A study on low energy demand materials used in glasscrete to counteract alkali-silica reactions

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Abstract The potential of waste glass use in concrete as an alternative outlet to landfilling is excellent; however glasscrete (i.e. concrete with glass aggregate) suffers from durability problems caused by alkali-silica reactions (ASR). The use of pozzolanic materials to counteract ASR has been increasingly studied. This paper investigates the ability of selected low-energy demand binders/pozzolans to counteract ASR in glasscrete: these include paper sludge ash (PSA), a by-product of the paper making industry, used together with a standardised pozzolanic material for concrete, i.e. Pulverised Fly Ash (PFA) an industrial by-product of electric power stations. A number of laboratory tests were performed on the different glasscrete mixes to assess properties (workability, compressive and tensile strengths and elasticity moduli and water absorption). Mortars were also tested for alkali-silica reaction (ASR) using the accelerated mortar bar test, which showed that ASR was effectively counteracted, towards better glasscrete durability. Glasscrete mixes were identified, with similar strengths as the respective control mixes with natural aggregates. Workability was however affected in all mixes and should be addressed in further research.

Keywords: Solid waste management, glasscrete, alkali-silica reaction, alternative concrete binders

1. Introduction

Discarded municipal post-consumer container glass constitutes one important part of solid waste that has historically been disposed of into landfills. Since the seventies however, the material was one of the first to be collected and recovered. Over the past decade the targets for waste glass recovery have significantly increased in the UK, in line with EU Directives. Glass is chemically inert, not biodegradable and can remain indefinitely in the environment; its thermal stability allows for infinite reprocessing operations (recovery/reuse). Thus, theoretically the entire amount of recovered waste glass could be reused for new glass manufacture. Practically however, only colour-sorted and contamination-free waste glass is reusable in the glass industry. Glass cullet refers to the mixed-coloured glass fragments resulting from the breakage of coloured glass containers that cannot be re-used by bottle manufacturers. These come predominantly from food, juice, beer and liquor bottles. Such containers equate to approximately 10% of the volume of the average household's waste in the UK (Day Group Ltd, 2007a). The differences between the proportions of different colours of glass in UK manufacturing and recovery streams cause concerns about the increasing amount of a surplus of waste glass in the form of glass cullet, which cannot be reused by glass manufacturers. Recent statistics showed that 34% of the municipal container glass was recycled in the UK so that near 2.5 million tonnes of glass were still landfilled (Waste Online, 2008). Therefore other applications of glass cullet are required to create secondary recycling markets for coloured glass. In general glass cullet is primarily silica, as are most natural sands and gravels. When crushed to pieces of gravel size and below, glass cullet closely resembles natural aggregate shapes. Aggregate market therefore creates an ideal opportunity for diverting waste glass away from landfill. In addition to this, the use of recycled rather than natural aggregate would reduce considerably the demand for new raw materials that are being depleted, and avoid creating other environmental problems related to the extraction of natural aggregate such as loss of land, disturbance, ecological damage both on land and in water courses and adverse effects on the landscape. Thus, in the recent years it was proven that recycled glass can be used in different construction applications such as unbound aggregate for fill and highway applications, in bituminous mixtures, and in concrete as a partial or full replacement of the natural aggregates. The latter application was one of the first to be considered and implemented already in the seventies. However, it was soon discovered that using glass in concrete to replace natural concrete aggregate, could develop deleterious Alkali-Silica Reactions (ASR) between alkali oxides available in the cement and the reactive silica included in glass aggregate. This produces a gel which then combines with moisture and expands. Consequently, the resulting concrete also expands leading to structural weakness, cracks and deformation of concrete, which affect its durability. To counteract ASR, research has shown that pozzolanic materials such as Pulverised Fuel Ash (PFA), Ground Granulated Blast Furnace Slag (GGBS) or metakaolin (MET) could be used; these are established cement-replacement materials whose use in concrete may have been standardised. Some of these pozzolans e.g. PFA or GGBS are waste or industrial by-product materials that also need to be disposed of, therefore their use in concrete is viewed as an excellent alternative route to landfilling. The additional environmental advantage of using these materials as a partial replacement for Ordinary Portland Cement (OPC) is the low or no energy demand for their production compared to OPC, one of the most energy intensive materials: CO_2 emissions from cement clinker production contribute about 4.8% to the global total in 2013 (or about 10% when including combustion-related emissions for heating the kilns), constituting the largest source of non-combustion related CO_2 emissions (Olivier *et al*, 2014). A disadvantage of waste/by-product materials such as PFA or GGBS, is the potential reduction in their availability in sufficient quantities for concrete, with the expected decline in the use of coal in electrical power generation plants and industrial patterns linked to iron consumption; on the other hand materials such as standard metakaolin that do not come from waste source are relatively expensive. There is therefore a need for additional cheap materials that can be potentially used to partially or fully replace cement. Paper sludge is becoming abundant in the UK, as paper recycling rates increase, with recent statistics reporting an annual production of approximately 1 million tonnes (Dunster, 2007). A large amount of this sludge is incinerated to waste paper sludge ash (PSA) in combined heat and power (CHP) plants at approximately 800ºC and disposed of in landfills. Paper Sludge Ash (PSA) as it contains reactive silica and alumina (in the form of metakaolin) as well as lime (CaO) and is therefore potentially a suitable cementitious material. An additional advantage of PSA is that it is a fairly consistent material due to high controls in the CHP plants. A recent report (Dunster, 2007), commissioned by the UK Department for the Environment, Food and Rural Affairs (DEFRA) mentioned that trials were conducted by UPM, one of the two UK recycled paper sludge ash manufacturers, with Lafarge Cements, utilising paper sludge ash as an ingredient in blended cements with some success. It was however mentioned that details on the trials were limited. There is also a paucity of international research on the use of PSA in cement/concrete. Some examples include work conducted in Japan and briefly presented in Ishimoto *et al* (2000), showing that mortars containing modest amounts of PSA maintained better compressive strengths after exposure to acid rain. Studies conducted at the University of Glamorgan, UK, investigated the use of blended PSA and GGBS in concrete and patented a process intended to increase the workability and compressive strength of PSA-GGBS cements. The method utilises a two stage mixing process with wet-grinding of the PSA prior to its mixing with the other binders (Mozaffari *et al*, 2006 and 2009). Mavroulidou *et al* (2013) investigated the properties of concrete in which PSA was used in concrete to partially replace cement (CEM-I) at varying percentages also considering ternary mixes of PSA with other pozzolanic materials used for partial CEM-I replacement, namely PFA, GGBS and MET and identified the best mixes also allowing for the highest CEM-I replacements. However other than such isolated publications there is generally a lack of information in the international literature; the potential use of PSA in concrete needs further investigation for the material to be used with confidence in industrial production. In addition, PSA used as partial cement replacement in glasscrete has not been investigated to the authors' knowledge. The aim of this research was therefore to perform a set of consistent tests for a wide range of properties of glasscrete, in which PSA or ternary mixes of CEM-II with PFA and PSA would be used to counteract ASR also partially replacing a fair amount of CEM-II. The testing results follow below.

