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Effects of recycled glass on properties of architectural mortar before and after exposure to elevated temperatures

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A B S T R A C T

When put into practical uses, self-compacting architectural mortars (SCAM) containing recycled glass (RG) may face the risk of exposure to fire. It is of great interest to investigate the effect and the roles of RG acting in the SCAM after exposing to high temperatures. In this study, RG was used to replace river sand at ratios of 0%, 25%, 50%, 75% and 100% by weight. The results showed that at room temperature, the increase in RG content slightly reduced the thermal conductivity, compressive strength and elastic modulus of the SCAM samples, but had a negligible influence on the chloride-ion penetration rate. Although increasing the exposure temperatures resulted in reductions in compressive strength and elastic modulus of the SCAM samples, when the temperature was increased to 800 °C, the incurred melting and re-solidification process of the RG enabled a pore-filling effect to fill up micro-cracks and pores in the mortar matrix. Such beneficial effects were more obvious for elastic modulus than for compressive strength. It was also found that the 100% RG incorporated SCAM was able to maintain a pleasant appearance (negligible changes were induced in its appearance) after undergoing 800 °C exposure. This study demonstrated that the introduction of 100% RG in the SCAM allowed an attractive combination of high strength (45.7 MPa) and aesthetically pleasing appearance even after exposure to 800 °C. This paved way for further and broader applications of RG based SCAM products in the market. However, the melting properties of RG may incur adverse effects on the mechanical properties of the SCAM sample under loading conditions, which necessitate further studies to clarify such a potential limit.

1. Introduction

The daily generation of glass waste in Hong Kong reached to about 220 tonnes in 2012. Due to the lack of a glass manufacturing industry to serve as a viable recycling outlet, the recovery rate of waste glass was rather low (less than 20%) (EPD, 2012).These discarded waste glass bottles have already become a burden on the landfills and a major challenge for achieving sustainable development in Hong Kong. Similar to natural sand, all commercial glass products are made up by more than 70% SiO_2 (Ling et al., 2013). Keen interests to incorporate recycled glass (RG) into construction materials have been developed, leading to a large body of research in this area (Dal Bó et al., 2014; Torres-Carrasco and Puertas, 2015).

Early research attempts mainly focused on utilizing RG as a replacement for aggregates (Ismail and AL-Hashmi, 2009; Borhan, 2012; Zhao et al., 2013). The incorporation of RG in mortar and concrete brings a variety of benefits, for example, increased workability, improved resistance to chloride ion penetration, and reduced drying shrinkage, mostly due to the near zero porosity and non-hydrophilic nature of glass (Topcu and Canbaz, 2004; Chen et al., 2011). But the major drawback is the reduction in strength due to weak bonding between the smooth glass surface and the cement hydration products (Seung et al., 2004; Adnan and Rodger, 2012), and the potential deleterious expansion due to alkali–silica reaction (ASR) slowly occurring between silica-rich glass aggregate and alkali in the cement paste. The latter problem, however, can be controlled by adding appropriate mineral additives with pozzolanic activities (Miao, 2011).

Also, some research studies were conducted on the use of RG as a pozzolanic material for cement replacement (Federico and Chidiac, 2009; Oliveira et al., 2015). It has been found that the

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fineness and composition of most pozzolans determine their pozzolanic behaviour. To activate the pozzolanic reactivity, RG needs to be ground into powder form of size less than 150 μm (Shi et al., 2005; Schwarz et al., 2008). Some studies showed using glass powder to replace cement from 10% to 20% may yield a slight increase in compressive strength (Shao et al., 2000; Terro, 2006; Laldji and Tagnit-Hamou, 2007). The reactive silica in the fine glass powder is able to react with Portlandite in the hydrated cement paste to form the primary binding phase - calcium silicate hydrates (C—S—H). As a result, some strength can be gained to compensate for the loss due to the reduction in cement content and the ASR is effectively suppressed (Shi and Zheng, 2007; Özkan and Yüksel, 2008; Tata and Nounu, 2008).

Previous works by the authors were intensively devoted in developing self-compacting architectural mortars (SCAM) with high aesthetic quality and pleasing appearance for decorative building material applications (Ling et al., 2012). The combined use of RG as aggregates and titanium dioxide (TiO_2) as a photocatalytic material in preparing SCAM favourably enhanced the effectiveness in removing gaseous nitric oxide (NO). The light-transmitting characteristic of RG could allow the light to enter a greater depth, activating more TiO_2 particles (Guo et al., 2013).

