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Effect of using glass powder as cement replacement on rheological and mechanical properties of cement paste

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HIGHLIGHTS

- Glass powders improved the formation of CSH than CH at late ages.
- Glass powders improved the compressive strength of cement paste at late ages.
- Glass powders were effective in suppressing ASR expansions in cement paste.

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ABSTRACT

Glass powder (GP) is considered as a pozzolanic material, thus it can be used as a partial cement replacement material. Its effect on the microstructure and on the mechanical properties is controlled by its chemical composition, particle size distribution (PSD), the amount of replacement and the curing conditions. The effect of cement replacement by glass powder on the rheological and the mechanical properties of cement paste is studied. Two types of cements were used (CEMI and CEMII) at five different percentages of glass powder replacement (0, 10, 20, 25 and 30%). The results showed an increase in the cement paste flow using CEMI compared to CEMII. Also, the initial and final setting times were lower at CEMI than CEMII. Increasing the replacement percentages by higher glass powder resulted in a decrease in the linear and volume expansion of the mixes due to the reduction of the ASR. The 10 and 20% GP mixes showed a higher compressive strength at longer ages than the control mix which is related to the pozzolanic reactivity of the glass powder.

Bottom Ash was added to the 20% GP mix, at different percentages (2.5, 5, 10 and 20%). The maximum compressive strength was obtained at 5% BA mix.

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1. Introduction

The rheology of cement paste is governed by many parameters; chemical composition, grain size distribution, water to cement ratio, curing temperature and additives.

Glass powder is considered as a pozzolanic material [2,3,5,6–12,14,16–19,22–24]. Its particle size and chemical composition govern its reactivity; smaller particles give higher pozzolanic reactivity and decrease the alkali silica reaction [1,7,9,10]. The glass powder dissolves in water and combines with the hydrated binder to form a silica reaction gel (CSH) with expansive features [7]. Idir et al. proposed that the glass particles dissolve and the very fine particles will totally dissolve in water, then precipitation of CSH hydrate in the solution will result after which silica reaction will occur with the precipitation of N, K, SH hydrate by the diffusion process [12]. They shows that relative strength usually increased with time, especially for the finer glass powder size, which is a sign that there was still significant pozzolanic activity at later ages. Also, they proved that finer glass powder than 40 μm has a higher lime ($Ca(OH)_2$) consumption than glass powder bigger than 1 mm, which comes from the significant differences of fineness of the two glass powder and that confirmed the significant pozzolanic activity of the smaller glass powder particles [12]. Tognovi et al. showed that the increase of the water content in the mix increases the pozzolanic reaction due to the dissolution of glass powder in the pore solution [16].

The pozzolanic reaction increases with the decrease of the particle size [9–12]. Frederico and Idir [10,12] showed that the use of particles below 300 μm increased the reactivity, while Pereira et al. [9] showed that the increase of the pozzolanic reaction is higher when the particle size is between 45 and 75 μm. They also showed

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that the use of 30% glass powder increases the pozzolanic reactivity. Khmiriet et al. used particles smaller than 20 μm to increase the pozzolanic reaction. They showed that the use of glass powder size smaller than 100 μm increased the pozzolanic reactivity while the use of bigger glass particles cracked due to the destructive alkali-silica reaction [15].

Jani et al. showed that the use of 10% of glass replacement of cement is considered as an acceptable pozzolanic material in cement paste [18]. The work of Pereira et al. showed that the use of glass powder size between 75 and 150 μm with replacement up to 40% results in decreasing shrinkage which is attributed to the reduction of the ASR effect [21].

Taha et al. Showed that the use of glass powder reduces the concentration of OH in the pore structure and as a result reduces the risk of ASR expansion. On the other hand, the glass powder will contribute in the formation of CSH and the decrease in the amount of alkalis to form alkali silica reaction. The work of Vijayakumar et al. showed the same result of reducing the ASR at smaller glass powder particles [24].

Kamali et al. [19] showed that the replacement by glass powder leads to higher free water in the mix to react with cement and as a result a decrease of porosity and improvement in the early hydration of cement. The measurements at 90 days showed the largest decrease in the amount of CH which indicates higher pozzolanic reactivity and refinement of porosity.

Schwarz et al. showed a higher degree of hydration when using 20% glass powder. The glass powder has a similar or more effect on hydration as fly ash, where the glass releases a small amount of alkali to the pore solution and the amount of sodium is very small to have an effect on setting time [20].

Kamali et al. [1], Harbec [4] and Omran [25] showed a decrease of CH as a function of age and a refinement of the pores in the cement paste with glass powder especially at an early age. This is attributed to the fine particle size of glass powder which reacts with CH to form more packing of CSH.

