Materials and Design 33 (2012) 127–135

Contents lists available at ScienceDirect

Materials and Design

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

Effect of colloidal nano-silica on the mechanical and physical behaviour of waste-glass cement mortar

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ARTICLE INFO

Article history:
Received 21 May 2011
Accepted 4 July 2011
Available online 14 July 2011

Keywords:
Nano-materials
Concrete
Mechanical

ABSTRACT

This paper presents a laboratory study of the properties of colloidal nano-silica (CS)/waste glass cement composites. The microstructure, alkali–silica reaction (ASR), and the mechanical properties of cement mortars containing waste glass powder (WG) as a cement replacement with and without CS are investigated and compared with plain mortar. In addition, the hydration of cement compounds was followed by differential thermal analysis (DTA), thermogravimetric analysis (TGA), and X-ray diffraction (XRD). The results show that incorporation of WG has a positive effect on the mechanical properties of cement mortars especially when CS is presented. In addition, the DTA/TGA results and XRD analysis show a reduction in the calcium hydroxide (CH) content in mortars with both WG and a hybrid combination of WG and CS. This confirms the improvement of mechanical properties and the occurrence of the pozzolanic reaction after 28 days of hydration.

1. Introduction

Worldwide, around 2.6 billion tons of cement are produced annually. This huge size of production consumes large amounts of energy and is one of the largest contributors to carbon dioxide (CO_2) release. Accordingly, there is a pressing demand to minimise the quantity of cement used in the concrete industry. The main challenge to this is to produce durable concrete with less cement and with a reasonable cost [1,2]. The economic, environmental and engineering benefits of reusing waste-glass powder (WG) as a partial cement replacement has been studied previously by many authors [3–14]. As these works show, the reuse of WG in the concrete industry is accompanied by two antagonistic behaviours depending on the size of the glass particles: alkali–silica reaction (ASR), which causes negative effects, and the pozzolanic reaction, which improves the mechanical and physical properties of concrete.

The concept of using waste glass in concrete is not new; early efforts were conducted in the 1960s to use crushed waste glass as a replacement for aggregate [3]. However, these attempts were not satisfactory due to the strong reaction between the alkali in cement and the reactive silica in glass, namely ASR [3,4]. In addition to ASR, using waste bottle glass limits the size and shape of coarse aggregate, as crushed bottles tend to form flat and elongated shapes, which may negatively affect workability and reduce compressive strength. Also, most mixed-colour bottles are of different chemical composition and may be contaminated due to paper and plastic labels, caps, and sugars remaining from the original content of the bottles [5]. Furthermore, using waste glass as an aggregate could decrease slump, air content, fresh unit weight, and tensile and flexural strengths [6].

In the last decade, the reuse of waste glass in the cement and concrete industries has attracted many researchers due to the high disposal costs for glass and stricter environmental regulations [7]. Currently several efforts have been made to overcome the limitation of ASR, focussing on reducing the particle size of the waste glass through prolonged grinding [5]. The results of this work showed that the very fine glass powder greatly decreased the ASR expansion. Furthermore, the results revealed an improvement in compressive strength, resistance to sulphate attack and chloride ion penetration with very fine glass powder (less than 100 μm) [8,9].

Work by Shi et al. [8], as well as Schwarz et al. [9], indicated that below 100 μm glass can have a pozzolanic reactivity greater than fly ash, a low cement replacement (10–20%), all after 90 days of curing. When using up to 50% of waste glass as cement replacement, Chen et al. [10] found that a particle size less than 75 μm possesses cementitious capability and improves compressive strength, resistance of sulphate attack and chloride ion penetration. In another work, Corinaldesi et al. [11] used sodium–calcium

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doi:10.1016/j.matdes.2011.07.008

Table 1
Chemical composition of waste glass powder and other pozzolans [5].

Compound	Glass	OPC	Slag	Silica fume	Volcanic ash
SiO_2	63.79	20.33	35	90.9	73.68
Al_2O_3	3.02	4.65	12	1.12	12.25
Fe_2O_3	1.57	3.04	1	1.46	2.2
CaO	13.01	61.78	40	0.69	1.13
MgO	0.89	3.29	–	0.77	0.23
K2O	0.54	0.59	–	–	3.95
Na_2O	11.72	0.24	0.3	–	3.6
SO_3	0.165	3.63	9	0.38	0.32
Others	4.55	–	1	3	3.05

glasses with a particle size ranging from 36 μm to 100 μm, to study the effect of glass particle size on ASR. Their results did not detect any deleterious effect at a macroscopic level due to the reaction between cement paste and ground waste glass with a particle size up to 100 μm. Also, their results showed a strong improvement in the compressive and flexural strength of the mortar, due to the positive contribution of the waste glass to the micro-structural properties. Work by Karamberi and Moutsatsou [12] indicated that a finely ground colour glass cullet of up to 90 μm was found to increase pozzolanic activity, to improve compressive strength and to cause negligible ASR expansion. Idir et al. [13] showed that the pozzolanic activity increases with glass fineness and an equivalent or superior compressive strength can be attained when using up to 40% of mixed-colour glass (less than 40 μm), compared to their reference specimen without glass.

