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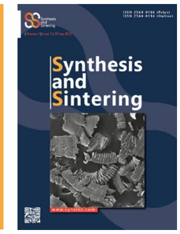

Research article

Effect of glass waste as a cement replacement on the mechanical properties of concrete

Sara Ahmadi

Construction and Minerals Research Group, Technology and Engineering Research Center, Standard Research Institute, Karaj, Alborz, Iran

ABSTRACT

Every day several tons of glass are disposed of as waste. Glass waste, as a non-degradable waste, causes many environmental problems. Using glass waste powder in concrete as a partial substitute for cement has notable effects on reducing environmental pollutants, energy consumption, and concrete production costs. In this study, the impact of using waste glass powder in levels of 5, 10, 15, and 20 wt% as a substitute for cement on the mechanical properties of concrete was evaluated. Chemical analysis of glass and cement samples was determined using X-ray fluorescence (XRF). The flexural and compressive strength of the samples were measured according to ISO 679, Methods of testing cement–Determination of strength, in 3, 7, 28, and 90 days. The compressive strength test results showed that the strength of concrete increases by the amount of used glass powder in the concrete composition. The highest value of compressive strength was obtained by the sample with 15 wt% of glass powder.

KEYWORDS

C–S–H gel synthesis
Green concrete
Glass waste
Mechanical properties

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1. Introduction

Concrete made from Portland cement (PC) is the most extensively used material in the world. Cement production in the whole world is one of the factors of pollution and the introduction of greenhouse gases. Carbon dioxide gas emission in the Portland cement industry is considered a critical environmental issue [1, 2]. About 3% of greenhouse gases in the world are generated from the cement industry. It is estimated about 522 million tons in 2016. Between 1930 and 2013, cumulatively, about 43% of the CO_2 gas emission was caused by the cement industry [3, 4]. The production of one ton of Portland cement causes about 0.8 to 1 ton of CO_2 gas emission into the atmosphere [5, 6]. In addition, this industry is highly energy-consuming. On the other hand, worldwide cement production is increasing due to the increasing demand for PC [5, 7]. Considering the awareness of the need for environmental protection, the conversion of waste materials or by-products into concrete constituents has attracted increasing attention [8].

Using substitute materials to replace the cement in concrete is a promising way to reduce the environmental impact of the cement industry. So far, several industrial by-products have been successfully used, including silica foam (SF), blast furnace slag (GGBS), and fly ash. These materials are used to create composite cement that can improve concrete durability, efficacy, initial and long-term strength, and decrease production costs [9–12].

Another material that has the potential to be used in concrete as a substitute for cement, but has not yet achieved commercial success, is waste glass. Only a part of the glass waste is reused in the production of new glass, and the rest of it cannot be used in glass production due to impurities or its color and is discarded as waste. In this regard, given the ungradability of glass, disposing of them as waste has environmental impacts and entails a lot of costs [10]. In 2010, the estimated production of waste glass was 425,000 tons, of which only 192,000 tons were recycled [13].

The use of waste glass in concrete production is economically and environmentally beneficial. Glass has an amorphous structure and

* Corresponding author. *E-mail address:* s.ahmadi@standard.ac.ir (S. Ahmadi)

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contains a large amount of SiO_2 and CaO in the composition. Therefore, glass waste has cementitious properties and can be used as a partial substitution for cement [14, 15]. Studies have been conducted on the potential of ground glass waste powder as a pozzolanic material, showing that the softness and composition of glass waste affect the properties of concrete [16]. Pozzolans are a broad class of siliceous and aluminous materials that, in themselves, possess little or no cementitious value but in the presence of water, react chemically with calcium hydroxide ($Ca(OH)_2$) at ordinary temperature to form compounds possessing cementitious properties. Furthermore, pozzolanic activity is a measure of the degree of reaction over time or the reaction rate between a pozzolan and Ca^{2+} or calcium hydroxide ($Ca(OH)_2$) in the presence of water. The rate of the pozzolanic reaction is dependent on the intrinsic characteristics of the pozzolan such as the specific surface area, the chemical composition, and the active phase content [17].

