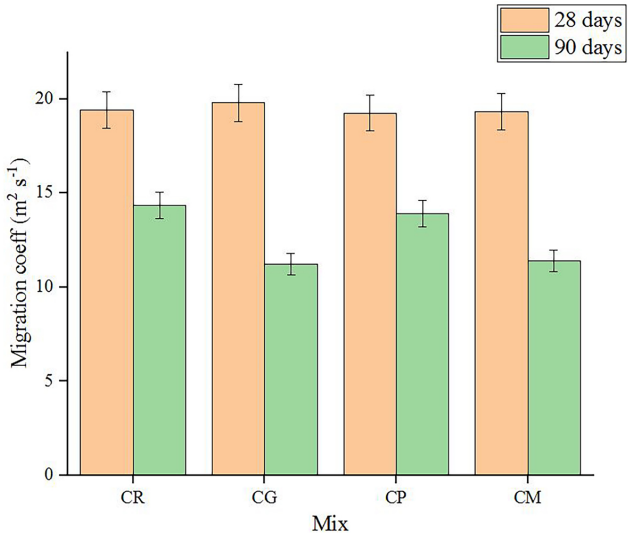

Fig. 7 Chloride diffusivity in different concrete mixes at 28 and 90 days of curing

Table 4 Chloride penetration resistance of different types of concrete based on 28-day diffusivity

Chloride diffusivity $D_{28} \times 10^{-12}$ m^2 s^{-1}	Resistance to chloride penetration
> 15	Low
10–15	Moderate
5–10	High
2.5–5	Very high
< 2.5	Extremely high

The decrease in the chloride migration coefficient of the CM mixture at both curing ages was related to the combined effect of the glass powder and plastic fibers in this mixture, resulting in a decrease in porosity and filling microscopic cracks.

3.2.2 Effect of high temperature on compressive strength

The main effects of elevated temperatures on concrete include dehydration of the cement paste, thermal expansion, strength reduction, increased porosity, thermal creep, thermal spalling caused by excessive pore pressure, and changes in water content and pore pressure [38].

Fig. 8 shows the effect of high temperature on the compressive strength of the concrete mixtures. At 25 °C, the strength of the CG mix decreased by 15.51% compared with that of the reference mix. This may be due to the slow pozzolanic reaction at room temperature; therefore, a long curing period is required to observe its positive effects [39]. The 14.27% decrease in strength observed in the CP mixes can be attributed to the formation of air voids within the matrix due to the incorporation of plastic fibers [40].

At temperatures of 200 °C and 400 °C, the compressive strength of the CG mix reached 92.69% and 99.12% of the strength exhibited by the control mix, respectively. This occurred because the inclusion of CG mitigated the decrease in compressive strength induced by the thermal decomposition of $Ca(OH)_2$, whereas GP enhanced volcanic ash activity, facilitating its reaction with $Ca(OH)_2$ to produce additional CSH gels [41]. In contrast, the strength decreased by 6.65% and 18.87% at 200 °C and 400 °C, respectively, in the CP mix compared with that in the

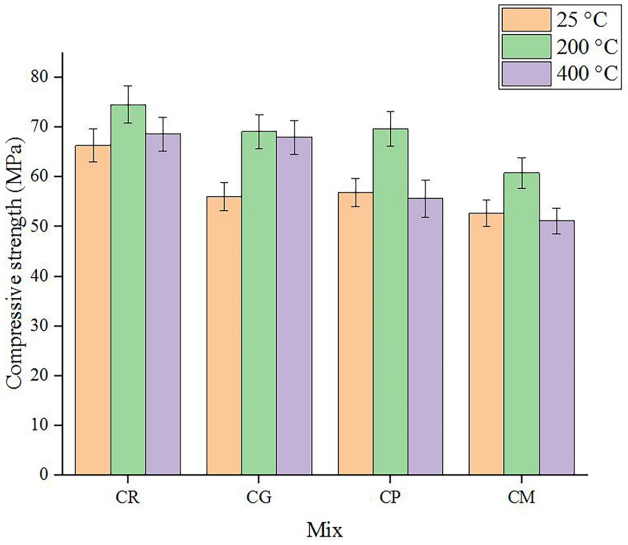

Fig. 8 Effect of high temperature on the compressive strength of concrete mixes

control mix. This is attributed to the decrease in bonding between the plastic fibers and cement paste, which causes cracking [42]. The combination of the two wastes in the CM mixture led to a decrease in the strength at all temperatures. This indicates that the plastic fibers were more effective than the glass powder, resulting in crack formation between the concrete elements.

