

Behaviour of glass in cement-based materials: its role on ASR

D. Serpa^{1,a}, A. Santos Silva^{2,b}, D. Soares^{2,c}, M. Barreto Santos^{3,d}, J. de Brito^{1,e}

¹DECivil-IST, Technical University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

²National Laboratory of Civil Engineering, Av. do Brasil 101, 1700-066 Lisbon, Portugal

³Polytechnic Institute of Leiria, Campus 2, Morro do Lena, Alto Vieiro, 2411-901 Leiria, Portugal

^adiogo_serpa@hotmail.com, ^bssilva@Inec.pt (corresponding author), ^cdsoares@Inec.pt,

^dmbarreto@estg.ipleiria.pt, ^ejb@civil.ist.utl.pt

Keywords: Waste-glass, Alkali–silica reaction, Pozzolanic reaction

Abstract.

One of the most worrying degradation mechanisms in hardened concrete is the occurrence of chemical expansive reactions, namely due to the alkali-silica reaction (ASR). This pathology involves the formation of expansive products inside the material. This situation is very difficult to deal with, because presently there is no efficient method to repair concrete structures affected by ASR. Hence, there is an urgent need to find preventive methods that may inhibit these reactions in new concrete structures. Nowadays, the use of pozzolanic mineral additions is recommended to mitigate this type of degradation. Moreover, their effect depends on their chemical and mineralogical composition and also on the cement content replacement ratio.

Glass is a common material with some environmental problems regarding recycling and landfilling. Some studies exist about its use as fine powder, like a pozzolan, in cement-based materials. However, there are also some problems related to its use as coarse aggregate in cement –based materials due to ASR development. This paper, presents the results obtained of mortars exposed to 1M NaOH solution prepared with the use of crushed glass as aggregate and as addition in cement substitution. The results reveal that ASR is reduced with the incorporation of glass as aggregate or addition, being its efficiency dependent on its replacement content.

Introduction

The recycling of waste glass is a great environmental problem in worldwide. Due to its large availability the use of recycled materials in construction is among the most attractive options [1]. The glass, being amorphous and containing relatively large quantities of silica and calcium, is, in theory, pozzolanic when it is finely ground [2]. Recently, many studies have focused on the uses of waste glass as aggregates for cementitious materials or as cement replacements [2-6]. Early attempts to incorporate waste glass in concrete tended to focus on aggregate replacement. The properties of glass seemed comparable to those of large aggregate in terms of constitution, strength and durability, and the larger size of the glass meant lower processing costs. These early attempts however, were unsuccessful due to the alkali–silica reaction (ASR) which takes place in the presence of the amorphous silica and alkaline pore solution. In addition to ASR, several other challenges exist in incorporating waste glass into concrete, such as, size and shape of particles for coarse aggregate, which may negatively affect workability [7].

The objective of this study was to determine the effect of glass as aggregate replacement, of alkali-reactive and non-alkali reactive aggregates, and as pozzolanic addition in ASR mitigation.

Experimental Program

Test conditions and materials

This study was carried out on mortars according the ASTM C 1567 mortar bar-test [8], equivalent to the ASTM C 1260 [9]. The prismatic mortar specimens were cast using a Portland cement (OPC) type I 42.5 R, and aggregates of different lithologies and different alkali reactivity. Thus, we

selected three types of aggregates, one crushed siliceous gravel, classified as reactive (expansion > 0.20% at 14 days, according to ASTM C 1260) and designated by R-CA, and two non-reactive (expansion < 0.10% at 14 days) designated by NR-FA (rolled siliceous sand) and NR-CA (crushed limestone gravel), respectively.

The chemical compositions, obtained by WD-XRF, of the glass and cement used in mortars are presented in Table 1. Fly ash (FA), metakaolin (MK) and ground granulated blast furnace slag (GGBS) compositions are also shown for comparison, having known pozzolanic activity [10, 11].

Table 1: Chemical composition and pozzolanic activity index of the materials studied.