Several types of research have been conducted on using glass waste as aggregate in concrete preparation. It has been reported that using waste glass as fine aggregates gives concrete more resistance against chloride penetration [18]. However, considering the strong reaction between alkali in cement and reactive silica in glass, the use of glass in concrete as a part of aggregate has not been satisfactory due to the apparent loss of mechanical properties and excessive expansion [19–22]. It should be noted that the expansion is reported to be negligible in concretes, in which glass waste with particles smaller than 0.3 mm, was used as fine aggregate.

Despite using glass waste as an aggregate replacement in the concrete composition having economic and environmental benefits, substituting partial cement with glass waste powder has more valuable. In a study shown by a group of researchers, glass powder was used as a substitute for cement and as an additive in concrete preparation. The results showed that the setting time did not change with the addition of glass powder. Using glass powder up to 10% by weight increased the compressive strength, tensile strength, and density of concrete samples [23].

In another research, by adding 40 wt% of glass powder and 3 wt% of nano-silica to the concrete mixture, the 28-day compressive and flexural strength increased, and no reaction between silica and alkali was observed. This increase has been more significant in the presence of nano silica [24]. Matos et al. also observed that although soda-lime glass has a high alkali content, using glass waste as a substitute for cement in mortar, the resistance of concrete to alkali-silica reaction, chloride diffusion, and sulfate attack is improved without reducing the strength. Therefore, these waste materials can successfully increase the durability and efficiency of concrete and contribute to sustainability in construction [25]. It has also been reported that increasing the amount of glass powder in concrete affects the properties of fresh and hardened concrete such as workability and density. This issue can be attributed to the decrease in cement in concrete and so less water necessity to hydrate the cement. Mixtures with more glass powder showed low porosity and lower absorption rate [26].

In another study, using glass waste powder with clay nanoparticles, it was observed that the mechanical properties of concrete increased. Clay nanoparticles increase the rate of pozzolanic reaction. It seems that their nano size accelerates the reaction with C–H in cement and thus increases the amount of C–S–H in 28 days. The simultaneous use of clay nanoparticles and glass powder is a suitable method to reduce the amount of cement and achieve maximum efficiency and reduce costs [27].

In a study by Sobolev et al., the effect of glass composition on concrete properties was investigated. The highest compressive strength was obtained by using soda lime glass and the workability of the samples was increased using glass powder. SEM images showed visible condensation around the glass grains due to the partial hydration of the glass particles and the formation of excess C–S–H. According to the SEM investigation, the main difference between the glass-cement pastes and the control Portland cement is related to the decrease in the size and amount of CH, which is caused by the consumption of CH as a result of the pozzolanic reaction due to the use of glass powder [28].

In another research, it was observed that the compressive strength increases with the reduction of glass powder particle size. In this study, evaluation by DSC, XRD, and SEM of a system consisting of 75% waste glass and 25 wt% of $Ca(OH)_2$ mixed with water proves that the hydrolysis of Si–O–Si bonds occurs at high pH and leads to the formation of insoluble calcium silicate and hydrated calcium aluminosilicate. Additionally, XRD confirmed the presence of sodium carbonate hydrate, which is formed from the carbonation of sodium in the glass composition. This issue can explain the resistance to the expansion of prepared mortars, which is generally caused by the reaction of silica and alkali and the formation of hydrated sodium silicate. Finally, SEM observations and EDS confirmed the presence of H–S–C and its increase with curing time [29].

Despite the various research on the effect of using glass waste powder on different properties of concrete, there are no studies in which the samples containing glass powder and the control are prepared and compared in a standard way. In this article, the effect of using glass waste as a substitute for cement on the mechanical properties of concrete has been investigated, and to achieve more reliable results, the process of preparing samples and their evaluation method has been carried out based on international standards, and finally, the obtained results have been compared with the requirements of ASTM C150/C150M: 2019, entitled “Standard Specification for Portland Cement”.

2. Experimental Procedure

2.1. Materials and preparation

Commercial Portland cement type 1-425, complies with the requirements of ASTM C150. The soda-lime glass was used as glass waste. To prepare glass powder, glass waste was crushed in a mill and passed through a 200-mesh sieve (75 μm). The chemical composition

Table 1. Chemical composition of cement and glass powder.

