THE USE OF GROUND GLASS AS A POZZOLAN

Michael Thomas[1], David Smith[2], and Edward Moffatt[3]

[1] Department of Civil Engineering, University of New Brunswick, Fredericton, NB, Canada
[2] WSP, Vancouver, BC, Canada
[3] Department of Civil Engineering, Queens University, Kingston, ON, Canada

Corresponding author email: mdat@unb.ca

Abstract

The paper presents data on the durability of concrete produced using ground glass as a pozzolan. Various sources of glass were used including soda glass, e-glass and Pyrex glass. All the materials showed excellent pozzolanic activity when ground to pass 75-microns. The use of ground glass resulted in substantial reductions in permeability and chloride penetrability, and improved resistance to sulfate attack. Air-entrained concrete containing glass showed good freeze-thaw resistance. E-glass and borosilicate glass were effective in preventing deleterious expansion due to alkali-silica reaction (ASR). Bottle glass, which contains substantial amounts of alkali, was not efficacious with regards to ASR. The inclusion of bottle glass results in very substantial increases to the pore solution alkalinity and this can result in substantial increases in expansion in concrete containing reactive aggregate and low-alkali cement. It is shown that the accelerated mortar bar test is not suitable for evaluating the impact of high-alkali materials on ASR as the alkalis contributed by the cementing materials are released when the mortar bars are masked by the conditions of the test (first immersed in hot water and then in hot NaOH solution).

Keywords: ground glass, pozzolan, concrete, durability, alkali-silica reactivity.

1. State-of-the-Art: Alkali-Silica Reactivity and Pozzolanicity of Glass

1.1. Crushed glass as (alkali-silica) reactive aggregate

The potential for crushed glass aggregate to undergo deleteriously alkali-silica reaction (ASR) has been reported by numerous workers, some of the earlier reports including Johnston (1974) and Phillips, Cahn & Keller (1972), but this has been known since shortly after the initial discovery of ASR. The U.S. Bureau of Reclamation (Gilliland & Moran 1949; Moran & Gilliand 1950) developed a mortar bar expansion test using Pyrex glass as a "standard reactive aggregate" to evaluate the efficacy of pozzolans for controlling ASR. For example, in the specification for the Davis Dam in Arizona the requirement for the pozzolan, among other properties, was to affect a reduction of at least 75% in the 14-day expansion of mortar bars produced with high-alkali cement plus 20% pozzolan plus Pyrex glass when stored over water at 100°F (38ºC). This test method became the "Pyrex mortar bar test", ASTM C 441 which was first published in 1950.

In his formative work on ASR, Thomas Stanton (1940) demonstrated that reactive aggregate did not produce damaging expansion when it was finely ground below a certain maximum particle size. Numerous workers have since shown that this is also the case for ground glass with little expansion being observed when the particle size is reduced below somewhere in the region of 75 microns; earlier studies include Samtur (1974) and Pattengil & Shutt (1973), and more recent studies include Jin et al (2000), Shayan & Xu (2004) and many others.

Previous studies have also shown that when crushed glass is used as a coarse or fine aggregate in concrete deleterious expansion can be reduced or, possibly eliminated, by the incorporation of a sufficient quantity of a suitable pozzolan. For example, Johnston (1974) demonstrated this with fly ash, Shayan & Wu (2004) with silica fume, and there have, of course, been a multitude of studies conducted using the ASTM C 441 mortar bar test to demonstrate the efficacy of pozzolans and slag with crushed and graded Pyrex glass since Pepper & Mather (1959).

1.2. Ground glass as a pozzolanic material

The potential use of ground glass as a pozzolan was reported by Pattengil & Shutt (1973) who tested soda-lime container glass crushed and milled to a pass 325 mesh (45-microns sieve). Since this time other workers have confirmed that ground glass exhibits good pozzolanic provided it is ground to sufficient fineness. Little pozzolanic reaction is evident for glass above 300 microns but the pozzolanic activity increases as the particle size is reduced below this size with good pozzolanic properties generally being achieved below about 45 microns (Federico & Chidiac 2009).