	Cement	Glass Powder	FA	MK	GGBS
Chemical analysis (%)					
SiO ₂	18.81	80	53.22	54.66	38.09
Al ₂ O ₃	5.15	2.01	23.20	37.98	9.38
Fe ₂ O ₃	3.18	0.11	5.85	1.22	0.89
CaO	63.70	9.60	5.36	0.01	36.24
SO ₃	2.69	-	1.00	0.01	0.27
TiO ₂ + P ₂ O ₅	-	-	1.87	-	-
MgO	1.50	8.00	1.63	0.46	7.40
Na ₂ O	0.19	(Na ₂ O+Mg)	0.44	0.00	0.25
K ₂ O	1.02	0.39	1.42	3.09	0.52
Na ₂ O _{eq.}	0.86	-	1.37	2.03	0.59
LOI	3.18		5.16	0.94	2.66
Poz. Act. Index (%) (EN450-1:2005+A1:2007)					
28-day	-	57,8	87	118	88
90-day	-	-	101	119	94

In addition, a composition (80OPC + 20GP) with the inclusion of fine glass powder (< 125 μm) in replacement (20 %, in mass) of a part of cement was also prepared, in order to assess its behaviour as pozzolanic material in inhibition of expansion due to ASR, by comparison with the composition only with cement and R-CA aggregate.

The mortar mixes used are show in Table 2.

Table 2: Mortars mixes used.

Designation of mortars mixes		Cementitious material			Aggregate (4.75 mm – 150 μm)			Water ml
		Cement	Addition (mass replacement, in)		Aggregate	Glass (mass replacement, in)		
			g	g		%	g	
<i>Glass aggregate</i>	GA	440	-	-	-	990	-	207
<i>Non-reactive siliceous aggregate</i>	NR-FA	440	-	-	990	-	-	
	NR-FA 20	440	-	-	792	198	20	
<i>Non-reactive limestone aggregate</i>	NR-CA	440	-	-	990	-	-	
	NR-CA 20	440	-	-	792	198	20	
<i>Reactive siliceous aggregate</i>	R-CA	440	-	-	990	-	-	
	R-CA 20	440	-	-	792	198	20	
	R-CA + (80OPC + 20GP)	352	88	20	990	-	-	

Expansion tests

Mortar prisms (25 mm x 25 mm x 285 mm) were cast according to the test method ASTM C 1567-08 [8]. The specimens were demoulded 24 hours after mixing, placed in water at 23° C and placed in a climatic chamber at 80° C for a further 24 hours. After which initial measurements (zero) for each specimen were taken. Then, the specimens were placed in a solution of NaOH 1M at 80° C where they remained 14 days, being undertaken several length measurements during this period. According to the test method, a mix is considered reactive if its expansion at 14 days is higher than 0.20% [9]. For a given reactive aggregate, the rate of incorporation of mineral admixtures is considered effective when the expansion at 14 days is below 0.10% [8, 12]. In this study, the expansion measurements have been extended until at least 28 days in order to evaluate the expansion behaviour of the blended mixes at the largest age.

SEM/EDS analysis of mortars

To complement the expansion tests and to evaluate the morphology and composition of the hydrated products formed, we performed SEM observations of the prismatic specimens after 28 days of test by scanning electron microscopy (SEM) JEOL JSM-6400 coupled with an OXFORD energy dispersive spectrometer Si(Li) X-ray detector (EDX), using secondary electron image mode.

Results and discussion

Expansion tests

The results obtained with only crushed glass as aggregate (Fig. 1) show that, according to the expansion limits of the test-method, this material is classified as non-reactive (0.03% at 14 days). However, after 28 days, the evolution of the expansion curve shows an increase in the reaction rate. This means that glass presents slow and delayed alkali reactivity [13].