Weight percent	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	TiO_2
Glass waste	72.5	3.1	0.2	6.1	4.3	11.5	2.3	-	> 0.01
Cement	23.1	5.6	3.59	62.1	1.8	0.36	0.68	2.57	-

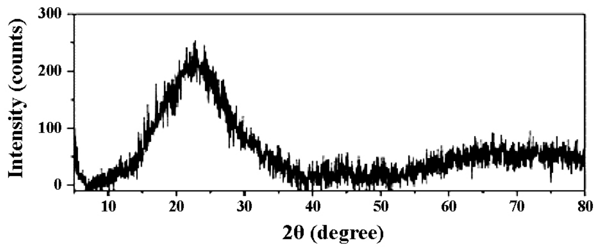

Fig. 1. XRD pattern of glass powder.

of the used cement and glass powder is shown in Table 1. The finesse of cement and glass waste powder is summarized in Table 2.

Concrete samples were prepared with different percentages of glass powder and according to the ISO 679, entitled "Methods of testing cement-Determination of strength". Mix proportion of concrete is shown in Table 3. To prepare concrete samples, standard sand was used according to DIN En196-1. After mixing, the samples were poured into steel molds with dimensions of 160 × 40 × 40 mm. Material within the mold is kept in a moist condition for 24 h at a temperature of 20 ± 2 °C and a humidity of 90%, and then after demolding, the specimens were placed in a curing tank for 3, 7, 28, and 90 days. After a specified period of curing, a strength test of the specimens was conducted shortly after taking those out from storage water.

2.2. Characterization techniques

X-ray fluorescence (XRF, Spectro expos) and X-ray diffraction (Siemens-D500) were used to determine the chemical and phase composition of used cement and glass waste powder, respectively. Flexural and compressive strength of concrete samples were measured with the Toni Technik apparatus.

The finesse of the glass powder and cement used was measured by the Blaine method according to the ASTM C204-07, 2008: Standard Test Methods for Fineness of Hydraulic Cement by Air Permeability Apparatus. The setting time of the samples with different percentages of glass powder was determined according to ASTM C191: 2019, Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle.

Table 2. The specific surface of raw materials measured by Blaine's method.

Raw material	Glass powder	Cement
Blaine (cm^2/g)	4180.32	3310.51

3. Results and discussion

Table 1 shows the chemical composition of cement and glass powder used in the research. Giving to the table, the total weight percentage of SiO_2 + Al_2O_3 + Fe_2O_3 in glass powder is more than 70%. Therefore, according to ASTM C618-02, such composition can be classified as class N natural pozzolan and consequently, probably show pozzolanic properties. However, the chemical composition is not the only criterion for predicting the pozzolanic property, the amorphousness of the material is also required. Fig. 1 displays the X-ray diffraction pattern of the glass powder used in the study, which confirms it is amorphous. As a result, pozzolanic properties can be expected from the used waste glass powder.

Table 2 illustrates the comparison of the specific surface area of glass powder and cement, which was measured by Blaine's method. It can be seen that the finesse of both raw materials has values close to each other.

3.1. Mechanical properties

The flexural and compressive strength of the samples were evaluated at different ages of 3, 7, 28, and 90 days. Glass powder was substituted for cement in amounts of 5, 10, 15, and 20 wt%. Also, a control sample without glass powder was made to compare the results. The mixing details for the prepared mixture are summarized in Table 3.

To evaluate the compressive and flexural strength, three samples with dimensions of 40 × 40 × 160 mm were cast at each age. The flexural strength was obtained from the average of three, and their compressive strength was obtained from the average of six samples. Figs. 2 and 3 show the flexural and compressive strength of the samples vs. curing time, respectively. According to the figures, it can be seen that in all the samples with different weight percent of glass, the flexural and compressive strength of concrete increases regarding the curing time. This issue is related to the progress of hydration reactions and the development of the reaction of calcium silicate phases present in

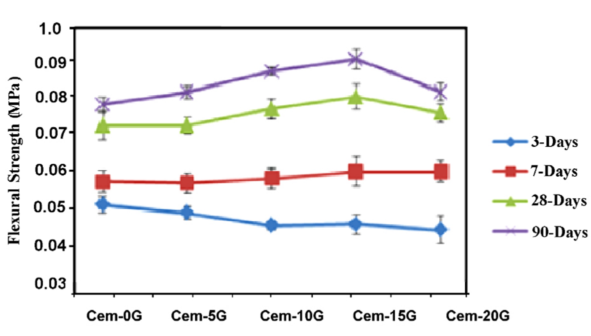

Fig. 2. Flexural strength of concrete prepared with different amounts of glass powder and curing time.

