USE OF WASTE GLASS IN CEMENT-BASED MATERIALS

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Abstract:
Demand for recycled glass has considerably decreased in recent years, particularly for mixed-glass. Glass is cheaper to store than to recycle, as conditioners require expenses for the recycling process. There are several alternatives for the reuse of composite-glass. According to previous studies, all these applications, which require pre-conditioning and crushing, are more or less limited and unable to absorb all the quantities of waste glass available. In order to provide a sustainable solution to glass storage, a potential and incentive way would be to reuse this type of glass in concretes.
Depending on the size of the glass particles used in concrete, two antagonistic behaviours can be observed: alkali-silica reaction, which involves negative effects, and pozzolanic reaction, improving the properties of concrete.
The work undertaken here dealt with the use of fine particles of glass and glass aggregates in mortars, either separately or combined. Two parameters based on standardised tests were studied: pozzolanic assessment by mechanical tests on mortar samples and alkali-reactive aggregate characteristics and fines inhibitor evaluations by monitoring of dimensional changes. It is shown that there is no need to use glass in the form of fines since no swelling due to alkali-silica reaction is recorded when the diameter of the glass grains is less than 1mm. Besides, fine glass powders having specific surface areas ranging from 180 to 540m² / kg reduce the expansions of mortars subjected to alkali-silica reaction (especially when glass aggregates of diameters larger than 1 mm are used).

Keywords: Waste-glass, recycling, glass aggregate, glass powder, alkali-silica reaction, pozzolanic reaction, mortar.

1. INTRODUCTION

Glass is a common product that can be found in different forms: bottles, jars, windows and windshields, bulbs, cathode ray tubes, etc. These products have a limited lifetime and must be recycled in order to avoid environmental problems related to their stockpiling or landfilling. Several recycling channels already exist for glass recovery.

This paper deals with the recycling of glass bottles, which can usually be reused after being crushed and melted.

This operation is easily feasible when the glass is recovered as separate colours to produce glass products of the same colour. However, most of the time, the collected glass is mixed and so unusable for the production of bottles of a given colour. Consequently, this glass can either be reused for other but limited purposes, or be sent to a landfill.

One of the possible channels for the recycling of mixed glass is cement-based materials, but most of existing studies recommend its use only as fine powders [1, 2, 3]. Fine particles of glass usually present pozzolanic activity beneficial to the concrete, while coarse particles are usually deleterious to concrete due to alkali-silica reaction (ASR). Although the use of fine particles is an effective solution for glass in concrete, the crushing of glass represents a significant cost since several hours of treatment are needed to obtain an efficient fineness of glass (almost equivalent to cement).

The aim of this study is to recycle glass in cement-based materials by combining fine and coarse glass particles, leading to a decrease in the crushing energy used. It is assumed that it is possible to take advantage of the beneficial activity of fine particles to counteract the deleterious effect of coarse grains.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

The glass used in this study was bottle soda-lime silica glass of mixed colours, coming from the Unical group (Canada). It was composed of 40, 33, 20 and 1% of colourless, brown, green and blue glasses, respectively. The material also contained around 6% of impurities. The density was 2.5 g/cm^3.

Different sizes of glass particles were obtained after grading, washing, drying, crushing and sieving the raw material. Tables 1 and 2 give the chemical composition and the fineness respectively of the classes used in this study.

The cement used was a Portland cement, CEM I 52.5R, according to EN 197-1 [4], having a Blaine specific surface area of 440 m^2/kg. Its chemical composition is given in Table 1.

The aggregate was a non-reactive marble sand having a density of 2.7 g/cm^3. Four size classes were prepared after crushing and sieving. The particle size distribution ranged from 160 to 2500 µm. Particles under 160 µm were rejected to avoid the interaction of fine non-reactive particles with fine glass particles. Table 3 gives the different classes used for this non-reactive marble.