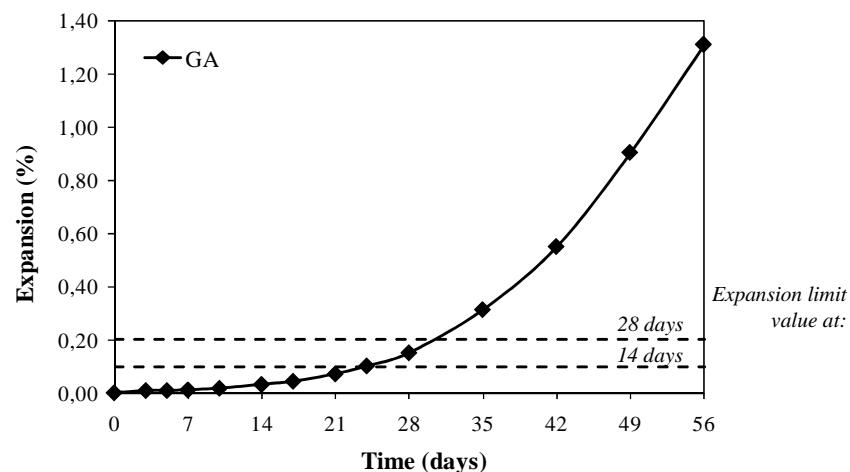


Figure 1: Results of ASTM C 1567-08 mortar bar test: effect of crushed glass as aggregate.

Figure 2 presents the expansion behaviour of the different mortar mixes tested according to the ASR test method ASTM C 1567-08.

The results with a replacement rate of 20% of a non-reactive aggregate (siliceous or limestone) by glass aggregate (NR-FA 20 and NR-CA 20) show that the expansion value observed at 14 days is almost the same without glass. However, we observe a slightly increase of the expansion value at 28 days when comparing with the mix without glass aggregate. Nevertheless, despite the increase of expansion at 28 days, the obtained values are below the maximum allowed (< 0.20% at 28 days) according to ASTM C 1260.

On the other hand, when the glass aggregate replaces 20% of a reactive aggregate (R-CA 20), the expansion at 28 days is lower than the mortar with only reactive aggregate. Despite this reduction, the expansion presented is still high.

In the mix with glass powder as mineral addition (R-CA + 80OPC + 20GP), we observe a greater reduction in the expansion when comparing with the R-CA mix, even then, the expansion value exceeds the limit of the ASTM C 1567-08. This reduction was also observed when comparing with the R-CA 20 mix, which could be due to the pozzolanicity of the GP (Table 1).

