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ALKALI-AGGREGATE REACTION EXPANSION OF MORTAR BARS CONTAINING GROUND GLASS POWDER

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ABSTRACT

This paper examines alkali-silica reaction expansion of mortar bars containing ground container glass powder using ASTM C1260. The expansion of the mortar bars decreases as the glass content increases. It requires 50% cement replacement with ground soda-lime glass powder to reach 0.1% expansion at 14 days. Alkali content of cement does not show a significant effect on the expansion of mortars when the aggregates used are reactive. The glass particle itself generates little expansion when it is smaller than 300 μm and is used with inert sands. Microstructural examination of these mortars after the alkali-aggregate reaction expansion measurements indicated that the replacement of 10% Portland cement with glass powder reduces the observable free lime content and improves the interfacial zone between cement paste and aggregate significantly.

Keywords: Glass powder; Alkali-aggregate reaction; Expansion, Microstructure, Particle Size

1. INTRODUCTION

The management of waste consumer glasses poses a major problem worldwide. Use of recycled materials in construction is among the most attractive options because of the large quantity in need and widespread sites of construction. The current applications of recycled glasses include a partial replacement for aggregate in asphalt concrete, as fine aggregate in unbond base course, pipe bedding, landfill gas venting systems, gravel backfill for drains [1]. Attempts have been made for a long time to try to use mixed waste glasses as aggregates in cement concrete, but cement concrete made with waste glasses as aggregates always cracks [2-5]. On other hand, very limited work has been conducted on the use of ground glass as a cement replacement in concrete [6-8]. The main concern for the use of glass powder as a cement replacement in concrete is that alkalis in glass powder can be leached out, resulting in alkali-aggregate reaction (AAR) expansion when the aggregate is alkali-reactive.

It is generally agreed that AAR can be divided into two categories: (a) alkali-silica reaction (ASR) and (b) alkali-carbonate reaction (ACR). ASR is of more concern than ACR because the occurrence of aggregates containing reactive silica minerals is more common. ASR has been extensively investigated and its reaction mechanism can be summarised in following five main steps [9-12]: 1) breaking Q4 siloxane bonds (Si-O-Si) into Q3 silanol bonds (Si-OH) due to hydroxide ions (OH^-) attack; 2) reaction of silnaol sites with OH^- in solution to neutralize those sites; 3) the negatively charged Q3 sites are counter-balanced by K^+, Na^+ and Ca^+ cations; 4) dissolution of silica due to continued hydroxide ions attack on Q3 sites to form silica ions; 5) afterwards, reaction of silicate species in solution with cations in the pore solution to form C-S-H and/or C-K-S-H hydrate.

The objectives of the current investigation were to examine the effects of glass powder replacement levels and fineness on the ASR expansion of mortars containing glass powder as a cement replacement.

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2. EXPERIMENTATION

2.1 Cement and Glass Powders

A typical commercial ASTM Type I Portland cement with total equivalent alkali content (Na_2O + 0.658 K_2O) of 0.65% was used. Four glass powders were obtained from a glass beads manufacturer in New York, USA. One is from the screening of crushed glasses (GP-fine), one from a dust collector for the crushing of glasses (GP-dust) and the other two, GP-4000 and GP-6000, from the grinding of GP-dust in a ball mill. The chemical composition and some physical properties of the cement and glass powders are listed in Table 1.

The particle size distributions of four glass powders were measured using a particle size analyzer and shown in Fig.1. The particle size distribution of the ASTM Type I Portland cement used in this study is also plotted for comparison purpose. It can be seen that the GP-fine from screen process are very coarse and the particle size ranges from 40 to 700 μm. The GP-dust from dust collector is finer than the GP-fine, but still much coarser than Portland cement. Portland cement contains about 40% of particles smaller than 10 μm, while the GP-dust contains only about 20% particles smaller than 10 μm. The particle size distributions of the glass powder GP-4000 and GP-6000 are very similar to that of the portland cement.