It is well-established that the use of pozzolans can lead to improvements in concrete performance including increases in strength, enhanced durability in aggressive environments, and the ability to reduce the expansion due to ASR (Thomas 2013). In this paper the impact of low-alkali E-glass on various properties of concrete are presented for two levels of glass fineness.

1.3. Ground glass and ASR

Alkali-silica reactive aggregate when finely ground will behave like a pozzolan. This was first proposed by Vivian (1951) and has been taken advantage of in many places such as Iceland where ground rhyolite has been used to produce pozzolans for controlling ASR (Gudmundsson & Asgeirsson 1975). Several researchers have demonstrated that ground glass can be used to reduce the expansion due to ASR. Indeed, ground glass can be used to prevent ASR expansion where crushed glass from the same source is used as a reactive aggregate (Jin, Meyer & Baxter 2000). This is shown in Figure 1 from studies by one of the authors of this paper (Thomas 2011). The figure shows data from ASTM C 441 Pyrex Mortar Bar Test using crushed and graded Vycor glass (~ 96% SiO_2, 4% B_2O_3) in place of Pyrex as the reactive sand; mortar bars were stored over water in sealed containers at 38ºC. The control mix with 100% high-alkali (0.94% Na_2Oe) Portland cement expanded rapidly reaching an expansion of approximately 0.38% at 56 days. In a second mix 20% of the Portland cement was replaced with the same Vycor glass which was ground to pass 45-micron (median particle size ~ 10 micron). This expansion of this mix was significantly reduced compared to the control being less than 0.06% at 56 days. In a third mix, 20% of the Portland cement was replaced with quartz ground to a similar fineness as the ground Vycor. This mix expanded slightly less (~ 0.30% at 56 days) than the Portland cement control indicating that the ground Vycor had a beneficial effect beyond mere dilution of the cement.

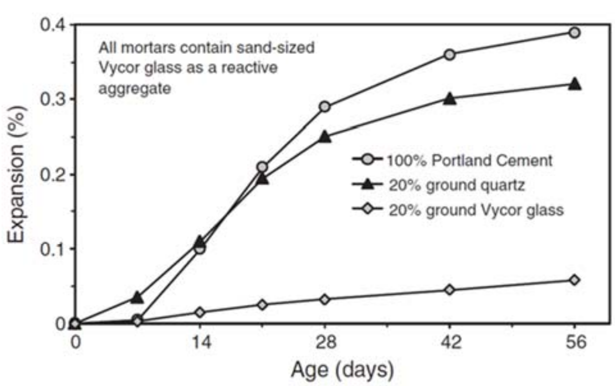

Figure 1 Role of particle size on the behaviour of Vycor glass (Thomas 2011)

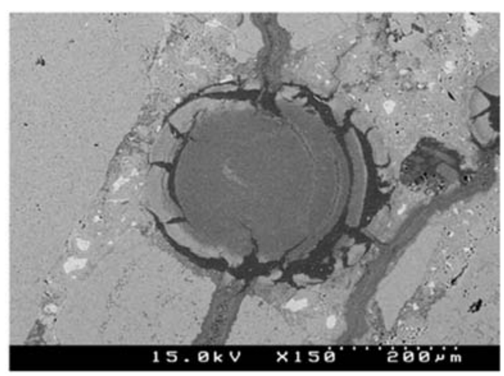

Figure 2 ASR expansion and cracking with agglomerated silica fume particle (Maas, Ideker & Juenger 2007)