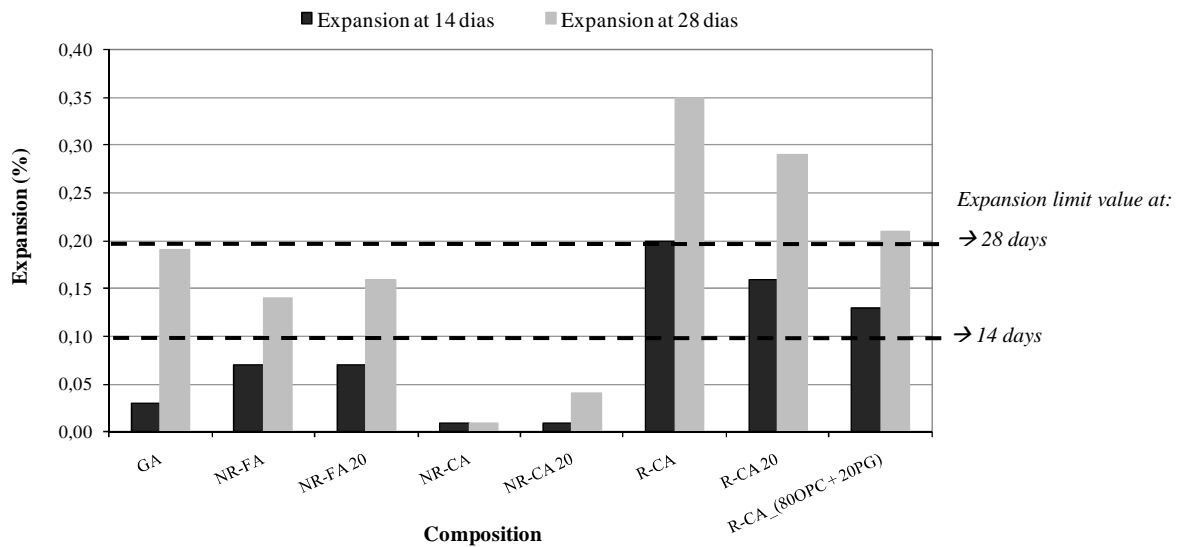


Figure 2: Results of ASTM C 1567-08 mortar bar test: effect of glass as partial replacement of aggregate and Portland cement (mass %).

SEM/EDS analysis of mortars

Observations by SEM/EDS revealed the presence in all mixes of ASR products, crystalline and amorphous forms, although with differences in the composition and location of these products. The EDS analysis has shown that the crystalline products are richer in alkalis than the amorphous products, being the latter richer in calcium and normally responsible for the expansion behaviour in cement-based materials.

The mortar mix that has evidenced higher quantity of ASR amorphous gel was, as expected, the R-CA mix (Fig. 3a), and dispersed through the entire specimen.

In the GA mix (Fig. 3b) we have also detected ASR amorphous gel, mainly localized in paste/glass interfaces as well in voids. The composition of the gel in this mix presents more aluminum than in the R-CA mix, which seems to be due to the glass composition.

In the mixes with 20% of glass replacing non-reactive aggregates, it was evident a decrease in the ASR gel content. The ASR products in these mixes are mainly located in voids in the paste and around the glass particles (Fig. 4). Besides, these mixes show a significant amount of calcium silicate hydrates. This, in the presence of non-reactive aggregates, shows that the glass aggregate do not modify the paste microstructure, resulting in the formation of dimensionally stable hydration products [14].

In the mortar mix with glass powder incorporated as mineral addition, the SEM analysis show also crystalline and amorphous ASR gel (Fig. 5), but in less quantities than the other mixes with the same reactive aggregate. Several studies have confirmed that glass particles will not generate deleterious expansion themselves once they have grain sizes smaller than 300 μm . However, glass powder has very high alkali content, and these alkalis can be leached out resulting in ASR expansion when the natural aggregate is alkali-reactive [6]. However, in some cases [1, 6] 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 (CaO) and form a calcium silicate hydrate (CSH) with a low C/S ratio, which retains the alkalis in the CSH. According to this author, with respect to that reactive aggregate, it seems that it requires a substitution of 50% of cement by glass powder to reduce the expansion to a safety level. These observations are in agreement with our results, since 20% of replacement was not sufficient to reduce the expansion below 0.10%.

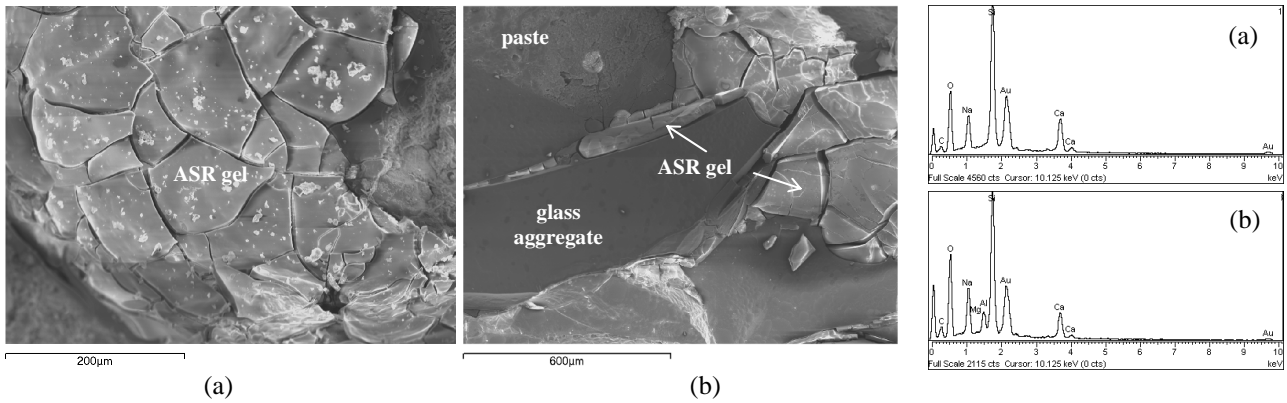


Figure 3: SEM images of the blended mortars and respectively analysis of ASR gel: (a) R-CA and (b) GA.

