Construction and Building Materials 98 (2015) 407–416

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effect of glass powders on the mechanical and durability properties of cementitious materials

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HIGHLIGHTS

- Glass powders improved the compressive strength of concrete at late ages.
- Concrete with glass powders showed significant resistance to chloride penetration.
- Glass powders were effective in suppressing ASR expansions in concrete.

ARTICLE INFO

Article history:
Received 16 January 2015
Received in revised form 5 June 2015
Accepted 7 June 2015
Available online 28 August 2015

Keywords:
Glass powder
Strength
Chloride permeability
Alkali-silica reaction
Pozzolanic property

ABSTRACT

This paper examines the mechanical strength and durability behavior of cementitious materials modified with two types of glass powders and a class F fly ash at various levels of cement replacement. Mechanical strengths were evaluated via compressive strength and flexural strength tests, and durability characteristics studied included alkali-silica-reactivity, electrical resistivity, chloride permeability and porosity. The findings from this study indicated that cementitious materials modified with glass powders showed an improvement in compressive and flexural strengths compared to the control concrete at late ages of curing. It was found that the addition of glass powders decreased alkali-silica reaction expansions of the modified cementitious materials when mixed with reactive sands and enhanced resistance to chloride permeability and electrical resistivity of cementitious materials. The improvement in the mechanical strength and durability of the cementitious materials modified with glass powders can be attributed to microstructure improvement arising from the pozzolanic property of the glass powders.

1. Introduction

There has been a significant emphasis on increasing sustainability in construction practices. One way to achieve this is to increase the use of green materials in cementitious materials, which are the primary materials used in the construction industry. Recycled glass powder has seen increased attention in the literature as a cement replacement material in recent years [1–6]. This is motivated by two primary factors: first, cement production is an energy intensive process, which accounts for 5% of the industrial energy consumption and 3% of the total energy consumption worldwide [7]. The environmental impact of cement production includes a large amount of greenhouse gas emissions and it is estimated that the production of one ton of cement generates about 0.9 tons of CO_2, which is released in the environment [8,9]. Second, use of waste glass in concrete increases the recycling rate of glass and helps to decrease the load from landfills, which are currently reaching their design capacity [5,6].

The use of waste glass cullet as aggregate in concrete was studied by previous researchers and it was shown to degrade the mechanical and durability properties of concrete [10–12]. The high content of silica in glass cullet with great potential to generate alkali-silica reaction (ASR) expansion was indicated as the primary deteriorating effect of glass cullet in concrete. Research has shown that ASR damages can be effectively mitigated by using fly ash and other supplementary cementitious materials (SCM's) in concrete [13–17]. The effect of glass particle size distribution on ASR behavior of concrete has been extensively investigated and a general trend of decreasing ASR expansion with decreasing mean particle size of glass was observed [1,18]. This size dependence trend motivated studies on the use of glass powders in cementitious materials and it was concluded that not only do glass powders with a mean size of below 50 μm not contribute to ASR expansion in cementitious materials, but they also suppress ASR reactivity when

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http://dx.doi.org/10.1016/j.conbuildmat.2015.06.010

used in combination with reactive aggregates [1–6]. The reducing effect of glass powders on the ASR expansion of cementitious materials was attributed to the pozzolanic characteristic of glass powder, which has been demonstrated in other pozzolanic materials such as fly ash, silica fume and metakaolin [19,20]. Transport characteristics of cementitious materials modified with glass powder were investigated by researchers [2–6,21,22]. Schwarz et al. [4] investigated the effect of a fine glass powder with a mean size of about 20 μm on the chloride permeability of concrete and observed a reduction in chloride permeability at early ages and a similar value to that of control concrete at later ages. Nassar and Soroushian [5] carried out experiments to characterize the moisture sorption of mortars modified with glass powder and indicated a significant improvement in moisture sorption resistance of the modified mortars. Their microscopic examination revealed a more densified microstructure in cementitious materials containing glass powder. The effect of glass powders on the mechanical strength of cementitious materials was the subject of prior investigations and the pozzolanic reactivity of glass powders was evaluated [1–3,5,6,18,22–24].

In this paper, an investigation into the effect of two glass powders produced from different recycling processes on the mechanical strength, transport and ASR reactivity of cementitious materials is presented and a comparison was made with the performance of cementitious materials modified with fly ash. The glass powders examined in this paper differed in chemical composition and, thereby, allowed studying the dependence of cementitious materials performance on chemical composition of glass powder as related to variation in recycled glass source or processing methods. Mechanical strength was evaluated using the compressive strength test (ASTM C39, ASTM C349) and the flexural strength test (ASTM C348). The rapid chloride permeability test (ASTM C1202), the rapid migration test (Nordtest Build 492 [25]), the electrical resistivity test and porosity measurement were utilized to characterize the transport characteristics of cementitious materials modified with glass powders. The ASR reactivity was quantified using the accelerated mortar bar test (ASTM C1260). In addition, the effect of glass powders on the dissolution of reactive aggregate as the first stage in ASR reaction in cementitious materials was examined.

2. Experiments

2.1. Materials and specimens preparation

Materials used in this study included type I/II Portland cement, limestone coarse aggregate, silica sand, glass powders (GP) and a class F fly ash (FA). Two glass powders designated as GP1 and GP2 were used in this study. GP1 is a post-industrial by-product derived from waste glass fiber and GP2 is a post-consumer by-product derived from recycled glass. The chemical and physical properties of glass powders and fly ash per the manufacturers' specifications are given in Table 1. The median particle size of GP1 and GP2 was close to each other at about 8.4 μm. The median particle size of FA was 13.1 μm. The scanning electron microscopic images of GP1 and FA showing the morphology and size distribution of GP1 and FA are shown in Fig. 1a and b, respectively. The X-ray diffraction spectra of GP1, GP2, and FA are depicted in Fig. 1c. It is seen from the X-ray diffraction spectra that GP1 and GP2 possess an amorphous structure as indicated from the absence of detectable peaks in their spectrum. The presence of peaks in the FA spectrum indicated that some crystalline phases were present in the microstructure of FA as shown in the figure. It has been pointed out that pozzolanic reactivity increases with increasing amorphous phases in supplementary cementitious materials [26,27].