Table 1 Chemical Composition of Raw Materials

Oxide	Composition (%)	
	Cement	Glass
SiO_2	20.33	72.5
Al_2O_3	4.65	0.16
Fe_2O_3	3.04	0.2
CaO	61.78	9.18
MgO	3.29	3.65
SO_3	3.63	0.39
Na_2O	0.24	13.2
K_2O	0.59	0.12
Total alkali as Na_2O	0.63	13.28
Blaine Fineness (m^2/kg)	383	*
Specific gravity	3.15	2.47

* GP-fine = N/A; GP-dust = 264; GP-4000 = 467; GP-6000 = 582

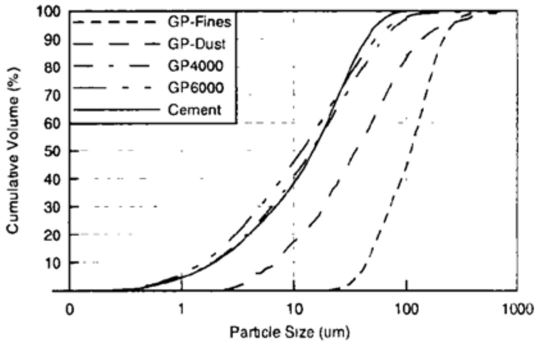


Figure 1 Particle Size Distribution of Glass Powders and Portland Cement

2.2 Aggregates

A known highly reactive siliceous limestone sand from Spratt Quarry in Ottawa, Ontario, Canada was used. Spratt has been extensively investigated in Canada and is designated as a standard alkali-reactive aggregate in the specification of the Canadian Standard Association (CSA). Another known non-reactive crashed limestone sand was used to examine whether different sizes of glass powder would cause expansion. These sands were sieved and mixed in proportions as per ASTM C1260.

2.3 Specimen Preparation and Length Measurement

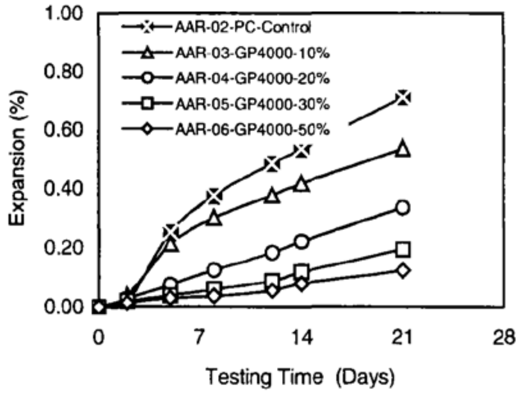
The rapid mortar bar test method ASTM C1260 was used to examine the expansion of different mortar bars. In one batch of the tests the cement was used as it is as per ASTM C1260. In other batches of the tests, additional NaOH was added into the cement to have total equivalent alkali content (Na_2O_e) of 0.90 as specified by Canadian Standard Association Specification CSA A23.2-25A.

Three 25 × 25 × 275 mm mortar bars were prepared for each test mixture in accordance with ASTM C227. The mixtures were proportioned to have an aggregate to cementitious material ratio of 2.25 and water to cementitious material ratio of 0.47. Immediately after casting, the molded specimens were taken into a moisture room at 23±2°C, and covered with plastic sheets. After 24 hours in moulds, the specimens were demolded, immersed in water in a closed container and maintained at 80°C for 24 h. Then, these specimens were measured for initial lengths and immersed in a 1 M sodium hydroxide solution in a closed container maintained at 80°C throughout the testing period. The length changes of these specimens were measured at 4, 7, 11, and 14 days as suggested by ASTM C1260. The measurements were performed very quickly so as to avoid a significant cooling of the specimens. All tests were extended to 21 days for the further observation of their expansions.

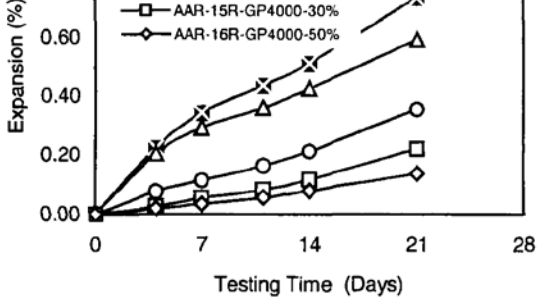
3. RESULTS AND DISCUSSION

3.1 Effect of Glass Replacement on Expansion

Fig. 2 (a) and (b) show the expansions of mortar bars containing reactive Spratt sand and different amounts of GP-4000. It used the cement as it was for Fig. 2 (a), while additional NaOH was added to the cement to have a total equivalent alkali content of be 0.9 for Fig. 2 (b). It can be seen that the two different alkali contents do not show a significant effect on AAR expansions. The mortar bars made with higher alkali cement show only slightly higher expansion than those made with low alkali cement after 21 days.