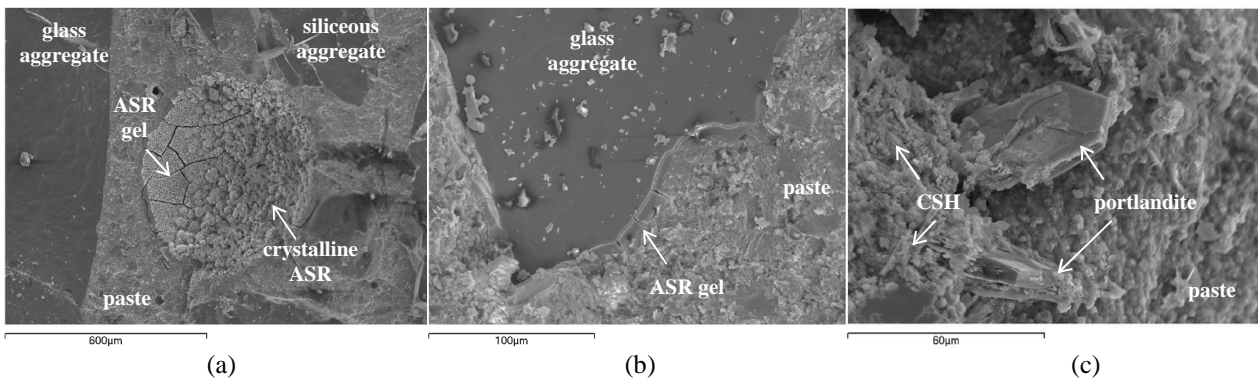


Figure 4: SEM images of the blended mortars: (a) NR-FA 20, void with ASR products in crystalline and amorphous form; (b) NR-CA 20, paste/glass interfaces with ASR amorphous; (c) NR-CA 20, CSH and portlandite in paste.

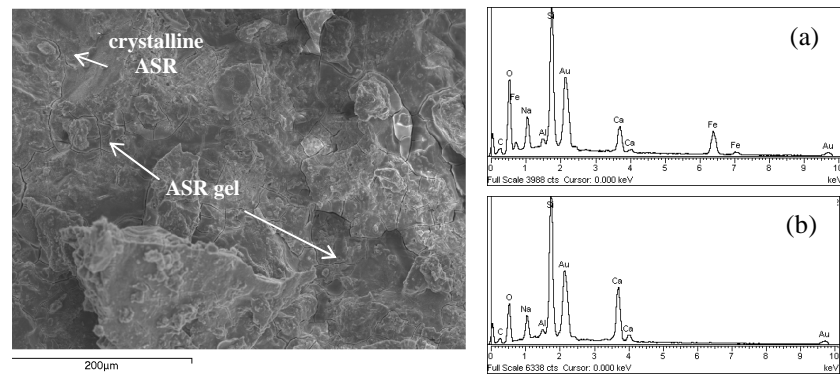


Figure 5: SEM images of the blended mortar of R-CA_(80OPC + 20GP), with crystalline (a) and amorphous (b) ASR gel.

Conclusion

The data presented in this paper show that there is a potential use in waste glass for cementitious materials, as aggregate or as pozzolan. Based on the experimental test results, the following conclusions can be drawn:

- The use of waste glass as aggregate do not increase the overall expansion of a mortar bar with a natural alkali-reactive aggregate.
- The waste glass could be used with natural non-reactive aggregates without deleterious expansion, depending on its replacement content.
- Glass powder exhibits some pozzolanic reactivity and can be used as mineral addition in cement replacement. However, depending of its replacement content, the alkalis and amorphous silica present in the glass powder can induce the formation of ASR gels in cementitious-based materials.

