Cement & Concrete Composites 35 (2013) 109–117

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

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

Use of waste glass as sand in mortar: Part I – Fresh, mechanical and durability properties

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ARTICLE INFO

Article history:
Received 9 November 2011
Received in revised form 29 August 2012
Accepted 30 August 2012
Available online 17 September 2012

Keywords:
Durability
Fine aggregates
Mechanical properties
Mortar
Sustainability
Waste glass

ABSTRACT

In this study, mortar made with waste glass as fine aggregates was investigated for its suitability for construction use. A reference mortar mixture was proportioned according to ASTM C 109 and the fine aggregates were replaced by waste glass particles by 0%, 25%, 50%, 75% and 100%, by mass, to study its effect on the properties of mortar. For each mixture, four types of glass sand, namely, brown, green, clear and mixed color glass, were used. Test results indicated that use of waste glass particles as fine aggregates would reduce the flowability and density of mortar, but increase its air content. Except drying shrinkage, the mechanical properties were compromised due to micro-cracking in glass sand and weakened bond with the cement paste. However, durability was enhanced, especially in terms of the resistance to chloride ion penetration. Accelerated mortar bar tests to ASTM C 1260 indicated that green and brown glasses were non-reactive while clear glass was potentially deleterious, with regards to alkali–silica reaction.

1. Introduction

In recent years, the sustainability of construction materials has become an important issue [1]. At the same time, the recycling and reuse of waste is necessary from the viewpoint of environmental protection [2]. Incorporation of recycled solid waste in concrete is a suitable way to preserve natural raw materials, save energy and reduce landfills [3]. Among various urban solid wastes, glass may be considered the most suitable as substitution for sand and cement, due to its physical characteristics and chemical composition [4]. The recycling of waste glass is especially significant as its recycling rate is quite low in many countries, compared to other solid wastes. In the United States, for example, 11,530 kilotons of waste glass was generated 2010 and only 27.1% was recycled, mainly for container and packaging [5]. In Singapore, 72,800 tons of waste glass was disposed in 2011 and 29% was recycled [6].

The effect of replacement of coarse and fine aggregates or even cement by recycled waste glass on the fresh and mechanical properties of concrete or cementitious composites has been reported [7–10]. However, the results appeared to be inconsistent. Air content in concrete, for instance, was reported to increase with the incorporation of glass sand by Park et al. [11] whilst the opposite result was reported by Topcu and Canbaz [12]. Both groups of researchers attributed the change in air content to the poor geometry of crushed waste glass. Inconsistent results were also found in alkali–silica reaction (ASR) expansion of mortar containing glass sand. Some previous work pointed out that serious ASR between glass particles and alkali in cement would be detrimental and this has limited the application of recycled glass in concrete [8]. Several methods were therefore proposed to mitigate the ASR expansion, such as the replacement of cement by pozzolans, addition of fibers, and the addition of lithium compounds [10]. However, some other researchers reported that severe ASR would not occur for glass sand concrete [13]. Also, the influence of glass sand on other durability properties of concrete or other cementitious composites has rarely been reported.

In this Part I paper, the fresh and mechanical properties of mortar with single and mixed-colored glass sand as fine aggregates were investigated. Furthermore, the durability of glass sand mortar, with respect to chloride permeability, ASR and sulfate attack was also examined. As ASR has been a major concern in the use of waste glass particles in concrete, further studies were carried out and reported in Part II paper.

2. Test program

Glass sand was used to replace natural sand as fine aggregates in mortar by 0%, 25%, 50%, 75%, and 100% by mass. Fresh and mechanical properties, including fresh density, air content and flowability; compressive strength, splitting tensile strength, and flexural strength, static and dynamic elastic moduli, as well as drying shrinkage were investigated for glass sand mortar. Durability properties, in terms of resistance to chloride ion penetration, ASR and

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http://dx.doi.org/10.1016/j.cemconcomp.2012.08.028

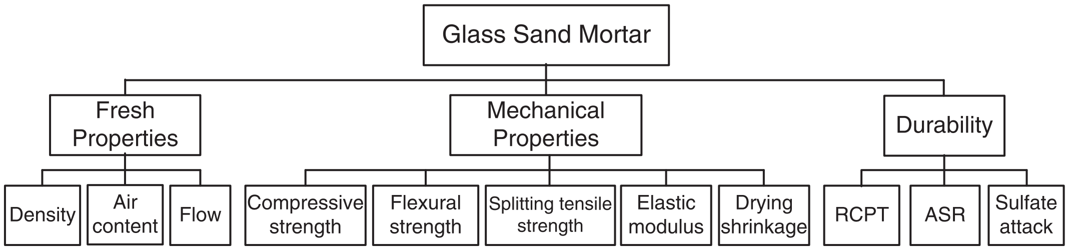

Fig. 1. Test program for mortar with recycled glass sand.

sulfate attack, were also carried out. The overall test program is summarized in Fig. 1. All properties were investigated using brown, green, clear and mixed-colored glass, that is, green and brown glass mixed in the ratio of 2:1 by mass.