(a) Cement Na_2O_e=0.63%



(b) Na_2O_e=0.90%

Figure 2 Effect of cement alkali content and GP replacement levels on AAR expansion

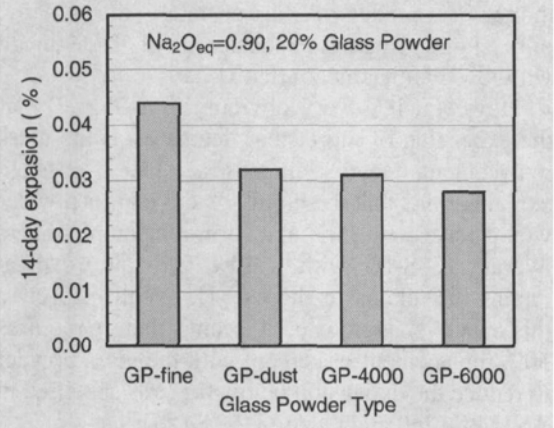
However, it is very obvious, from Fig. 2, that the expansion of mortar bar decreases as the glass replacement level increases. One possible explanation is that the highly reactive glass powder would react with lime and form a calcium silicate hydrate (C-S-H) with a low C/S ratio, which retains the alkalis in the C-S-H. With respect to this reactive aggregate, it seems that it requires 50% replacement of cement with the glass powder to reduce the expansion below 0.1% as specified in ASTM C1260 and CSA 23.2-25A.

3.2 Effect of Glass Fineness

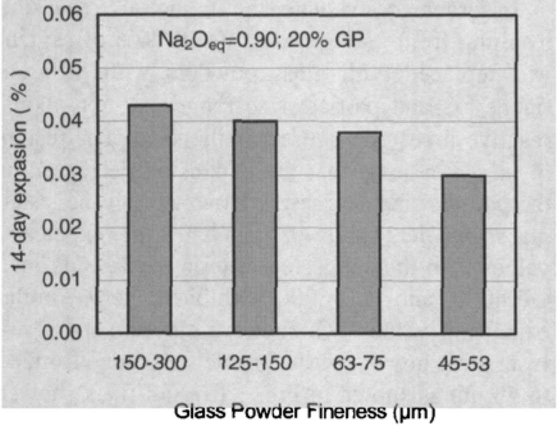
In order to evaluate the potential expansion resulting from glass powder itself, 20% of cement was replaced with glass powders with different finenesses and particle size ranges. A non-alkali-reactive limestone is used as the sand. The results in Fig. 3 indicate that the expansion decreased as the particle size decreased. However, all the tested glass powders showed much lower expansion values than the suggested criteria 0.1%. GP-dust, GP-4000 and GP-6000 exhibited very similar expansion values, which were close to the result from glass powder with particle size range from 45 to 53 μm as shown in Fig. 3 (b). GP-fines showed an expansion value similar to the result from glass powder with particle size range from 150 to 300 μm. Therefore, it can be concluded from this study that the glass powder itself will not produce deleterious expansion if it is smaller than 300 μm.

3.3 Microstructure of Mortar Bars

The microstructures of these cement mortar bars containing different amounts of glass powder GP-4000 were examined after 28 days expansion measurements using a personal SEM. Fig. 4 is a typical SEM picture of the fracture surface of the control mortars, which indicates that all the fractures go through the interface between and cement paste. Under high magnifications, a very porous interfacial transitional zone could be observed between the sand and cement paste, which is often observed in Portland cement mortars [13]. On other hand, massive gel could be observed on the cement paste where an aggregate particle was pulled out, as shown in Fig.5. Chemical analysis by EDAX indicated that the gel consisted mainly of Na_2O, CaO and SiO_2. This means that it is a $Na_2O.CaO.SiO_2.H_2O$ or N-C-S-H gel.