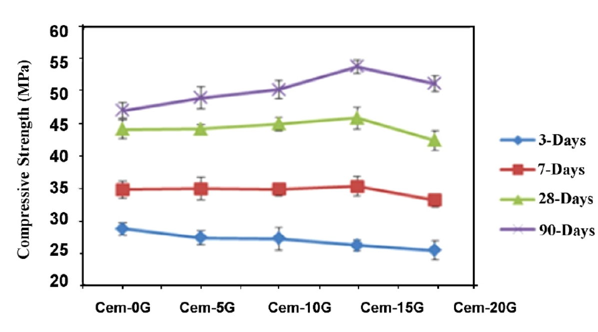

Fig. 3. Compressive strength of concrete prepared with different amounts of glass powder and curing time.

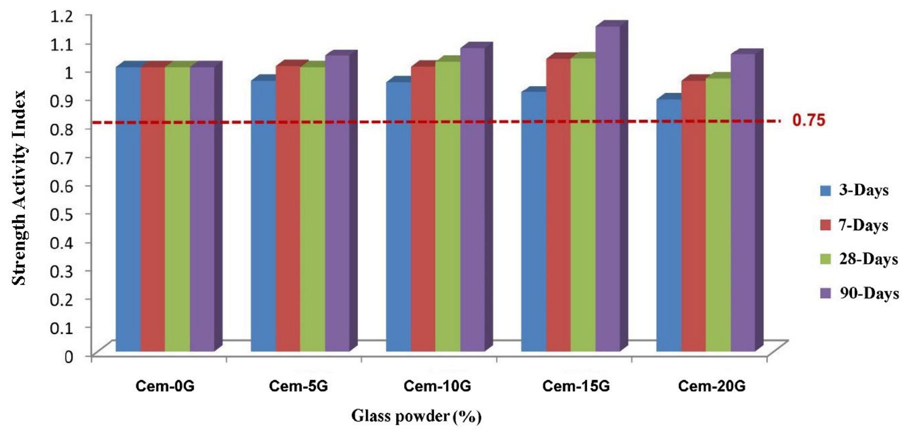

Fig. 4. Strength activity index of samples with different amounts of glass powder.

cement, i.e., C_3S (alite) and C_2S (belite) with water, and so the increase of hydrated calcium silicate phase (CSH) content, which has the most impact on concrete strength.

Also, according to ASTM C150, the 2-day and 28-day compressive strength of Portland cement type 1-425 are at least 10 MPa and 42.5 MPa, respectively. As can be seen in Fig. 3, in all samples with different amounts of glass, the initial and 28-day compressive strength confirmed the standard values, which indicates the success and supportive impact of using glass powder waste as a substitute for cement in concrete.

According to Figs. 2 and 3, it can be seen that the compressive and flexural strength variations of the samples are the same. The flexural and compressive strength of the samples shows a gradual decrease in the first three days with the increase in the amount of glass powder, accordingly the flexural and compressive strength of the sample with different percentages of glass powder is lower than the control sample (with 0% glass). However, by increasing the curing time to 7, 28, and 90 days, the flexural and compressive strength of the prepared concretes increases to 15% by increasing the amount of glass powder and then decreases in the sample with 20% glass powder. This incensement in flexural and compressive strength is more intensive at 90 days. After 90 days of curing, compared to the control sample, the compressive strength of the sample with 15% and 20 wt% glass powder improved by 14.3% and 9%, respectively. In contrast, the 28 days-compressive strength showed a 4% increase in the Cem-15G sample and a decrease in the Cem-20G sample compared to the control sample. According to the figures, it can be supposed that the addition of glass powder as a cement replacement in concrete has an optimal amount, which is determined as 15 wt% of glass for 28 days. This result agrees with the results obtained by other researchers [23–27].