Dyer and Dhir [26] showed that the heat released by the hydration of glass powder, as cement replacement, decreased because of the decrease in the amount of cement. However, later at a longer age, the pozzolanic reaction takes place, thus resulting in a decrease of the amount of CH in favor to formation of more CSH.

Nwaubani and Konstantinos [27] concluded that in early ages the compressive strength decreases as the amount of glass powder increases, but at later stages the strength becomes higher due to the effect of the pozzolanic reaction. This result was confirmed by other researchers [29–32]; they showed that the smallest particles give the highest compressive strength.

Many optimum percentages (10% to 40%) of the glass powder are noted to give the highest compressive strength. Table 1 shows a summary of some results for the optimum percentage of the powder used to give the highest compressive strength for cement paste, mortar and concrete.

Table 1
Previous studies on the optimum percentage of glass powder which gives the highest compressive strength.

Percentage	GP size	Mix	Refs.
10%	<45 μm	Mortar	[26]
30%	<38 μm and <75 μm	Concrete	[28]
20%	<90 μm	Mortar	[29]
10%	<40 μm, 40–80 μm and 80–100 μm	Mortar	[30]
10%	<90 μm	Mortar and Concrete	[32]
10%	No information	Concrete	[33]
10%	No information	Concrete	[34]
10%	Pass from sieve 8	Mortar	[35]
15%	<90 μm and between 90 and 150 μm	Mortar	[36]
20%	No information	Concrete	[37]
25%	No information	Cement paste	[38]
40%	<75 μm	Concrete	[24]
40%	<90 μm	Concrete	[39]

2. Experimental and testing program

2.1. Materials

2.1.1. Chemical composition of cement, glass powder and Bottom Ash

Cement type I (Sinai cement CEMI 52.5) and cement type II (Nesher CEMII AM SVL 42.5) were used in the testing program. The glass powder was obtained from crushed local glass sheets and broken pieces collected from a landfill. The particles were crushed to sizes smaller than 75 μm. Fig. 1 shows the glass powder used in the study. The Bottom Ash was obtained by the incineration of papers, carton and wood remainings.

Fig. 2 shows the SEM image of the glass powder particles. Most of the particles have an angular shape, which is the result of the method of crushing (see Fig. 2a). The figure shows the presence of a small quantity of particles bigger than 75 μm. Fig. 2b shows the XRF analysis of the glass powder, from which the percentage of oxides were calculated.

Table 2 shows the chemical composition of the glass powder (GP), CEMI and CEMII as determined by XRF measurements.

2.1.2. Cement and glass powder particle size distribution

Fig. 3 shows the particle size distribution (PSD) of the cement (CEMI and CEMII) and the glass powder (GP), according to ASTM C136/C136M-14 [43]. The figure shows that CEMII has finer particle size than both CEMI and GP, thus it will be more reactive and needs less water to hydrate completely [40].

2.2. Mix proportions

Cement paste was cast with a water to cement ratio of 0.4 in order to ensure full hydration of cement, according to ASTM C305-14 [44]. Five percentages of glass powder, as a replacement of cement, were used (0, 10, 20, 25 and 30%). The 20% GP mix was also tested with four percentages of Bottom Ash (BA) (2.5, 5, 10 and 20% as a function of cement content). The cement, glass powder and Bottom Ash were mixed for 2 min in order to obtain a homogenous powder mix. The water is then slowly added within 2 min and then the mixing speed was increased for another 2 min. Directly after mixing, the flow test was conducted in order to measure the workability. Then, the cement paste was poured in prismatic molds of 4 * 4 * 16 cm and covered with plastic sheets to prevent evaporation and conserved at 100% relative humidity (RH) for 24 h. The samples were then demolded and conserved in water at room temperature until testing. Table 3 shows the mix proportions of the cement paste with cement replacement by the glass powder for both CEMI and CEMII. Table 4 shows the mix proportion for the 20% GP mix with the Bottom Ash addition prepared with CEMII only.

For the linear expansion test, the samples were cast in 1 * 1 * 4 cm mold and conserved at 100% relative humidity for 24 h. The linear expansion is measured as the difference between the initial length and the new length as a function of age.

The samples used for measuring the volumetric change were cast directly in the membrane and immersed in oil. The volume change was measured as a function of age with a balance of 0.01 g precision.

For XRD, the samples were cast in 3 cm diameter plastic mold and conserved in 100% RH for 24 h and then demolded.

Fig. 1. Glass powder with size <75 μm.

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