Table 1. *Chemical composition of glass and cement (% by mass)*

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Loss on ignition
Glass	68.6	2.0	0.3	12.3	1.0	0.2	13.5	10.0	1.0
Cement	19.8	5.6	2.5	63.6	1.8	3.1	0.1	0.7	1.7

Table 2. *Fineness of glass particles*

Glass classes	C0	C1	C2	C3	C4	C5	C6	C7	C8
Mean diameters of particles (µm)	3750	1875	940	472.5	237.5	120	10,8	10,8	7.8
Specific surface area* (m^2/kg)	1.1	2.2	4.5	11	18	35	182	389	538

* calculated from the average diameter of particles

Table 3. *Mean diameters of classes of marble non-reactive sand*

Classes of sand	C1	C2	C3	C4
Mean diameters of particles (µm)	1875	940	472,5	237,5

2.2 Sample preparation and test methods

All tests were carried out on mortars made of one part of cement and three parts of sand, by mass. The water-cement ratio was set to 0.6. Alkalis (KOH tablet) were added to the water to reach 5.6 kg/m^3 of Na_2O_{eq} (including alkalis of the cement). Mortars were prepared according to standard EN 196-1. They were cast in 2x2x16 cm prisms and demolded 24 hours after casting. The prisms were then stored at 60°C, after being placed on grids in watertight containers containing 20 mm of water (mortar bars were not in contact with the water). Expansion was measured using the scale micrometer method (specimens had shrinkage bolts at both ends). Each measurement was the mean of three values from three replicate specimens. Expansion measurements were performed after the containers and the prisms had been cooled for 24 hours at 20ºC.

The first part of the study consisted in evaluating the swelling potential due to alkali-silica reaction of all size-classes of glass. So 20% of non-reactive sand was replaced in each mortar by glass of equivalent fineness. Grading curves were adapted when the tested glass class was out of the range of non-reactive sand (160-2500µm). In the second part of the study, the efficiency of fine glass particles to counteract the ASR of coarser ones (C0 and C1) was tested, by using three classes of fines (C5, C6 and C8) as 20 and 40% replacement of non-reactive sand. Tables 4 and 5 summarize the different mortars tested in both series.

3. RESULTS

3.1 The different classes of glass tested separately

Results of expansion measurements on mortar prisms made with 20% of glass of different classes (replacement of non-reactive sand) are given in Figure 1. It can be seen that the particle size of the glass is a major parameter controlling the expansion values. A critical threshold of grain size around 0.9-1mm was observed, under which no expansion occurred. Only coarse particle size classes (2.5-5mm and 1.25-2.5mm) led to significant expansion of mortar prisms. Particle sizes under that threshold had no effect on length variations. Some authors have already evoked the existence of a critical diameter causing abnormal expansion due to ASR. Jin et al. [5], Xie et al. [6] and Byars et al. [7] estimated this diameter to be between 0.60 and 1.18mm. However, other authors have found lower values: between 0.15 and 0.30 for Yamada et al. [8] and 0.038mm for Meyer et al. [9].

Table 4. *Mortars made to evaluate the swelling potential due to alkali-silica reaction of all size-classes of glass*

Classes of glass	**C0**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
Notation of mortars	M0	M1	M2	M3	M4	M5	M6	M7	M8
Replacement of sand					20%				

Table 5. *Mortars made to evaluate the efficiency of fine glass particles to counteract ASR of coarser particles C0 and C1*

Notation	**Type and content of aggregate**		**Type and content of fines**		
	C0	C1	C5	C6	C8
C0-20%C5	20%		20%		
C0-40%C5	20%		40%		
C0-20%C6	20%			20%	
C0-40%C6	20%			40%	
C0-20%C8	20%				20%
C0-40%C8	20%				40%
C1-20%C5		20%	20%		
C1-40%C5		20%	40%		
C1-20%C6		20%		20%	
C1-40%C6		20%		40%	
C1-20%C8		20%			20%
C1-40%C8		20%			40%

In the actual conditions of the test, glass particle sizes under 1mm were not deleterious in terms of alkali-silica reaction (ASR). In order to evaluate the consequences of this result on the mechanical behaviour of the mortars, compressive strength tests were carried out on all mixtures. Figure 2 gives the compressive strength results of mortars containing the different size classes of glass and cured in the same conditions as for ASR tests. It can be seen that, compared to reference mortar without glass, the strengths were up to 10 MPa lower when alkali-reactive classes C0 and C1 were used. In contrast, fines of classes C3 to C8 systematically gave extra strength, which increased with the fineness of the glass particles. The most significant effects were obtained with fines of 80µm or less, the strength increases being of about 30-35 MPa for the finer particle sizes (C6, C7 and C8).