The results in Figure 1 demonstrate that the impact of reactive silica when combined with Portland cement depends on its particle size. If present as fine (or coarse) aggregate the silica may undergo a deleterious reaction with the alkali hydroxides of the cement producing an expansive alkali-silica gel which causes internal disruption. The alkalis in the gel will slowly exchange with calcium in the surrounding calcium hydroxide and the composition of the gel slowly transforms from a high-alkali, low-calcium gel to a low-alkali, high-calcium gel similar in composition to C-S-H (Thomas 2001). If the same material is ground to a high fineness, it will react initially with the alkali hydroxides but will rapidly transform into C-S-H. This is the path of the pozzolanic reaction in Portland cement systems where both alkali hydroxides and calcium hydroxide are present. The fact that the reaction is occurring at sites of silica that are finely dispersed throughout the system means that there is no accumulation of reaction product at a single location that can become a site of expansive reaction. The C-S-H that is produced by the pozzolanic reaction has a relatively low Ca/Si (calcium-to-silica ration) compared to the C-S-H that results from the hydration of alite and belite in Portland cement and, consequently, binds more alkali (Bhatty & Greening 1978). Thus, less alkali is available for reaction with aggregate (Thomas 2011).

If an alkali-silica reactive aggregate can be ground to sufficient fineness to behave like a pozzolan, it stands to reason that a pozzolan may behave like a reactive aggregate if it is present as sand-sized particles. That this is the case has been demonstrated by Maas, Ideker and Juenger (2007) who showed that agglomerated silica fume particles can behave like reactive aggregates and induce expansion due to ASR. An example of this is shown in Figure 2.

The data shown in Figure 1 are for Vycor glass which has a negligible alkali content. Soda-lime glass, on the other hand, has a high alkali content, with soda contents being typically in the region of 13% NaO. Some authors have shown these high-alkali glasses to be effective in controlling expansion due to ASR when used with a reactive aggregate (Jin, Meyer & Baxter 2000; Shayan & Xu 2004; Idir, Cyr & Tagnit-Hamou 2010; Afshinnia & Rangaraju 2015). This is somewhat surprising when the mechanisms by which pozzolans control ASR expansion are considered. The main mechanism involves the sequestration of alkalis by the pozzolanic reaction and the products of the reaction as discussed briefly above (Thomas 2011). If the pozzolan itself contained significant quantities of alkali which were available to the concrete pore solution this would make control of ASR by the pozzolan very challenging. It has been observed that high-alkali fly ashes (5 to 10% Na_2Oe) are not able control expansion at normal levels (e.g. 25%) of replacement (Thomas 2011).

Much of the research that has shown ground soda-lime glass to be effective in controlling ASR expansion has utilized the accelerated mortar bar test, ASTM C 1260 (or the modified version, ASTM C 1567, specifically for evaluating the efficacy of pozzolans and slag). In this test small mortar bars (25 x 25-mm cross-section) are cast and cured for 24 hours at normal laboratory temperature, stripped and immersed in water for 24 hours during which period the temperature of the water is raised to 80ºC, measured for length, and then placed in 1 Molar NaOH at 80ºC for 14 days during which period the length change is measured. The one-day immersion in water can leach from the mortar bar a proportion of the alkalis originally contributed by the cementing materials. The subsequent immersion in 1 M NaOH then overwhelms the system in alkalis. Consequently, this test method may be insensitive to the role played by the alkalis in the constituent materials. For this reason, ASTM C 1778 *Standard Guide for Reducing the Risk of Deleterious Alkali-Aggregate Reaction in Concrete* states that the test method (ASTM C 1567) is not suitable for evaluating SCMs with high levels of alkalis.

In the current study various test methods were used to evaluate the efficacy of two types of glass.

2. Experimental Details

2.1. Materials

The testing conducted here utilized two types of ground glass; these were a soda-lime glass (Type GS) and E-glass (Type GE). The Type GE glass was finely ground to pass a #325 sieve (GE-1) and coarsely ground to pass a #80 sieve (GE-2). Table 1 presents some of the properties of the glasses. The other cementitious materials used were a low-alkali (0.44% Na_2Oe) and a high-alkali (0.91% Na_2Oe) Portland cement both meeting the requirements of ASTM C150, one low-calcium, low-alkali (1.2% CaO; 1.6% Na_2Oe) fly ash (FA) meeting the requirements of ASTM C618 Class F, and a silica fume (SF) meeting the requirements of ASTM C1240. Reactive aggregates included a highly-reactive gravel from New Mexico (PL), a siliceous limestone from Ontario (SP) and crushed Pyrex glass.