3.2.3 Mass loss of concrete related to temperature

The weight loss results for mixtures exposed to high temperatures are shown in Fig. 9. Maximum weight loss of 4.35% and 4.48% were observed in the CP and CM mixtures at 400 °C, respectively. A minimum loss was observed in the GC mixture at 200 °C by 1.67%. This is related to the loss of free water from the capillary pores and the dehydration of CSH [43]. At 400 °C, the mass loss increased by 4.35% in the GC mixture. This was due to the maximum evaporation of water at this temperature [44].

The weight losses of the CP and CM mixtures at 200 °C were 2.02% and 1.97%, respectively. The weight loss after exposure to high temperatures was explained by the differences in the physical and mechanical properties of the materials constituting the concrete mixtures [45].

3.2.4 Effect of high temperature on UPV

The results for all mixtures of ultrasonic pulse velocity at different temperatures are shown in Fig. 10. The UPV values were higher than 4.575 km/s at ambient temperature, which indicates that the quality of the concrete was excellent, as shown in Table 5 [46]. This indicates superior concrete performance in terms of density, homogeneity, and reduced crack and pore formation. The decrease in UPV for all mixes was noticeable with an increase in temperature. The pulse velocity increased in the CM mixture at ambient temperature because of the effective effect of combining the two wastes on reducing crack propagation and porosity in the same mix.

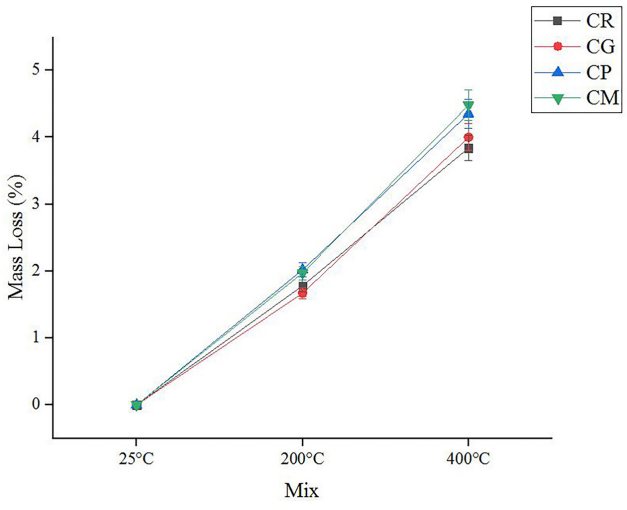

Fig. 9 Loss of weight of concrete mixtures exposed to temperatures

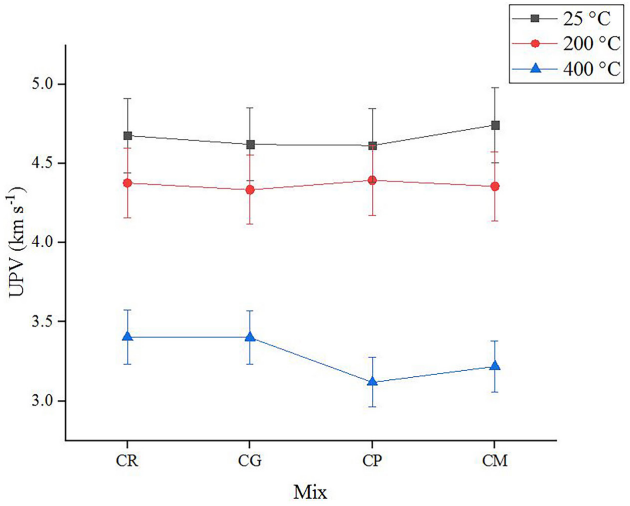

Fig. 10 Variation in pulse velocity in concrete mixes at 25 °C, 200 °C and 400 °C

Table 5 Concrete classification based on ultrasonic pulse velocity

Pulse velocity (m/s)	Concrete classification
V > 4575	Excellent
4575 > V > 3660	Good
3660 > V > 3050	Questionable
3050 > V > 2135	Poor
V < 2135	Very poor

The UPV values at 200 °C were between 4.33 and 4.40 km/s, which can be classified as good-quality concrete for all mixes. At this temperature, an increase of 1.31 was obtained in the CP mixes compared with the control mix. At 400 °C, the UPV values were between 3.12 and 3.40 km/s, indicating that the class of concrete was questionable. Similarity in UPV was observed in the CG and CR mixes at 200 °C and 400 °C. This indicates that the glass powder had no significant effect on the UPV at these two temperatures. At 400 °C, UPV values decreased by 8.4% and 5.46% in the CP and CM mixtures, respectively. This could be due to the melting of the fibers, which created a porous network with the molten fiber layer. Theoretically, this could also be the result of deterioration of the matrix microstructure [47].