Amorphous silica in glass composition dissolves in an alkaline environment such as OH^-. The ions in the pore solution of cement paste can react with calcium hydroxide (CH) and form hydrated secondary calcium silicate (C–S–H). This process is known as a pozzolanic reaction, which can be expressed as $CH + S + H \rightarrow C{-}S{-}H$. The pozzolanic reaction requires the hydration product of cement, namely CH, whose amount is determined by the cement [30–33]. Therefore, there is an upper limit for replacing cement with glass powder, above which the pozzolanic reaction does not occur, and the glass powder is only a filler between cement and sand particles and does not participate in the reaction. In other words, in the sample with 20% glass powder, the amount of CH that is necessary to activate the glass powder and the progress of the pozzolanic reaction is not sufficient due to the decrease in the amount of cement in the concrete.

Strength activity index at any age was obtained from the following relationship according to ASTM C311:

$$\text{Strength activity index with Portland cement} = (A/B) \times 100 \quad (1)$$

Where A is the average compressive strength of the test mixture and B is the average compressive strength of the control mixture.

This index shows the conformity of the strength values to the control sample. According to the ASTM C618 standard, pozzolan should have a minimum strength activity index of 75% (dashed line in Fig. 4); therefore, glass powder used in this study with sizes of less than 75 µm can be an appropriate pozzolan for Portland cement. This result was also obtained by other researchers [16].

3.2. The setting time

The setting time of concrete is considered the time between the state changes of fresh cement to hard. The setting behavior of concrete determines concrete workability. The subsequent strength and durability of concrete can be significantly influenced by the chemical reactions and microstructure formed during the setting. Therefore, the setting behavior of concrete and cementitious materials is essential in the performance of fresh and hardened concrete. The setting time is the time that starts from the moment of adding water to cement materials and continues until the mixture gets a degree of hardness that is

Table 3. Mixing detail of prepared concrete.

Sample	Cement (g)	Glass powder (g)	Water (g)	Sand (g)
Cem-0G	450	0	225	1350
Cem-5G	427.5	22.5	225	1350
Cem-10G	405	45	225	1350
Cem-15G	382.5	67.5	225	1350
Cem-20G	360	90	225	1350

Table 4. The final setting time of mortars with different percentages of glass content.

Sample	Cem-0G	Cem-5G	Cem-10G	Cem-15G	Cem-20G
Final setting time (min)	204	186	180	173	164

measured by a particular method such as Vicat's needle. In order to reach the initial setting time, a suitable and specific amount of C–S–H is needed to connect the different components of concrete and form a microstructure resistant to the penetration of the Vicat's needle. By progressing hydration and after the initial setting, continuing the hydration of calcium silicate (especially C_3S) produces more C–S–H gel, which increases the hardness of the mixture and finally attainment the final setting. Table 4 summarizes the final setting time measured by the Vicat needle method for the samples.

Between the four main phases of cement, C_3A is more reactive. The C_3A quickly reacts with water and gypsum sulfate ions, which are added to cement clinker during production, and leads to the deposition of ettringite needles (hexacalcium aluminate trisulfate) on cement's grains. Ettringite deposition limits access to more water and, as a result, slows down the hydration process and controls the setting time of cement. With the increase of glass powder and so a reduction of the cement content in the composition, the amount of gypsum in the final mixture is reduced. Finally, less ettringite phase is deposited on the grains, and as a result, the setting is done faster. It can also be said that with the increase in the softness of the cement, the setting time will decrease. By adding glass powder with a higher specific surface in the composition, the total specific surface of the cement and glass powder mixture increases. As a result, considering that the amount of water in all samples is considered constant, the setting time will be less.

4. Conclusions

In this study, the effect of glass powder waste as a substitute for cement on the mechanical properties of concrete was investigated. The results showed that in 28 and 90 days of curing, the amount of 15 wt% of glass powder demonstrates the highest compressive and flexural strength, which can be the optimal percentage of replacement. With the increase of glass powder up to 20%, although the compressive and flexural strength is reduced compared to the sample with 15% glass powder, it is still 9% higher than the strength of the control sample. Also, the value of flexural and compressive strength in all samples with different amounts of glass powder complies with the requirement of ASTM C150. Therefore, glass powder with a particle size less of than 75 µm used in this study can be a suitable pozzolan for Portland cement. Furthermore, the results showed that the setting time of concrete decreases with the increase in the amount of glass powder.

CRediT authorship contribution statement

Sara Ahmadi: Conceptualization, Methodology, Project administration, Formal Analysis, Writing – original draft, Writing – review & editing.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

The author declares no competing interests.

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