2. Materials, mixes and experimental procedures

For this study recycled glass of 5mm –63 μm (brand name EcoSand) was obtained from Day Aggregates, a major UK aggregate supplier (part of the Day Group Ltd). According to information obtained from the supplier, this is post-consumer container waste glass, collected by local UK authorities' recycling programs. The plant has the capacity to wash and crush up to 55,000 t per year of mixed container glass, collected from London homes and commercial licensed premises (restaurants, pubs, clubs etc.) through the recycling programs of local authorities (Searles and Vaux, 2004). The collected glass is processed using state of the art air-separation and washing equipment, that allows the suppliers to sort, crush, screen and wash glass material and thus produce a washed, mixed coloured (mainly green-coloured) sand-sized glass material, free of corks, caps, lids and labels, that has the potential to be used as a replacement for traditional sharp sand. The cleaning and crushing process of this glass is as follows: first, any loose metal is removed by an over-band magnet prior to primary crushing so that glass size is reduced to 24mm. Further loose metal released from the glass through the crushing process is then removed via a secondary magnet. The crushed glass then passes over the primary screen, so that the cleaned 24-6mm glass is conveyed to a secondary crusher and on to a rinsing screen. All 6mm glass from the primary screen and the crushed glass from the secondary crusher is washed, sized over the rinsing screen, transferred to the fines recovery plant and sent to stockpile via a dewatering screen. Any glass particles larger than 6 mm are circulated to the secondary crusher in a closed loop, whereas the very fine, silt-sized materials are thickened and processed into cake via a filter press. The cake is removed from the site for further processing elsewhere. Clean water is recovered from the water management plant and pumped to the rinsing screen for use in the washing process. According to testing performed by the suppliers, the 5 mm-0.063 mm material meets the grading requirements for precast concrete paving blocks. Moreover, according to the supplier's health and safety assessment, the material is safe to handle and does not present any hazards to health beyond those which exist for natural sand (Day Group Ltd, 2007b). The specific gravity G_s of the materials was determined as 2.65 and 2.49 for the sand and glass respectively; the G_s of glass aggregate is close to the typical G_s values for pure glass, which confirms that the tested cullet samples are free of debris such as labels, corks etc. (these would have further reduced the G_s of the glass aggregate).