The alkalis released from waste glass compromises its ability to suppress the ASR expansion at long-term. This situation could be minimized by the use of other supplementary cementing materials, such as FA, MK and GGBS, reducing the portlandite and pH of the cement paste. • According to some previous works, the ASR expansion decreases as glass replacement increases, showing the best result for glass replacements of 50% or more. This justifies the need for further studies regarding the use of glass as aggregate and as pozzolanic addition in cementitious materials.

Acknowledgement

This work is financed by National Funds through FCT - Fundação para a Ciência e Tecnologia under the project EXREACT (Mitigation of deleterious internal expansive reactions in concrete structures, PTDC/CTM/65243/2006).

References

- [1] Shi, C., Zheng, K., “A review on the use of waste glasses in the production of cement and concrete”, *Resources, Conservation and Recycling*, Vol. 52 (2007), 234-247.
- [2] Dyer, T.D., Dhir, R.K., “Chemical reactions of glass cullet used as cement component”, *J Mater. Civ. Eng.* 13 (6) (2001), 412–7.
- [3] Topcu, I.B., Canbaz, M., “Properties of concrete containing waste glass”, *Cem. Concr. Res.* 34 (2004) 267–74.
- [4] Shao, Y., Lefort, T., Moras, S., Rodriguez, D., “Studies on concrete containing ground waste glasses”, *Cem. Concr. Res.* 30 (1) (2000) 91–100.
- [5] Shayan, A., Xu, A., “Value-added utilization of waste glass in concrete”, *Cem. Concr. Res.* 34 (2004) 81–9.
- [6] Shi, C., Wu, Y., Shao, Y., Riefler, C., “Alkali-aggregate reaction of concrete containing ground glass powder”, In: *Proceedings of the 12th International Conference on AAR in Concrete*; 2004. p. 789–95.
- [7] Federico, L.M., Chidiac, S.E., “Waste glass as a supplementary cementitious material in concrete – Critical review of treatment methods”, *Cem. Concr. Comp.* 31 (200) 606-610.
- [8] ASTM C 1567-08, (2008): “Standard test method for determining the potential alkali-silica reactivity of combinations of cementitious materials and aggregate (accelerated mortar-bar method)”, ASTM International, West Conshohocken, United States, p. 6.
- [9] ASTM C 1260, (2001): “Standard test method for potential alkali reactivity of aggregates (mortar-bar method)”, ASTM International, West Conshohocken, United States, p. 5.
- [10] Santos Silva, A., Soares D., Matos, L., Salta, M., Ribeiro Bettencourt A., Gonçalves A., (2010a), “Reacções expansivas internas no betão: mitigação da expansão pelo emprego de adições minerais”, *Proceedings of the BE2010 – Encontro Nacional de Betão Estrutural*, Lisboa, Portugal, 11pp.
- [11] Santos Silva, A., Soares, D., Matos, L., Salta, M., (2010b): “Inhibition of internal expansive reactions in cement based materials with mineral additions”, *Proceedings of the MEDACHS’10 International Congress*, La Rochelle, França, p. 8.
- [12] Santos Silva, A., (2005), “Degradação do betão por reacções álcalis-sílica. Utilização de cinzas volantes e metacaulino para a sua prevenção.”, *Tese de Doutoramento*, LNEC/Universidade do Minho.
- [13] Dhir, R.K., Dyer, T.D., Tang, M.C., “Alkali-silica reaction in concrete containing glass”, *Materials and Structures* 42 (2009), 1451–1462.
- [14] Lee., G., Ling, T.C., Wong, Y.L., Poon, C.S., (2010), “Effects of crushed glass cullet sizes, casting methods and pozzolanic materials on ASR os concrete blocks”, *Construction and Building Materials*, article in press.