This series of tests seemed to show that glass particles need to be crushed in order to use them without risk of swelling. However, is it necessary to completely renounce the use of coarse glass particles in concrete? Although coarse glass can potentially deteriorate concrete, its use presents at least two benefits: a low crushing cost and an increase of the amount of glass that can be incorporated in the concrete. For instance, assuming a typical concrete mix design containing 1800 kg/m^3 of aggregates, a replacement of 20% of aggregate by the glass leads to the use of 360 kg/m^3 of glass. So a second series of tests were carried out to test the efficiency of fine glass particles to counteract the ASR of coarser ones.

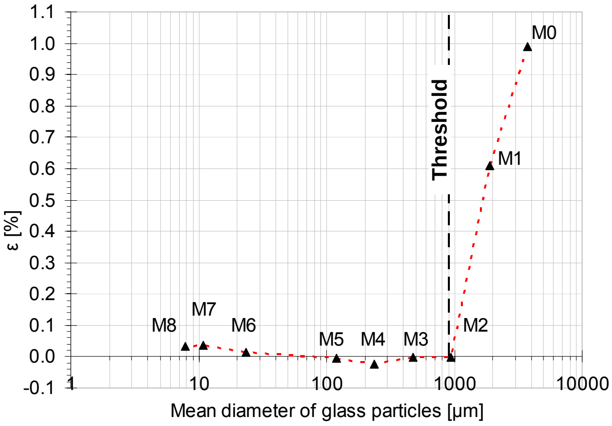


Figure 1. *Influence of glass particle size on expansion*

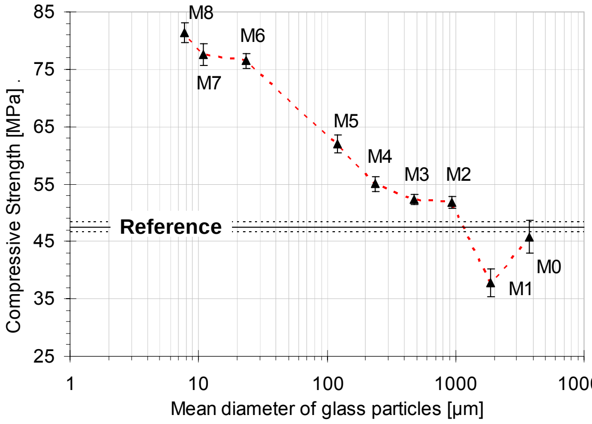


Figure 2. *Influence of glass particle size on compressive strength development*

Mortar bars containing 20% of different glass particle sizes (treatment: 78 weeks-60°C-100%HR)

3.2 Fine and coarse classes of glass combined in the same mortars

Figure 3 reports the expansion-time curves of mortars containing the combinations of C0 or C1 (20% of the aggregate) with one of the three classes of fines C5, C6 or C8 (20 or 40% replacement of non-reactive sand). It can be seen that the use of glass fines led to a reduction of expansion of mortars in comparison with mortars with coarse particles C0 or C1 alone. This reduction depended on the fineness of the glass (C5, C6 or C8) and the quantity of fines (20 or 40%). All three classes of fines systematically led to a decrease of the expansion provoked by C0 or C1, even for the class having the lowest fineness (C5). The general trend observed was that, the higher the particle finenesses, the lower the expansions of the mortars.

Figure 4 shows that the efficiency of fines in reducing expansion was significantly improved when the amount of fines increased, whatever the coarse particle size used (C0 or C1). The reductions reached 50 to 90% when 40% of fines were used, as against 25 to 70% for 20% of fines. 40% of fines C6 or C8 (i.e. particle size < 80µm) could lead to a reduction of 90%. Here, the effect of fineness was less significant. Figure 5 highlights the general trend of the effect of fines in mortars: they reduced the expansion and increased of strength of mortar prisms.