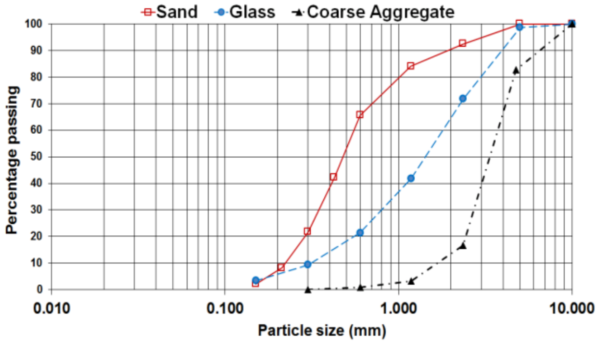

Figure 1. Particle size distribution of aggregates

Table 1. Oxide composition of PSA and PFA

Compound (wt. % as oxide)		
	PSA	***PFA***
SiO_2	33.9-16.43	45-51
Al_2O_3	18.86-2.8	27-32
CaO	61.2-36.82	1-7
MgO	5.44-0.9	1-4
Fe_2O_3	0.96-0.4	7-11
Na_2O	1.56-0.07	1
K_2O	1.31-0.22	3-4
SO_3	1.05-0.2	0.8
P_2O_5	0.52-0.1	
TiO_2	0.68-0.3	1
SrO	0.54-0.09	
MnO	0.04-0.03	
BaO	0.04-0.024	