2.1. Materials

Waste soda–lime glass bottles, originally used for beer, wine, cooking sauces, and others, were collected from a local recycler. Most of the beer bottles were either brown or green in color, while wine bottles and bottles for other uses were mainly transparent or clear. First, the metal or plastic taps and neck rings were removed from the bottles. After that, the glass bottles were thoroughly cleaned with tap water, to remove paper or plastic labels on the surface and to eliminate contaminations. After washing and drying, the glass bottles were reduced by a jaw crusher into small particles, which satisfied the ASTM C 33 grading requirement for sand [14]. Because of its brittle nature, the crushed glass sand exhibited angular shape, sharp edge, smooth surface texture and a higher aspect ratio than natural sand, as shown in Fig. 2.

Also, some micro-cracks were observed in clear glass particles after the crushing processing, as revealed by optical microscopic (OM) and scanning electron microscopic (SEM) images in Figs. 3a and b. In contrast, very few micro-cracks were found for green glass particle and almost no micro-crack existed in brown glass particle (see Fig. 3c and d). The difference in the amount of micro-cracking might be due to the different manufacturing processes of the glass bottles, as pointed out by Dhir et al. [15].

The chemical compositions of glass and natural sand are compared in Table 1 while the size distributions are shown in Fig. 4. The specific gravity (SSD) and water absorption capacity of glass were 2.53% and 0.07%, respectively, compared to 2.65% and 1.0% for natural sand. ASTM Type I Portland cement was used in the study, and the chemical composition and physical properties are listed in Table 2. The equivalent sodium alkali content was 0.6%, calculated from $Na_2O_{eq} = Na_2O + 0.658K_2O$.

Fig. 2. Appearance of natural and glass sand.

2.2. Mix proportion and test methods

Except for the ASR tests, the mix proportion of mortar was selected in accordance with ASTM C 109 [16], with water:cement:sand = 0.485:1:2.75 by mass, for each test property. For each mix, the sand content consisted of natural sand, glass sand or both. The portion of glass sand as a percent of the total sand content by mass was varied from 0% to 100% in steps of 25%. All tests were carried out as per ASTM Standards shown in Table 3 [14,16–26]. For ASR tests, the mixture proportion of mortar consisted of water:cement:sand in the ratio of 0.47:1:2.25, according to ASTM C 1260 [25]. Also, both natural sand and glass sand were used with percentages of 10%, 25%, 25%, 25%, and 15% passing/retained on sieve sizes 4.75/2.36, 2.36/1.18, 1.18/0.6, 0.6/0.3, and 0.3/0.15 mm respectively. No superplasticizer was added.

2.3. Preparation of mortar specimens

The numbers and dimensions of mortar specimens are summarized in Table 3. All the mortar specimens were covered with plastic sheets for 24 h after casting, followed by demolding and curing in water until the age of tests, including RCPT and sulfate attack tests. For the drying shrinkage tests, the mortar specimens were cured in water for 3 days after demolding and then transferred into a controlled room (simulating a tropical climate with a constant temperature of 30 °C and RH of 65%) for measurements up to 56 days. For the ASR tests, all specimens were put in 80 °C water for 1 day and the initial length taken before transferring to 80 °C 1 N NaOH solution. The expanded lengths were subsequently measured after 2, 4, 7, 10, 14, 21, and 28 days. ASR expansion was reported as the average value obtained from three mortar bars.

3. Test results and discussion

3.1. Fresh density

For all mortar mixes, no segregation or bleeding was observed during mixing and casting. The fresh density decreased with a higher content of glass sand, as shown in Fig. 5, due to the smaller specific gravity of glass compared to natural sand. The glass color had no effect on the fresh density, especially when the glass content was less than 75%. The fresh density of mortar with 100% brown, green, clear and mixed colored glass sand was 97%, 96%, 95%, and 97% of that of normal mortar, respectively.

3.2. Air content

As shown in Fig. 6, the air content of glass sand mortar was between 3% and 3.5%, increasing slightly with higher glass sand content up to 75%. In comparison, Park et al. [11] reported that air content consistently increased 12.2–41.4% for concrete containing glass sand content at 30%, 50%, and 70%. With 100% glass sand, clear glass mortar showed the highest air content of 5.9%, almost