Figure 6 gives the mean effects of fines on the compressive strength of mortars containing alkali-reactive classes C0 and C1: the particle size of fines had a significant effect on both expansion and compressive strength. The pozzolanic activity was responsible for these results. However, it should be kept in mind that high temperatures involve high energy of activation of the pozzolanic reaction. In-situ tests should thus be carried out to confirm these laboratory results.

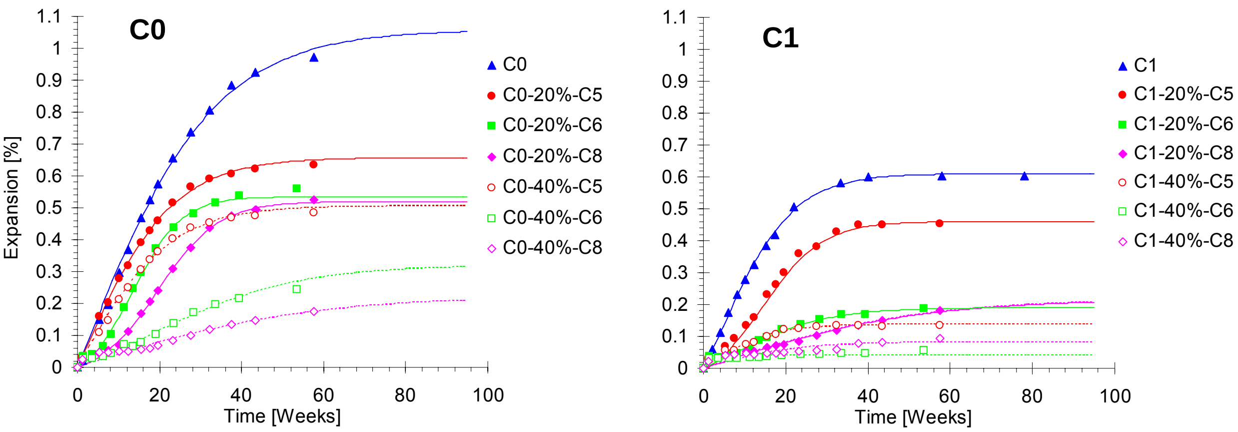
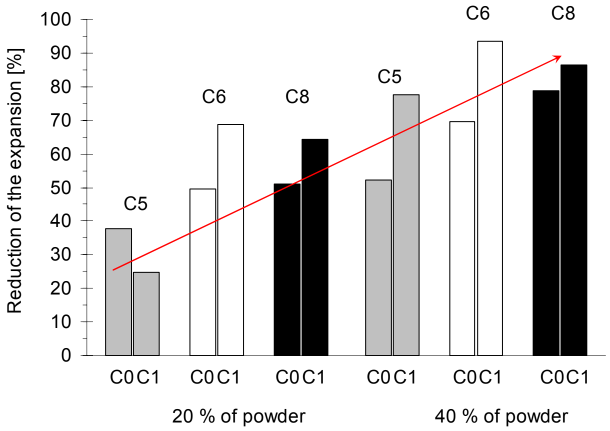


Figure 3. *Effects of fine glass on expansion of mortar bars containing reactive aggregate C0-C1 (mixes containing 20% coarse glass and various amounts of fine glass) (treatment:60°C-100%HR)*



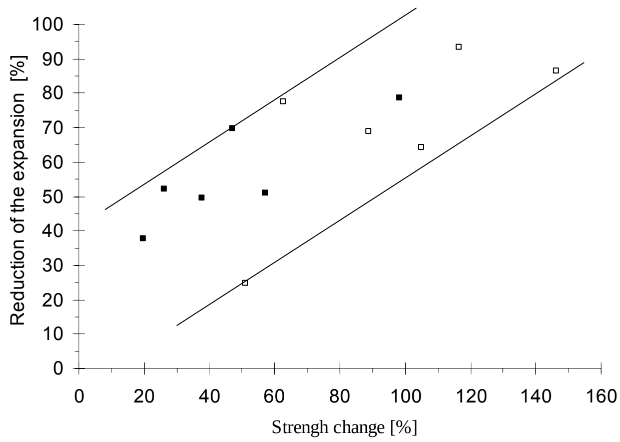


Figure 4. *Effect of glass powder (20 and 40%) on the reduction of expansion of mortar made with 20% glass aggregate (C0, C1)*