Concrete mix designs with various replacement levels of cement with glass powders GP1 and GP2, and fly ash FA were adopted in this paper, and are listed in Table 2. Water-reducing and air-entraining admixtures in the amount of 1651.7 mL and 3.9 mL, respectively, per cubic meter of concrete were added to the mixes. The water/binder ratio of mix designs was specified at 0.5. Concrete cylinders of dimensions 100 mm (diameter) × 200 mm (height) were prepared in accordance with ASTM C192. Concrete cylinders were cured in a moist room at more than 95% relative humidity and at a temperature of 23 ± 2 °C for 24 h, and then demolded and stored in the moist room until testing time. The fresh properties of concrete mixes were evaluated by the slump test (ASTM C143) and density measurement (ASTM C138). Cement paste cubes of dimension 50 mm following ASTM C109 with the same water/binder ratio as in the concrete cylinders and with 20% cement replacement level were prepared. Cement pastes were cast in molds in two layers. Each layer was tamped using a 13 mm by 25 mm tamper with 32 strokes. After casting, samples were placed in the moist room for 24 h, then demolded and stored in a saturated lime solution for curing until testing time. Cement paste cubes were used to measure the electrical resistivity of cement pastes at various ages of curing. A small piece obtained from the center of the cement paste cubes was dried and then saturated in methanol for porosity measurement as described later in this paper. Only the results of porosity measurement of the cement pastes are presented in this paper and the electrical resistivity results of the cement pastes will be reported in a future paper. Mortar bars with dimensions of 25 mm × 25 mm × 285 mm for assessing the alkali-silica reactivity of mortars were prepared in accordance with ASTM C1260. Mortar prisms for the flexural strength test with dimensions of 40 mm × 40 mm × 160 mm having the same water/binder and sand/binder ratios as concrete mix designs with only 20% replacement of cement with glass powders and fly ash were cast following ASTM C348. Mortar prisms for the flexural strength test were cast in two layers. Each layer was compacted with 12 strokes of a 22 mm by 58 mm tamper for about 15 s. The test specimens were cured for 24 h in the moist room at more than 95% relative humidity and at a temperature of 23 ± 2 °C. After 24 h, the mortar prisms were demolded and stored in a saturated lime solution until testing time.

Table 1
Chemical and physical properties of glass powders and fly ash.

Composition % by mass	GP1	GP2	FA
Silica (SiO_2)	50–55	50–80	54
Alumina (Al_2O_3)	15–20	1–10	28
Iron oxide (Fe_2O_3)	<1	<1	7
Calcium oxide (CaO)	20–25	5–15	1.4
Magnesium oxide (MgO)	<1	<1.5	1
Sodium oxide (Na_2O)	<1	1–15	0.3
Potassium oxide (K_2O)	<0.2	<1	2.4
Sulfur trioxide (SO_3)	<0.1		0.1
Titanium dioxide (TiO_2)	<1	<0.1	
Boron trioxide (B_2O_3)	0–6	0–5	
Loss on ignition (%)	<0.5	<1	3.4
Specific gravity	2.6	2.5	2.31
Passing sieve No. 325 (%)	98	>99	81
Median particle size (μm)	8.4	8.4	13.1

2.2. Mechanical strength tests

The compressive strength test of concretes modified with 5%, 10%, 15%, and 20% glass powders GP1 and GP2, and 20% fly ash FA using cylindrical specimens (ASTM C39) was performed at 7 days, 28 days, and 91 days of curing. The flexural strength test was carried out using mortar prisms (ASTM C348) with only 20% glass powders and fly ash at 28 days and 91 days of curing. The compressive strength of mortars using portions of prisms used in the flexural test was evaluated as per ASTM C349. Three specimens were used for each test at each curing age to assess repeatability of the test results and the average values were reported.

2.3. Alkali-silica-reaction expansion measurement

In this study the effect of GP1 and GP2 on the alkali-silica-reactivity of mortars was studied compared to that of FA. The susceptibility of mortars to alkali-silica-reaction expansion was evaluated using the accelerated mortar bar test (AMBT) in accordance with ASTM C1260. The water/binder ratio was 0.47 and limestone fine aggregate with a gradation as specified in ASTM C1260 was used in preparing the mortars. In order to induce alkali-silica reaction, reactive glass sand (GS) with a size distribution passing mesh #30 and remaining on mesh #12 was substituted for limestone fine aggregate at 80% level. Our prior experiments using 100% limestone aggregate did not show any alkali-silicate reactivity in mortars containing GP1 or GP2. Mortar bars of dimensions 25 mm × 25 mm × 285 mm with 10% and 20% replacements of cement with GP1 and GP2, and with 20% replacement of cement with FA, and having 80% replacement of fine aggregate with GS were prepared and designated GS-80/(GP1-10 and GP1-20), GS-80/(GP2-10 and GP2-20), and GS-80/FA-20, respectively. Three mortar bars were used at each cement replacement level and the average values were reported.

2.4. Glass dissolution

The dissolution of silica from reactive aggregates in pore solution is the first stage in alkali-silica reaction [28]; therefore, it is important to understand how the addition of glass powders affects the dissolution behavior of reactive aggregates in an alkaline solution. In this study, the effect of glass powders on silica dissolution was evaluated following the method used in Shafaatian et al. [14]. Soda lime