Table 1 Properties of Glasses

Glass Type	Retained 45-µm (%)	D_{50} (µm)	Oxide Composition (%)					
			SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O
GE-1	11	10	54.1	15.6	0.29	16.6	0.5	0.8
GE-2	64	25						
GS	3	8	75.1	1.61	0.52	10.6	13.1	0.46

2.2. Mixes and Test Methods

The Type GE glasses (GE-1 and GE-2) were tested in mortar to determine (i) pozzolanic activity with lime (ASTM C311 – now withdrawn), (ii) the compressive strength of mortars (ASTM C109), (iii) sulfate resistance – Type GE-1 only (ASTM C 1012), and (iv) electrical resistivity using the "Monfore Method" (Monfore 1968).

Three concrete mixtures were produced with a total cementitious material content (cement plus ground glass) of 375 kg/m^3, w/cm = 0.40, and three levels of glass: 0%, 10% and 20% GE-1. An air-entraining agent and high-range water-reducing admixture were added to meet a target air content of 5 to 8% and a target slump of 150 to 200 mm. The concrete was tested for compressive strength, drying shrinkage (ASTM C157), rapid chloride permeability (ASTM C1202), bulk diffusion (ASTM C1556), freeze-thaw resistance (ASTM C666 – Procedure A) and scaling resistance (ASTM C672).

Testing for alkali-silica reactivity included extraction and analysis of pore solution from paste samples, expansion tests on mortar bars containing either PL aggregate or Pyrex glass and stored over water at 38ºC (ASTM C227), accelerated expansion tests with mortar bars (SP aggregate) stored in 1 M NaOH at 80ºC (ASTM C1260/C1567), and expansion tests on concrete prisms (75 x 75 mm cross-section) with SP aggregate and stored over water at 38ºC.

3. Experimental Results

Only selective results are presented here because of space limitations.

3.1. Tests on Mortars

The results of the strength activity with lime (pozz:lime = 2:1) at 7 days were 6.2 MPa and 3.2 MPa for mortars produced, respectively with EG-1 and EG-2. These results compare with 7.1 MPa for silica fume (higher w/cm used for silica fume to achieve equal flow) and 6.8 MPa for a Class F fly ash (slightly lower w/cm). Results from compressive strength, electrical resistivity and sulfate resistance of mortars are shown in Table 2.

Table 2 Results of Tests on Mortars

Property	Control	EG-1		EG-2	
		10%	20%	10%	20%
Compressive Strength (MPa)					
7d at 23ºC	35.1	38.8	28.1	34.1	26.4
28d at 23ºC	37.6	47.2	36.9	37.4	32.5
7d at 60ºC	34.2	33.2	38.6	25.2	25.7
Electrical resistivity (Ω-m)					
7d at 23ºC	30	34	37	31	26
28d at 23ºC	41	69	175	37	36
7d at 60ºC	29	91	251	29	33
Sulfate Expansion (%)					
6 months	0.459	0.042	0.019	n.d.	n.d.
12 months	-	0.091	0.041		

The results of the mortar testing clearly show the importance of the particle size with regards to the pozzolanicity of the glass. It is interesting to compare the strengths of the mortars produced with lime-glass as a binder with those of the cement-glass combinations. The strength of mortars in the lime-glass mixes is solely a result of the pozzolanic reaction between the lime and the glass, and the coarse glass shows little pozzolanic behaviour. In the cement-glass mixtures, the strength is mainly attributed to the hydration of the cement and it is difficult to determine the precise contribution of the pozzolanic reaction of the glass. The finely-ground glass has a very profound effect on the electrical resistivity of mortar, whereas the coarse glass shows little difference when compared to the control. Electrical resistivity (or conductivity) maybe a useful tool for evaluating the performance of pozzolans especially with regards to their contribution towards durability.