In practical uses, SCAM products may also face a high risk of fire accident and exposure to high temperatures. Although our recent works (Ling et al., 2012; Ling and Poon, 2013) on the post-heating performance of self-compacting concrete (SCC) with glass have shown that a slight improvement in concrete properties (e.g. elastic modulus and resistance to water sorptivity) after exposure to elevated temperature of 800 °C, the paucity of research studies limits our understanding of the possible roles the RG plays in architectural mortars (without the use of coarse aggregate in the mortar based matrix). Further information regarding the behaviour of RG modified SCAM after exposure to high temperature is valuable for improving the properties of SCAM products to meet market needs and to make wider uses of RG.

In this study, a series of SCAM samples with 0%, 25%, 50%, 75% and 100% of sand replaced by RG were prepared. After 28 days curing, the samples were heated to temperatures of 300 °C, 600 °C, and 800 °C, separately. The effects of elevated temperatures on compressive strength, elastic modulus, chloride ion penetration and aesthetic appearance of the SCAM with different contents of RG were evaluated through a series of tests. The role of RG played in influencing the performance of the prepared SCAM was further discussed.

2. Experimental

2.1. Materials

The materials used to prepare the SCAM samples were fine aggregates, white cement (WC) and metakaolin (MK). WC (TAIHEIYO Cement Corp., Japan) and MK (Maoming Kaolin Science and Technology CO., LTD.) were used as the cementitious materials. MK was added as a pozzolana to control the ASR. Their physical and chemical properties are listed in Table 1. A fine natural river sand (mainly quartz sand) sourced from the Pearl River and crushed recycled glass (RG) derived from post-consumer beverage glass bottles were used as fine aggregates. The post-consumer beverage glass bottles were collected from a local eco-construction material company. The beverage glass bottles collected were mainly mixed coloured. The chemical compositions of the RG are given in Table 2. Prior to the experimental use, all the discarded glass bottles were washed and then crushed by a mechanical crusher, followed by sieving to a desired particle size. The typical particle size distribution of the river sand and RG used in the experiment are shown in Fig. 1.

Table 1
Chemical compositions and physical properties of WC and MK.

	WC	MK
Chemical composition	ms%	ms%
SiO_2	21.36	55.89
Al_2O_3	5.27	41.85
Fe_2O_3	0.2	0.68
CaO	67.49	–
MgO	1.14	–
K_2O	0.077	–
Na_2O	0.048	–
TiO_2	0.14	0.29
Sulphur content as SO_3	2.6	–
Loss in ignition	1.58	0.50
Physical properties		
Specific surface ($cm^2\ g^{-1}$)	3660	160,000

2.2. Mix proportions

To facilitate mass production in real applications, architectural tile products would be produced by a double layered casting method comprising a base layer and a surface layer. The mix proportions adopted in this study were used to prepare the surface layer with a higher volume fraction of fine materials aimed to give a more aesthetically pleasing appearance and dense structure for the surface layer. The base layer, which functions differently, would have a higher aggregate-to-binder ratio, which encourages a higher amount of RG usage. The mix proportions of the surface layer (SCAM) are given in Table 3. All the samples were prepared with a constant water-to-binder ratio of 0.4 and a total aggregate-to-binder ratio of 2. Five levels of sand replacement by RG (0%, 25%, 50%, 75% and 100%) were employed. To obtain the targeted mini-slump flow value of 250 ± 10 mm for self-compacting mortar as per EFNARC (EFNARC, 2002), different dosages of superplasticizer (SP) were added.

2.3. Samples preparation and heating regimes

The procedures for the preparation of the SCGM samples were as follows. First, all the proportioned materials were mixed uniformly for about 5 min using a mechanical mixer. The fluidity (workability) of SCAM was determined using a mini-slump flow cone with an internal diameter of 100 mm as per EFNARC (EFNARC, 2002). The spread diameter values in two perpendicular directions were measured and averaged. The samples were then cast by using the self-compaction method (i.e. without external vibration) into steel moulds of different sizes, and the samples were demoulded after 1 day and cured in a water tank at a temperature of 27 ± 2 °C for a further 27 days.

Table 2
Chemical compositions of RG.

Chemical composition	Mixed coloured RG (ms%)
SiO_2	63.81 ± 3.24
Al_2O_3	11.77 ± 0.01
Fe_2O_3	0.26 ± 0.01
CaO	5.56 ± 0.06
MgO	1.57 ± 0.06
K_2O	0.31 ± 0.02
Na_2O	16.62 ± 2.45
Cr_2O_3	0.04 ± 0.02
MnO	0.01 ± 0.01
CuO	–
TiO_2	0.04 ± 0.01