Concrete was made with a mix design of 1:1.5:3 (1 part binder; 1.5 parts sand and 3 parts coarse aggregate), according to guidelines for RC40 (BSI, 1997). The Thames river aggregate used in the concrete mix was supplied by Travis Perkins. The fine aggregate was sand of a maximum size of 5mm; the coarse aggregate was gravel of a maximum size of 10 mm. The particle size distribution of the aggregates is shown in Figure 1. It can be seen that the glass and sand distributions have some differences however the glass is within the limits for fine concrete aggregate (but overall rather coarser than the sand used). The admixtures/binders used were (a) Limestone PC (CEM-II/A-L) obtained from LAFARGE – UK (6-20% limestone content); (b) PFA from the power station Drax in North Yorkshire, commercially distributed by CEMEX with the brand name Cemex-450S. It is a dark grey powder of a grading 12% finer than the 45μm sieve; (c) PSA from non-hazardous paper sludge provided by Aylesford Newsprint Ltd. (Kent, UK). The PSA was not milled; in this form it has an average particle size (d_{50}) of 96.1 μm (Bernal *et al*, 2014). Table 1 shows the chemical composition (in terms of ranges of main oxide %) of these particular PFA and PSA materials according to information from the suppliers and in the case of PSA also a number of sources from the literature studying the same PSA (e.g. Bernal *et al*, 2014; Rahmat and Kinuthia, 2011; Mozaffari *et al*, 2009). It can be seen that PSA is mainly a calcium aluminosilicate, as its principal compounds are lime (CaO) and silica (SiO_2). As the total content of the three major oxides in the PSA (namely silicon dioxide, aluminum oxide and ferric oxides) does not exceed 50%, the material is not strictly speaking a pozzolan. On the other hand, due to the high CaO content (much higher than that usually found in type C fly ash), the material is likely to have cementitious properties. The reason for using ternary mixes of CEM-II, PSA and PFA was that in Mavroulidou *et al* (2013) PSA was found to lower the workability of CEM-I mixes, whereas PFA is known to usually increase workability (see e.g. Mavroulidou *et al*, 2015), therefore it was added targeting this effect. Based on preliminary testing of a number of ternary mixes of CEM-II, PSA and PFA, in terms of slumps, strengths, water absorption (related to concrete durability) and accelerated mortar bar testing for alkali-silica reaction (where the natural concrete sand aggregate was fully replaced by glass culled aggregate) according to ASTM C1260-01 (ASTM, 2003) a control mix with 15% PSA and 15% PFA as partial replacement of CEM-II was selected for further testing. Different contents of glass aggregate (by mass) were used in this ternary CEM-II/PSA/PFA mix to replace the natural fine aggregate (20%, 40%, 60%, 80%, 100% of glass respectively). Several batches were made from each mix. The dry material comprising cement plus other binders, coarse aggregate, sand and/or glass aggregate was well mixed before the water was gradually added in accordance with BS EN 12390-2:2009 (BSI, 2009a) using a rotating mixer. For consistent comparisons the water/binder ratio was kept constant (i.e. 0.55) for all samples. The workability of all fresh mixes was then assessed using the slump test (BSI, 2009b). The specimens were then placed in moulds and compacted using a vibrating table. The compacted specimens were demoulded 24 hours after casting and placed in a steel tub of water, to cure as required at a minimum temperature of 20°C (± 2°C). A number of tests on the hardened mixes were then performed. These included cube compressive strength (100mm cubes) according to BS EN 12390-3:2009 (BSI, 2009c) using a Zwick Roell ToniPACT II 2000kN compression test plant. The tensile strength of mixes was determined based on the tensile splitting strength of 150 mm diameter and 300 mm height cylinders tested according to BS EN 12390-6:2009 (BSI, 2009d) using the Zwick Roell ToniPACT II 2000kN compression test plant. Prior to tensile strength testing, the static modulus of elasticity was determined using the same cylinders (BSI, 1983). Finally water absorption was tested (BSI, 2011); this is undesirable, as it allows for the ingress of aggressive chemicals, leading to premature corrosion of reinforcing steel, spalling and deterioration of concrete. The tests were performed on 72-hour oven-dried 100 mm^3 concrete cubes (cured for 28 days), which were subsequently left to cool in a dry airtight vessel for 24 h. The cubes were then completely immersed in water for 30 min; the moisture absorption was calculated as the increase in the mass of the cube after immersion, expressed as a percentage of the mass of the dry cube.

3. Results

Figure 2 shows average cube compressive strengths of triplicate specimens of the tested mixes for 7 and 28 days of curing respectively. It can be seen that some glasscrete mixes showed similar strengths as the control mix although early strength gain was lower for all glasscrete mixes (without however a particular pattern regarding the glass content). In line with the compressive strengths, the 28-day moduli of elasticity of cylinders (Fig. 3) show a small reduction in stiffness with respect to the pure CEM-II mix, with the best results being those for 20% glass. On the other hand the 28-day splitting cylinder results of glasscrete mixes show generally higher strengths to that of CEM-II mix, with the best mix being again the 20% glass mix (Fig. 4). Note that a reduction in strength is usually noted for glasscrete containing glass of above 20% (Topçu and Canbaz, 2004; Limbachiya, 2009). However Mavroulidou *et al* (2011) achieved higher strengths than those of the 0% glass mix even for high glass contents by including MET (and reactive MgO cement) in the mixes; this was at the expense of workability, which was however of pumpable levels in a number of mixes. It is notable that the control mix (0% glass) where CEM-II was partially replaced by PSA and PFA shows a somewhat reduced compressive strength compared to that containing pure CEM-II. This was presumably due to the presence of PFA, which was generally shown to reduce compressive strength (see e.g. Mavroulidou *et al*, 2015). On the other hand the mix showed a good resistance to ASR, with a recorded 14-day mortar bar expansion of 0.07%, which is below the recommended limit of 0.1%; it also allowed for a fair replacement level of CEM-II. Consequently, it was selected as the base cement mix for glasscrete in this study. Mixes with up to 40% glass also showed improved (less) water absorption than the CEM-II mix. All mixes however (including the 0% glass control mix) were found to be of low to very low slump, which would prevent mixes from being pumpable, hence they would only be applicable to specific concrete types. This issue can be addressed by the use of super-plasticisers, which was beyond the scope of this study.