3.2. Tests on Concrete

The results from testing of compressive strength, rapid chloride permeability (electrical conductivity), bulk diffusion and cyclic freeze-thaw testing for concrete with various levels of ground glass EG-1 are shown in Table 2. These data show that the E-glass is an extremely effective pozzolan as it produces significant increases in long-term compressive strength and very substantial increases in the concrete's resistance to chloride-ion penetration whether measured indirectly by determining electrical conductivity or directly by determining an apparent bulk chloride diffusion coefficient. The concrete containing glass performed well in cyclic freeze-thaw test ASTM C666) and the mix containing 20% glass showed little significant scaling when exposed to freeze-thaw cycles in the presence of de-icing salt (ASTM C672).

Table 3 Results of Tests on Concrete

Property	Control	EG-1	
		10%	20%
Compressive Strength (MPa)			
3d	25.6	23.2	19.2
7d	29.1	26.5	21.3
28d	31.7	31.6	26.4
90d	35.7	39.7	36.9
3y	43.5	51.2	59.5
"Rapid Chloride Permeability" (Coulombs)			
28d	4309	3411	2573
90d	4362	1089	1017
3y	2564	689	312
Chloride Diffusion Coefficient ($x10^{-12}$ m^2/s)			
3y curing followed by 91d ponding	4.3	2.5	1.3
Cyclic Freeze-Thaw			
Durability Factor after 300 cycles (%)	102	105	108
De-icer Salt Scaling Test			
Scaled mass after 50 cycles (g/m^2)	533	2603	159

3.3. Pore Solution Testing

The results from pore solution tests up to an age of 38 days is shown in Figure 3. Both types of glass reduce the concentration of potassium ions in the pore solution and this is attributed to both dilution of the Portland cement and the pozzolanic action. The sodium-ion concentration is also reduced by the Type GE glass, whereas the Type GS glass significantly increases the concentration of sodium. The pozzolanic action and resulting increased alkali binding of the Type GS glass is not able to compensate for the very high sodium levels in the glass.

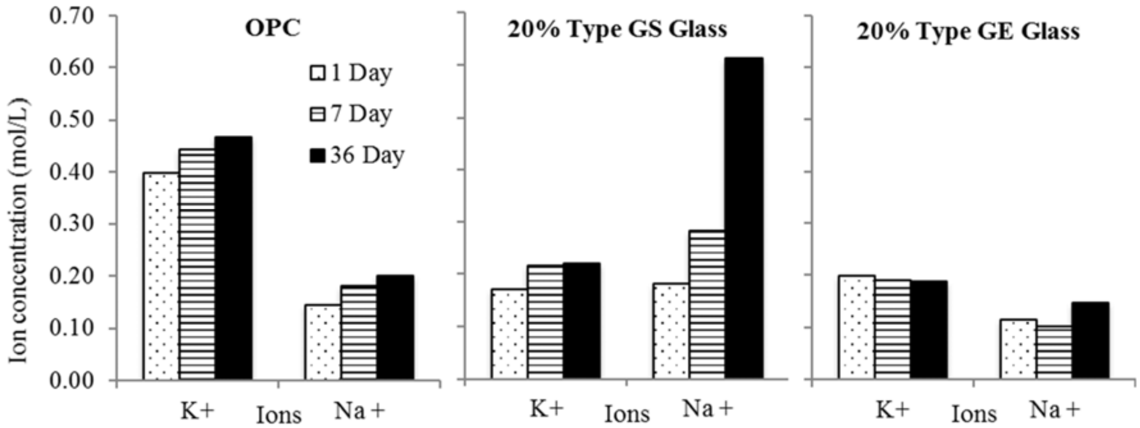

Figure 3 Results of pore solution extraction and analysis

3.4. Expansion testing of mortars

The results of the accelerated mortar bar test (ASTM C1567) with SP aggregate, the Pyrex mortar test (ASTM C441) with Pyrex sand, and the mortar test (ASTM C227) with PL aggregate are shown, respectively in Figures 3, 4 and 5.