As the previous works show, the use of waste glass as a cement replacement has shown mixed results over a range of levels of replacement and particle sizes. In relevance to the requirements of ASTM C 618 [15], as shown in Table 1 [5], glass has the potential to acceptably function as a cement replacement; however, proper methods must be developed to control the ASR/pozzolanic reaction and increase the glass powder reactivity.

Recent studies have shown that nano-sized particles such as colloidal nano-silica (CS), consisting of an amorphous silicon dioxide (SiO_2) core with a hydroxylated surface, have a high surface area to volume ratio that has the potential for tremendous chemical reactivity [16]. As the previous works show, addition of a small amount of nano-silica (up to 3 wt.%) accelerates pozzolanic activity, improves workability, increases the level of control of ASR, and increases the strength and durability of concrete [16–19]. Therefore, using CS to increase the pozzolanic activity of WG would be a promising approach to improving the performance of WG and controlling the damaging effect of ASR. The literature review has shown that studies on this subject are very limited. This work investigates the hybrid effect of CS and WG on the ASR, microstructure, hydration of cement compounds, and the mechanical and thermal properties of cement mortars.

In this study, green WG obtained from alcohol bottles and CS were used as partial replacements for cement. In order to characterise these developed composites, a series of tests were conducted. These consisted of a study of the ASR, microstructure properties, fracture energy, and the impact, compressive and flexural performances. In addition, the hydration of the cement matrices was followed by differential thermal analysis (DTA), thermogravimetric analysis (TGA), and X-ray diffraction (XRD).

2. Materials and methods

Ordinary Portland cement (PC) was used in this study and supplied by Irish Cement Ltd. The cement was grade 42.5, with a specific gravity of 3.15 g/cm^3. Sand with a particle size up to 1.18 mm and a specific gravity of 2.65 g/cm^3 was obtained from a local supplier in Ireland. The colloidal silica sol used (Cembinder 50^{TM}) contained 15 wt.% of solid material. The particle size was 5 nm with a 500 m^2/g specific surface area, supplied by EKA Chemicals AB, Sweden. The super-plasticizer was obtained from Sika Ireland Ltd.

Table 2
Chemical composition of green waste glass powder used in this work.

Na	Al	Si	K	S
10.7	6.65	75.06	4.49	3.1

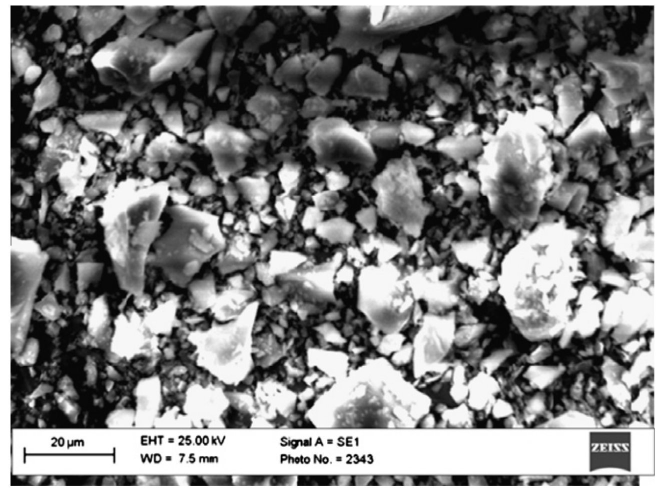

Fig. 1. SEM photographs of ground green waste glass powder.

The WG used in this study was obtained from recycled green alcohol bottles. In order to satisfy the physical requirement for fineness, the glass has to be ground fine enough to pass through a 75 μm sieve. This is accomplished by crushing and grinding the glass in a ball mill in the laboratory and sieving the ground glass to the desired particle size. Table 2 shows the chemical composition of green WG used in this work. Scanning electron microscopy (SEM) examinations indicate that the ground WG consists mainly of fine angular particles with a narrow particle size range, as shown in Fig. 1.

To prepare cement mortars, the CS (if applicable) was stirred with the mixing water at high speed (120 rpm) for 1 min. After that the Portland cement (PC) and waste glass powder (if applicable) were added and stirred at medium speed (70 rpm) for 1 min. Afterward, the sand was added into the mixture and stirred at medium speed (70 rpm) for 2 min. Then, the super-plasticizer (0.1 wt.%) was added and stirred again at medium speed (70 rpm) for 2 min. Then, the well mixed composite was poured into moulds. After moulding, the specimens were covered with a wet cloth and a polyethylene sheet and allowed to cure in the moulds for the first 24 h. Then the specimens were allowed to cure in water for the next 3 days. Finally the specimens were kept in sealed laboratory conditions of 19 ± 2 °C and 50 ± 5% relative humidity for the next 24 days. For all specimens an equal ratio of binder and sand was used for all mixes. The water/binder ratios were tested to reach a flow of 110 ± 5 to permit a medium workability to be used for mixing the specimens. A range of composites were prepared based on variations of the composition as follows:

- Control: PC only used as a binder.
- WG20: PC replaced by 20% ground glass powder.