(a) glass powder types



(b) Glass Powder Particle Size

Figure 3 Effect Of Fineness of Glass Powders on Expansion of Mortar Bars

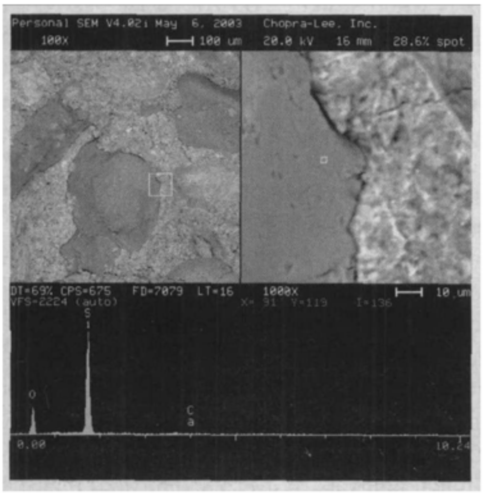


Figure 4 Typical Fractured Surface of Mortar Bar Containing 100% Portland Cement and Spratt Sand After Alkali-Aggregate Reaction Test for 28 days

The interesting thing is that when 10% Portland cement was replaced with glass powder, no obvious exposed aggregate could be observed on the fractured surface. Extensive search did identify an interfacial zone, as shown in Fig.6, which looked like a bulk paste. Some massive gel still could be observed on the cement paste side. EDAX analysis indicated that the gel consisted mainly of Na_2O, CaO and SiO_2 (Fig. 6-a). Trace amounts of Al and Mg were also detected. EDAX also confirmed that the other particle in the picture was the limestone aggregate particle (Fig 6-b).

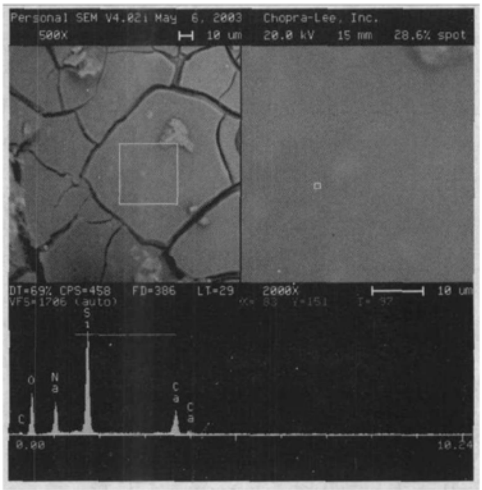


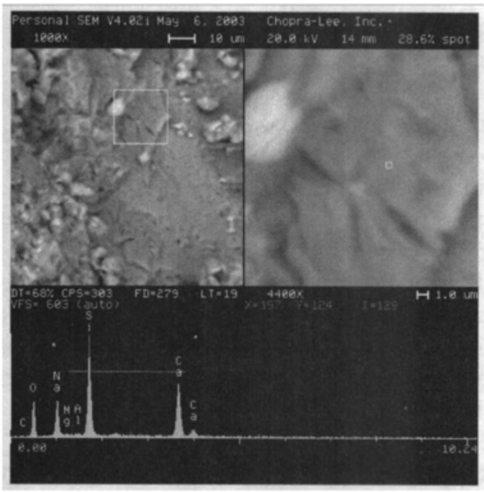
Figure 5 Massive N-C-S-H Gel in Mortar Bar Containing 100% Portland Cement and Spratt Sand After Alkali-Aggregate Reaction Test for 28 days

When the glass powder content was increased to 20% or more, it was also very difficult to identify the exposed aggregate on the fractured surface. Some small aggregate particles could be occasionally identified. However, no obvious massive gels could be identified like in the control mortars or in the mortars containing 10% glass powder, as shown in Figs. 7 and 8.