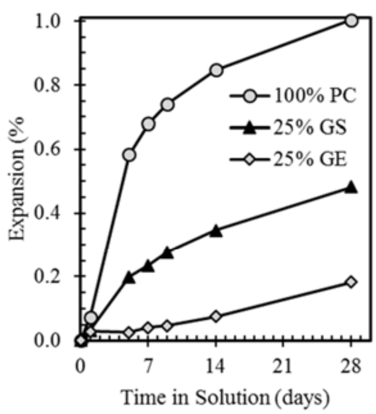

Figure 4 Expansion in ASTM C1567 with SP aggregate

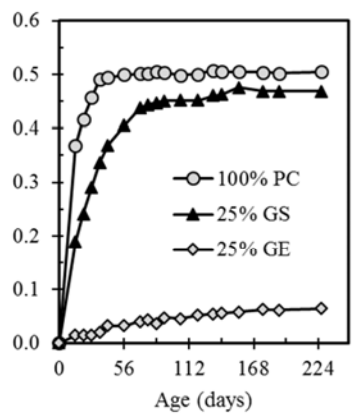

Figure 5 Expansion in ASTM C441 with Pyrex aggregate

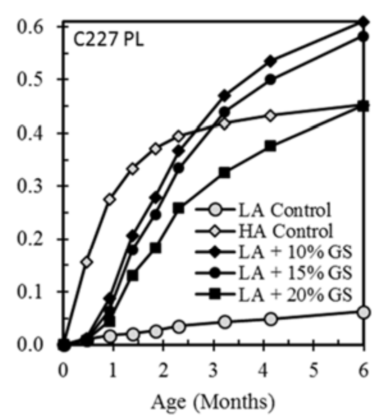

Figure 6 Expansion in ASTM C227 with PL aggregate

The results show that the low-alkali Type GE glass is effective in significantly reducing the expansion of mortar bars in all the tests regardless of the test condition and the type of reactive material. Although the test limits for these parameters vary between different specifications and practices, commonly used limits are expansion ≤ 0.10% at 14 days, ≤ 0.10% at 56 days, and ≤ 0.10% at 6 months for, respectively ASTM C1567, C441 and C227. Based on these limits, 25% GE glass appears to be a sufficient level of replacement to control expansion. The results for the Type GS are highly variable. In the accelerated mortar bar test 25% GS glass reduces expansion by slightly more than 50% compared with the control. As discussed above, other workers have shown expansion can be controlled to an acceptable limit (< 0.10%) by GS glass in this test. In the C441 test with Pyrex glass the GS glass produces very little reduction in expansion compared with the control and the ultimate expansions are essentially the same for the mortar with and without GS glass. Perhaps more alarming are the results of the C227 test with PL aggregate which indicate that the combination of low-alkali (LA) cement and 10 to 20% GS glass not only expands more the LA control but, eventually, the expansion of the mortars with GS glass exceed that of the high-alkali (HA) control. It should be noted that the PL aggregate is classifies as a very highly reactive aggregate by ASTM C1778 and is very sensitive to the amount of alkalis available.

3.5. Expansion testing of concrete

The results of concrete prism tests (ASTM C1293) are shown in Figure 7 and 8 for concrete produced with, respectively, SP and PL reactive coarse aggregates. Note that for the tests with the SP aggregate the mixes with high-alkali (HA) cement and blends of HA cement with pozzolans (GE, GS and FA), the alkali content of the cement was boosted to 1.25% Na_2Oe by the addition of NaOH to the mix water. For tests the with PL aggregate the alkalis were not boosted with NaOH.