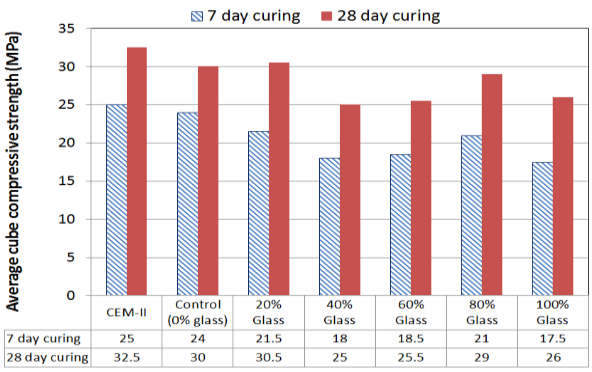

Figure 2. Cube compressive strength of mixes

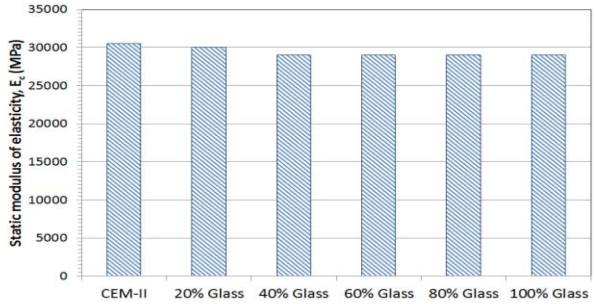

Figure 3. Static modulus of elasticity (28-day)

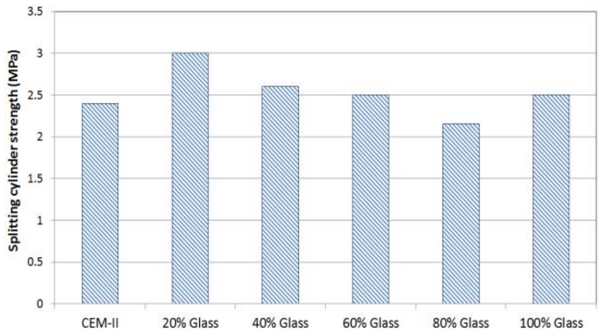

Figure 4. Indirect tensile strength (splitting cylinder)

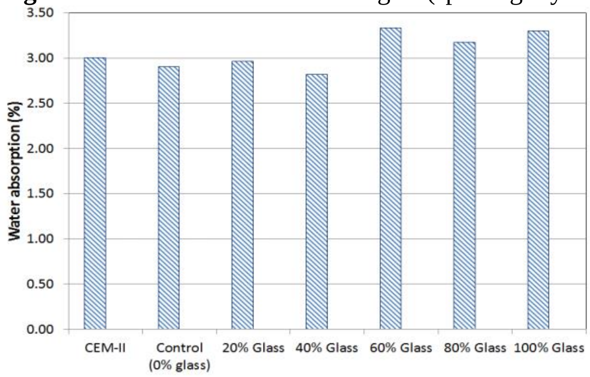

Figure 5. Water absorption of 28-day cured cubes

4. Conclusions

This study investigated the potential use of waste paper sludge ash (PSA) as a partial CEM-II replacement in glasscrete mixes with the advantages of (a) reducing ASR of the glasscrete mixes and (b) finding an additional outlet for PSA as an alternative to landfilling, while producing less energy-intensive types of concrete. The results showed that when used together with PFA at modest CEM-II replacement levels, PSA can maintain acceptable glasscrete strengths and stiffnesses compared to regular CEM-II concrete, for glass replacements of low levels (these glass contents were consistent with literature on glasscrete). On the other hand, durability performance such as water absorption improved for a number of mixes, while PSA and PFA counteracted ASR. Further mix optimisation can address the issue of reduced workability and potentially allow for higher glass or cement replacement levels in the mixes.

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