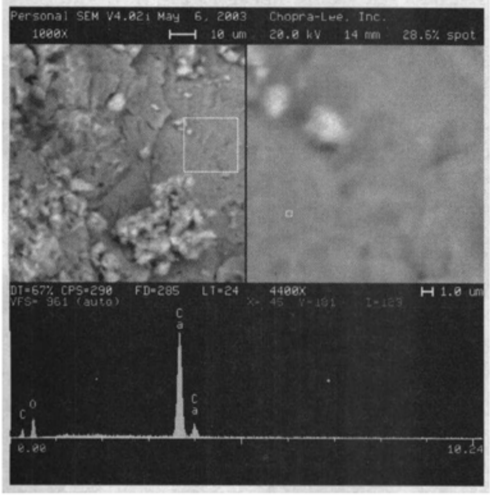
4. DISCUSSIONS

The glass powders were from container glasses and consist of approximately 72% SiO_2, 13% Na_2O, 9% CaO and 4% MgO. A previous study [8] confirmed that finely ground glass powder is a highly reactive pozzolanic material, even much more reactive than a quality coal fly ash due to its high concentrations of Na_2O and CaO.

In a Portland cement – glass powder – water system, appreciable concentrations of Na^+, K^+, OH^-, Ca^{2+} and SO_4^{2-} from the cement components enter



(a) SEM/EDAX of Cement Paste



(b) SEM/EDAX of Aggregate

Fig.6 SEM/EDAX of Cement Mortar Containing 10% Glass Powder

into the mixing water during mixing. The high concentration of OH^- in the solution attacks the surface of glass particles very quickly. Since Na-O and Ca-O bonds are much weaker than Si-O bonds, Na^+ and Ca^{2+} in the glass particles are dissolved into the solution first, followed by the depolymerization of silicate network in the glass:

$$\equiv Si\text{-}O\text{-}Si\equiv + 3OH^- \rightarrow [SiO(OH)_3]^- \ldots\ldots\ldots\ldots\ldots(1)$$

Na^+ and Ca^{2+} react with $[SiO(OH)_3]^-$ in the solution to form N-C-S-H which precipitates:

$$Ca^{2+} + Na^+ + [SiO(OH)_3]^- \rightarrow \text{N-C-S-H} \ldots\ldots\ldots\ldots(2)$$

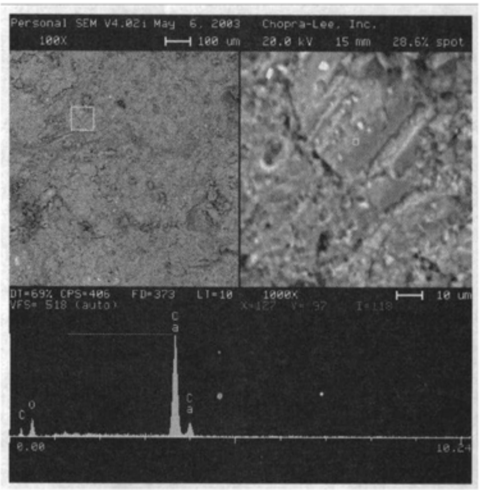


Figure 7 Typical Fractured Surface of Mortar Bar Containing 20% Glass Powder and Spratt Sand After Alkali-Aggregate Reaction Test for 28 days

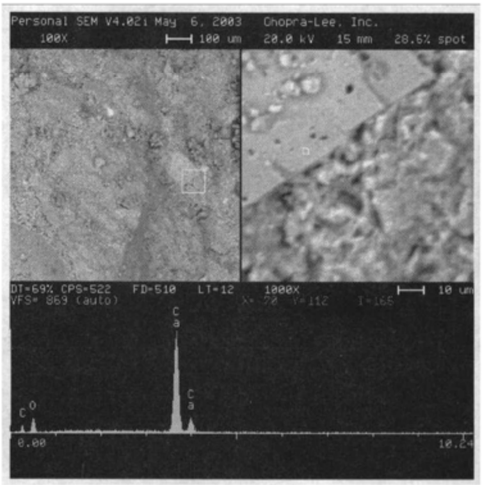


Figure 8 Spratt Particle in Mortar Bar Containing 30% Glass Powder and Spratt Sand After Alkali-Aggregate Reaction Test for 28 days

Of course, the N/S ratio in the N-C-S-H is dependent on the concentrations of Na^+ in the solution and the C/S ratio in the N-C-S-H [14].