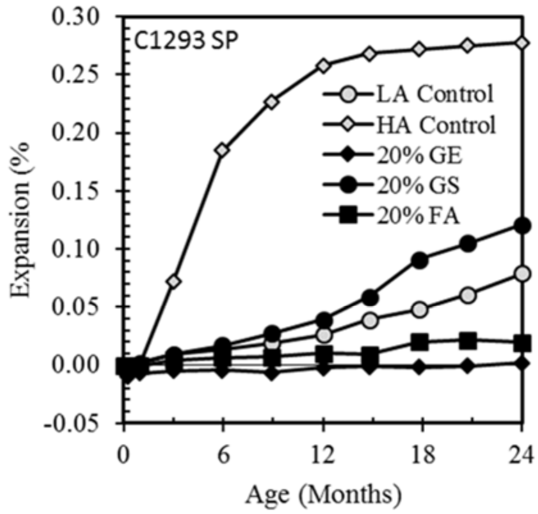

Figure 7 Expansion in ASTM C1293 with SP aggregate

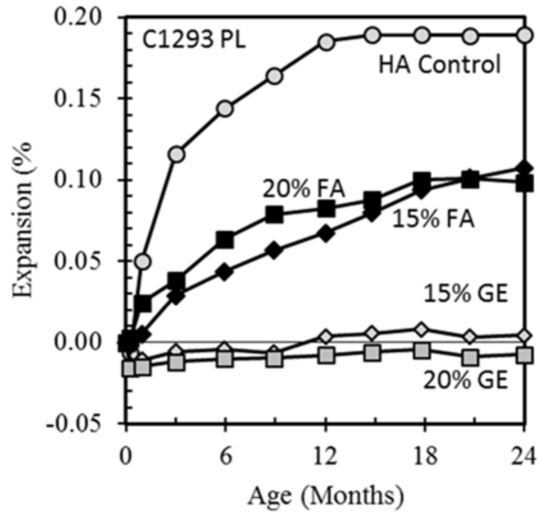

Figure 8 Expansion in ASTM C1293 with PL aggregate

As with the mortar tests, the expansion tests on concrete indicate that the low-alkali Type GE glass is effective in controlling expansion to an acceptable level (≤ 0.04% at 24 months typically used as a performance limit for ASTM C1293) with both the highly-reactive SP aggregate and the very-highly reactive PL aggregate. Although not shown in Figure 7, replacement levels of 10% and 15% GE glass were tested with SP aggregate and the expansion values were below 0.04% at 24 months. With the SP aggregate 20% fly ash (FA) was also effective in controlling expansion. However, these same levels of fly ash were not effective in reducing expansion to an acceptable level with the PL aggregate, although the expansion was reduced compared to the control. It can be concluded from these data that the GE glass is more efficacious with regards to ASR control that low-calcium Class F fly ash.

The GS glass was not effective in controlling expansion of the concrete produced with the SP aggregate. The GS glass did reduce the expansion compared to the HA control, but the expansion was greater than the LA control. The GS glass was not tested with the PL aggregate in concrete.

4. Discussion

It has been demonstrated in this and previous studies that ground glass can be an effective pozzolan if it is ground to a sufficient fineness. It is likely that the performance of glass in concrete for most applications will be controlled to a greater extent by its fineness rather than its chemical composition. However, the performance of glass with regards to alkali-silica reaction (ASR) is dependent on both particle size and composition. Glass that is crushed to produce coarse or fine aggregate may result in deleterious ASR unless preventive measures are taken to reduce the risk of expansion. Finely ground glass will not behave like a reactive aggregate but will exhibit pozzolanic properties and, in some cases, act to mitigate ASR expansion with a reactive aggregate. Finely ground low-alkali GE glass is a highly effective pozzolan and an efficient means for controlling ASR. With high-alkali (soda-lime) glasses the high sodium content will work to offset the beneficial pozzolanicity of the glass. Even though the products of the pozzolanic reaction consume a portion of the alkalis it would seem that the significant quantity of alkalis supplied by the glass are overwhelming. It is possible that at sufficiently high levels of replacement, the pozzolanic benefits of the GS glass will outweigh the alkali contribution. This has been found to be the case with very high alkali fly ashes (Shehata & Thomas 2000). Furthermore, it is probable that GS glasses can be used with reactive aggregates if used in combination with other pozzolans or slag.

The data presented here highlight one of the shortcomings of the accelerated mortar bar test. The conditions of the test mask the role played the alkalis in the component materials. The test method is, at best, a rapid screening tool and should not be used in research to evaluate new or emerging materials.

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