3.2.5 Carbonatation

The results of the carbonation depth and carbonation coefficient are shown in Fig. 11 and 12, respectively. An increase in the carbonation depth was observed in the GC mixture at 70 and 85 days. This was due to the reduction of portlandite CH in this mixture, which reacted with silica to form

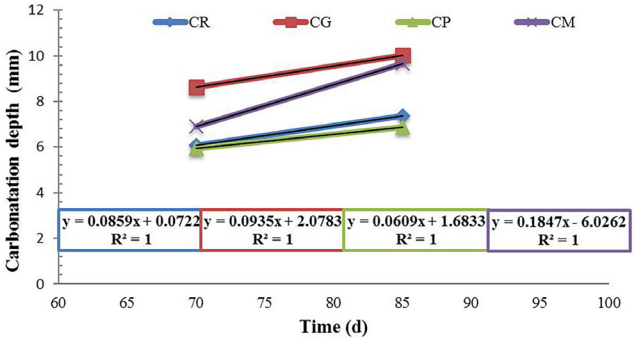

Fig. 11 Carbonation depth as a function of time in different concrete mixes

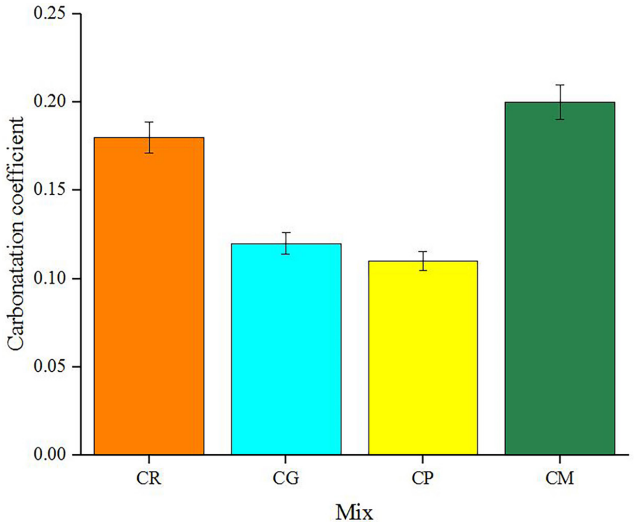

Fig. 12 Carbonation coefficient in concrete mixes

calcite, and may be due to carbonation of the sodium oxide present in large quantities in the glass, which becomes soda carbonate or bicarbonate through CO_2 fixation [48, 49]. The depth of carbonation was reduced in the CP mix compared with that in the control concrete. This may be related to the plastic fibers that minimize carbon penetration. The increase in carbonation depth in the CM mix is evidence of the effective effect of the glass powder compared with the plastic fibers in this mix. The carbonation coefficient of the concrete was observed to increase in the CM mix compared with that in the control mix. However, the coefficient decreased for the CG and CP mixes.

4 Conclusions

This study investigated the effect of combining plastic and glass waste to improve the performance of concrete. This makes it possible to contribute to sustainable development by eliminating industrial waste dispersed in the environment and reducing concrete costs in future studies.

1. The addition of glass powder to concrete as a partial replacement for cement increased the slump of fresh concrete. However, the slump was reduced in the concrete with the incorporation of fibers from plastic waste.
2. Glass powder decreased the air content in concrete because of the closing of the pores between the particles, and concrete containing plastic fibers increased the air content because of the voids created by these fibers in the concrete.
3. The addition of glass powder and plastic waste fibers to concrete significantly improved the resistance to chloride penetration at an advanced age.
4. The addition of glass powder to the concrete achieved 92.69% and 99.12% of the compressive strength of the control mix at 200 °C and 400 °C, respectively.
5. Minimum weight loss was observed in the mixture containing only glass powder at 200 °C.
6. Excellent quality concrete with UPV values above 4.575 km/s was found at room temperature, and the UPV values in all mixes were reduced.
7. The use of plastic and glass wastes in concrete is important and desirable because of their environmental and possible economic benefits due to the replacement of cement with waste glass powder.
8. For future research, it is suggested to use glass and plastic wastes with different proportions and particle sizes or dimensions and to check their effect on the improvement of filling and durability properties or concrete performance. In addition, an economic study should be conducted on this type of concrete to establish the exact cost.

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