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Mechanical properties and ASR evaluation of concrete tiles with waste glass aggregate

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ABSTRACT

This work describes a statistical design of experiments (DoE) testing campaign on 396 samples to evaluate the effect of replacing quartz aggregate in concrete with waste glass, and Portland cement with metakaolin to develop a novel generation of sustainable concrete tiles. The properties assessed were bulk density, permeability, dynamic modulus and length changes due to alkali-silica reaction (ASR) expansion. Metakaolin (MK) was used to replace Portland cement (PC) to verify the possibility of obtaining lower ASR expansion. Higher permeability and lower bulk density were obtained when the quartz was replaced with glass particles. The statistical analysis also confirmed that the dispersion of 15 wt% of MK was able to mitigate any possible ASR expansion caused by the presence of coarse glass particles. The composite mixes evaluated in this work constitute promising materials to be used in concrete tiles or similar semi-dry compacted products.

1. Introduction

Glass has been widely used since the middle Ages and its use has been extensively increased in the 21st century. Glass has remarkable characteristics, such as the relatively easiness of manufacturing, a transparent surface, resistance to abrasion, safety and durability (Topçu & Canbaz, 2004). The amount of waste glass (WG) has gradually increased over recent years due to an ever-growing use of glass products (Park & Lee, 2004). United Nations estimate that out of 200 millions of tonnes of waste generated worldwide each year, 7% is represented by of glass (Topçu & Canbaz, 2004). The use of recycled WG in glass manufacturing reduces the overall energy consumption, use of raw materials and decreases damages to related machinery. However, not every type of WG can be recycled into new glass products because of the impurities and undesired mixed colours (Shi & Zheng, 2007). The non-recyclable WG constitutes a problem for the disposal of solid waste, as glass is a non-biodegradable material (Khmiri, Chaabouni, & Samet, 2013). For this reason, there is an impelling need to develop new applications for mixed waste glass (Shi & Zheng, 2007). A potential way to use WG is within the manufacturing of construction materials, mainly mortars and concretes. The construction industry does consume a significant amount of mixed materials, residues and wastes (Khmiri et al., 2013). Among various types of urban solid waste, glass (if finely ground) may replace Portland cement in mortars and concretes and act as a reactive supplementary material (pozzolan) (Schwarz, Cam, & Neithalath, 2008; Shayan & Xu, 2006). Glass also presents remarkable physical characteristics as a composite dispersion (Tan & Du, 2013), i.e., low water absorption (Topc, Boga, & Bilir, 2008) and lower density when compared with traditional concrete aggregates. However, high amounts of WG decrease not only the concrete weight, but also the compressive strength due to the weak adhesion with the cement paste (Topçu & Canbaz, 2004).

The main factor limiting the addition of glass particles in cement-based materials is however the well-known expansive alkali-silica reaction (ASR) (Mitchell, Beaudoin, & Bellew, 2004; Taha & Nounu, 2008a; Topc et al., 2008). The amorphous silica in glass is likely to be attacked by the alkaline environment provided by the porous solution of the cement paste, giving rise to the monomer $Si(OH)_4$, which further react with cement alkalis, such as Na^+, K^+, and with Ca^{2+} to form a gel-like structure (ASR gel) (Du & Tan, 2013; Maraghechi, Shafaatian, Fischer, & Rajabipour, 2012). The ASR gel can absorb water and swell inside the microstructure of concrete, resulting in internal stress. Once the internal stress

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exceeds the strength of concrete, severe cracking and damage may occur (Du & Tan, 2013). The degree of expansion of ASR gel is dependent on the valence and relative concentrations of cations present in the ASR gel (Rodrigues, Monteiro, & Sposito, 2001). Some methods have been used to mitigate the ASR expansion, such as the employment of low-alkalis cement and the reduction of water-to cement ratio (i.e., the availability of free-water in the system). Another method considered to reduce the ASR effect consists in replacing the Portland cement with pozzolans, because the pozzolanic reaction products retain alkalis in their structure and also reduce the free OH^- ions that attack amorphous silica and start the process (Kandasamy & Shehata, 2014; Ling & Poon, 2011). Several studies have also shown that using lithium-based admixtures, which form silica-gel products, do not absorb water and, therefore, do not swell (Kandasamy & Shehata, 2014; Ling & Poon, 2011; Tan & Du, 2013). Another alternative to reduce the effect of ASR is the inclusions of fibres in concrete, which delay the formation and extent of cracks (Turanli, Shomglin, Ostertag, & Monteiro, 2001; Haddad & Smadi, 2004).