Kalousek [15] found that the limited composition for N-C-S-H system is $0.25Na_2O.CaO.SiO_2.xH_2O$. The N/S and C/S ratio in soda-lime glass are 0.134 and 0.10, which means that the glass has a large potential to consume free lime and alkalis in the solution. This may explain why even the replacement of 10% Portland cement with glass powder can still reduce the expansion of the mortars.

SEM observations have confirmed that the replacement of 10% portland cement with glass powder significantly improve the interfacial zone between cement paste and aggregate. The molar weight of SiO_2 is 46 and the molar weight of CaO is 56. The complete reaction of the 10% glass powder could consume up to 15% $Ca(OH)_2$ by mass if $1.5CaO.SiO_2.nH_2O$ is formed. This means that 10% of replacement of Portland cement with glass powder can consume most of the free lime in the cement mortars. As more glass powder is used to replace cement, more alkalis and Ca^{2+} will be consumed by the glass powder into pozzolanic reaction product N-C-S-H, which results in lower potential for alkali-aggregate reaction and associated expansion.

Meyer et al. [5, 16] investigated how glass particle size affected the expansion of cement mortars when glass is used as an aggregate. The results indicated that there is a pessimum size for expansion, which differs from different type of glass. Fig.9 shows how the particle size of soda-lime (container) glass affects the expansion of cement mortars. The results in Fig.9 indicated that the pessimum size for the soda-lime glass is between #8 and #16 sieve size (or between 1.18 and 2.36 mm), and the size shows only a slight effect once the size is passing #50 mesh (or smaller than 300 um). This is in agreement with the findings in this study. Since once the glass particle is smaller than certain size, the glass particle will react with lime and alkalis from the hydration of the cement or in the glass itself to form N-C-S-H very quickly, which does not cause significant expansion itself.

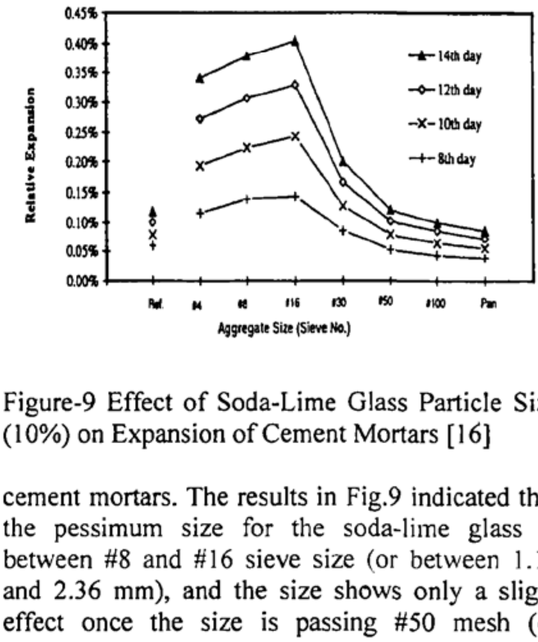


Figure-9 Effect of Soda-Lime Glass Particle Size (10%) on Expansion of Cement Mortars [16]

5. CONCLUSIONS

The results of ASTM C1260 testing indicated that the ASR expansion of mortars containing ground glass powder decreased as the glass replacement level increased although ground glass was not effective as coal fly ash in reducing the expansion. It required a 50% replacement of cement with ground glass in order to control the expansion on the mortars below 0.1%.

In the ASTM C1260 test, the alkali content of cement did not show a significant effect on the expansion of mortars when the aggregates used are reactive.

SEM observation of these mortars after the alkali-aggregate reaction expansion measurements indicated that the replacement of 10% Portland cement with glass powder improved the interfacial zone between cement paste and aggregate significantly. Massive N-C-S-H gel could be easily identified in the control cement mortars, but with difficulty in the mortars containing 10% glass powder, but not in those mortars containing 20% or more glass powder.

Results from this study indicated that expansion from glass powder itself was minimal if the particle size was smaller than 300 μm although the expansion might still increase as the glass powder particle size increased. The combined use of cement containing glass powder and inert aggregate did not show any substantial expansion.

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