Figure 5. *Reduction of expansions with increased compressive strength of mortars containing fine particle of glass*

(treatment: 43 weeks-60°C-100%HR)

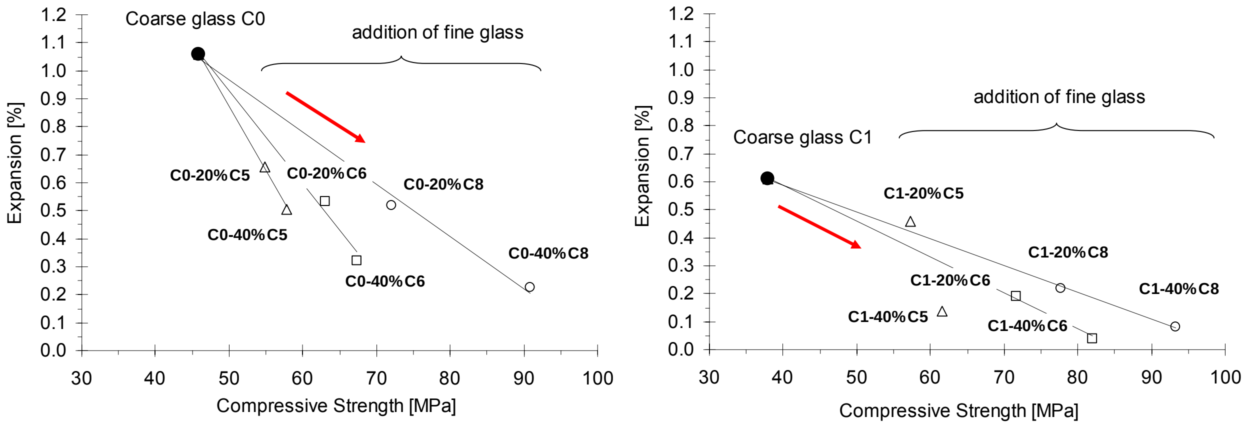


Figure 6. *Effect of fine glass on the expansions and the compressive strengths of mortars containing glass aggregates C0 or C1.*

4. DISCUSSION

It has been suggested that the deleterious or beneficial activity of a material towards ASR depends on its particle size [10, 11]. Thus glass powders and typical pozzolans, such as fly ash or silica fumes, could probably be classified in the same category and their activity as ASR-reducers might be explained using the same mechanisms as proposed for pozzolans. Several mechanisms have been put forward to explain the effectiveness of pozzolans against ASR:

- A decrease in the permeability of the concrete and thus in the ionic mobility, leading to a reduction of the migration of alkalis towards the reactive aggregate [12-20].
- An improvement in the strength of the cement paste and a consequently higher resistance to the expansive stresses due to ASR-gels [13,15,17,19].
- A dilution of alkalis in concrete when low-alkali pozzolans are used as cement replacement [14].
- A depletion of portlandite, leading to a decrease in pH and/or to the production of non-destructive gels [21-23].
- A production of low-expansion gels having high $CaO/(Na_2O)_e$ ratios [20].
- A production of pozzolanic C-S-H of low C/S ratio, which have the capacity to absorb a significantly higher quantity of alkalis than normal C-S-H, thus reducing the quantity of alkali ions and the pH in the pore solution [12,14,19,24-27].

5. CONCLUSION

This study aimed to evaluate the preventive role of pozzolanic glass fines in counteracting the deleterious effect of alkali-reactive glass aggregates. It has been shown that the use of both types of glass particles is pertinent. The main results were that:

- Only glass classes of more that 1mm gave expansions related to alkali-silica reaction.
- The use of glass fines led to the reduction of mortar expansion due to coarse particles; moreover, fines increased the compressive strength of mortars.
- No excessive crushing of glass fines was needed since the quantity of fines was the main parameter controlling the reduction of expansion due to coarse glass aggregates. It is thus preferable to use 40% of class C5 (d_{50} of 120µm) rather than 20% of class C8 (d_{50} of 8µm). These results lead to economic benefit: more glass can be used and the crushing time required can be limited.

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