The effect of size, content and composition of glass aggregates on the formation of ASR has been well documented (Saccani & Bignozzi, 2010), and there is general agreement that the reduction of the size of glass particles contributes to decrease of crack propagation phenomena (Farshad, Hamed, & Gregor, 2010; Penacho, Brito, & Veiga, 2014). The dispersion of fine particles (glass powder) make a positive contribution, given that glass powders undergo a pozzolanic reaction with the presence of alkaline activator (lime, cement and alkalis) that creates hydration products (Taha & Nounu, 2008a).

1.1. Research significance

Previous studies have shown the effects of WG on the properties of concrete, as well as the employment of pozzolanic materials to mitigate ASR. However, much research has focused on structural concrete rather than prefabricated elements such as concrete tiles. The latters have a particular mix design: (i) the mixes are very dry because they need to be extruded; (ii) the particle size envelope of aggregates is different (from 0.15 to 5 mm). Fine pozzolans (such as metakaolin or silica fume) are not usually employed in those mixes because they demand too much mixing water or superplasticizers. The first lower the strength; the latter has little effect on dry mixes for extruded concrete. So, the majority of concrete tiles mixes will contain only pozzolans or fillers with fineness in the same order of magnitude of Portland cement, which are blastfurnace slag, fly ash or limestone fillers.

This paper presents three contributions to the concrete science and sustainability:

(i) Study on the addition of metakaolin in the mixes used for extruded concrete: this pozzolan is very effective to mitigate ASR, but it may adversely affect the properties of the concrete tiles. The mixes are even drier and the compaction may worsen; porosity and permeability could jeopardize the mechanical properties and durability as well.
(ii) To the authors' knowledge, recycled glass is not employed as aggregate in the manufacturing of concrete tiles. This study, therefore, presents the characterization of alternative mixes for concrete tiles with the aim to develop sustainable roofing elements for cities worldwide.
(iii) Statistical analysis was used to ensure that the results are reliable and have a statistical significance. This is often forgotten in the development of building materials. For those involved in the development of new products, it is important to determine not only the individual factors that significantly affect the properties of the materials, but also the interaction between the factors themselves and their level of significance.

Table 1
Chemical composition and physical properties of Portland cement and metakaolin.

	Portland cement	Metakaolin
Chemical		
CaO (%)	64.14	0.2
SiO_2 (%)	19.45	56.0
Al_2O_3 (%)	4.75	36.0
Fe_2O_3 (%)	3.12	2.0
SO_3 (%)	2.85	–
CO_2 (%)	1.13	–
MgO (%)	0.80	0.2
K_2O (%)	0.66	1.5
Na_2O (%)	–	0.1
TiO_2 (%)	–	1.0
Loss on ignition (%)	–	2.5
Physical		
BET specific surface (m^2/g)	0.47	24
Density (g/cm^3)	3.12	2.65

This paper describes an experimental analysis based on a full factorial design. It investigates the effect of partial replacement of the natural aggregates with WG and Portland cement (PC) with metakaolin (MK) in the properties of sustainable concrete tiles. The ANOVA study employed a level of significance of 5%, i.e., 95% probability of the effect being significant.

2. Materials and methods

2.1. Raw materials

A rapid-hardening Portland cement (ASTM III) was used as main binder. The cement was produced by Holcim-Brazil. The metakaolin (MK) was supplied by Metacaulim do Brasil (Brazil), and the quartz aggregate by Moinhos Gerais (Brazil). Table 1 shows the chemical composition and the physical properties of the Portland cement and metakaolin used. The chemical composition was determined by x-ray fluorescence; loss on ignition according to the ASTM C114; specific surface using a Quantachrome High Speed Gas Sorption Analyser (BET); density according to the Le Chatelier method – ASTM C188-14). The pozzolanic activity of MK was determined using the Chapelle method, which calculates the amount of calcium hydroxide that reacts with one gram of pozzolan. The result was 1000 mg $Ca(OH)_2$/g, which indicates that the MK used is a high pozzolanic material. A local recycling plant in São João del Rei (Brazil) supplied the WG particles, which were ground in a lab mill machine to obtain different particle sizes.

2.2. Experimental planning

Three experimental factors were investigated in this work: the glass particle size, the glass particle fraction and the addition of metakaolin. Table 2 shows an aggregate particle size distribution (PSD) used in the production of concrete tiles as well as the particle size envelope used in the work. The PSD was always constant in order to keep the same rheology for all the experimental conditions. Three levels of particle size range were considered for the quartz/glass replacement: 4–10 US-Tyler, 10–20 US-Tyler and 20–60 US-Tyler (Table 2). The quartz particles were partially replaced by glass particles at 7.5 wt% and 15 wt%. The MK replaced Portland cement at 7.5 wt% and 15 wt% (Bashar & Ghassan, 2008).

Design of experiment (DOE) is a systematic method based on a regression model to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information