Proceedings of the 12th International Conference on Alkali-Aggregate Reaction in Concrete

ALKALI-SILICA REACTION OF RECYCLED GLASS IN CONCRETE

Zhu Hui-ying* and Dr Ewan A. Byars
(Centre for Cement & Concrete, Department of Civil & Structural Engineering
University of Sheffield, Sheffield S1 3JD, UK)

ABSTRACT

Waste glass from container, plate, end-of-life vehicles and electrical items poses a major solid waste disposal problem in many countries. Its use in concrete has been tried in the past but deleterious alkali-silica reaction (ASR) between cement paste and glass aggregates has been observed. This paper reports a major fundamental study of the alkali-silica reaction between glass aggregates and concrete conducted at Sheffield University, UK. Materials tested include green, amber, flint and blue glass cullet with particle size ranges from sub 35 micron to 12 mm. ASTM C 1260 and BS812-123 test methods have been reported. The results show that the ASR reactivity of glass cullet varies with glass type and particle size and that, with appropriate use of pozzolanic materials, ASR expansion is significantly reduced and, possibly, mitigated.

Key words: Recycled glass, Glass aggregate, alkali-silica reaction, Test methods

1. INTRODUCTION

Post-consumer and other waste glass types are a major component of the solid waste stream in many countries and currently most is still landfilled [1]. The EU Landfill Directive 1999/31/EC [2] and the UK Landfill Tax Regulations [3] have emerged to divert such waste into recovery and recycling programmes and, specifically for post-consumer glass, the Packaging Waste Regulations [4] have provided legislative pressure to increase recycling.

Glass can be infinitely remelted without degradation of its physical properties and, theoretically at least, the glass manufacturing industry could use 100% recycled glass as a primary feedstock. However due to tolerances on contamination there is a practical limit and it is estimated [5] that approximately 650,000 tonnes/year of waste container glass cannot be recycled into new glass manufacture. There are also arisings of over 1m tonnes/year from other waste glass streams (e.g. plate glass, windscreens and lighting) that need to be recovered and re-used. Whilst some markets for recycled waste glass already exist in UK construction (170,000 tonnes as aggregate in asphalt, pipe bedding, backfill, loose fill, decorative aggregate and golf bunkers), there is a huge potential for this to increase in the concrete construction sector.

Published research work in the UK and USA since 1997 [6-11] has shown that finely-ground waste glass will react in a pozzolanic manner in cementitious systems and contribute to the strength development without apparent detriment to concrete. This means that raw post-consumer glass could be processed and used to replace a percentage of the Portland cement in concrete mixes. Considering the size of the cement industry (over 10 million tonnes/annum in the UK) this would appear to be a potential high volume, economic and environmentally friendly solution to part of the waste glass problem.

Alternatively, waste glass could be used as a concrete aggregate; either as direct replacement for normal concrete aggregates (low value) or as an exposed, decorative aggregate in architectural concrete products (high value). However, there is a fundamental problem that needs to be overcome with both of these solutions; that of expansive alkali-silica reactions (ASR) between the glass particles and the cement paste. Various laboratory studies have investigated this [12-15] and the results appear to suggest that in moist conditions and without modification of the cement chemistry, ASR may occur. Of course, the ASR reaction is not confined to glass aggregates but has caused premature deterioration of concrete structures throughout the world and whilst the mechanisms of ASR expansion are complex, it is now accepted that reactive silica, sufficient alkalis and moisture are required to initiate the reaction [16, 17].

*Corresponding author. Tel: +44-114-22257128; Fax: +44-114-2225700.
E-mail: h.zhu@sheffield.ac.uk, zhy278@yahoo.co.uk

With these facts in mind, several potential solutions exist to reduce the propensity of a potentially reactive aggregate to undergo ASR. These include the use of pozzolanic mineral admixtures that react with and reduce the alkalinity of cementitious systems, low alkali cements and indoor (dry) concrete environments. In addition to these, researchers in the US [7, 8] have used alkali-resistant glass and glass modified by the addition of minor constituents at the melt stage. These latter two methods of avoiding ASR may have potential benefit in concrete applications if post-consumer glass were to be melted and re-coloured specifically for the highly lucrative decorative concrete aggregate market.

2. MATERIALS AND TEST METHODS

In this research study, the effects of glass colour, particle size and potential suppressants on the ASR reactivity of glass aggregate concrete were investigated using the ASTM C1260 [20] test method and the BS 812-123 [21] mix proportions. These are detailed in the following sections.

2.1 Materials

2.1.1 Cement

Ordinary Portland cement (OPC) to BS EN 197-1:2000 supplied by Castle Cement Ltd was used through the study.

2.1.2 Control Aggregate

Non-reactive 5-10mm coarse aggregate and sand from Trent Valley were used in control mixes.

2.1.3 Glass Cullet

Various colours and particle sizes of clean post-consumer glass cullet that has been rejected by the glass industry were used, Table 1.

2.1.4 Potential ASR Suppressants

A wide range of potential ASR suppressants have been investigated, including BS 3892 PFA, GGBS, MS (micro-silica), MK (Metakaolin) and green/amber/flint glass pozzolan (GP, AP and FP). Typical chemical and physical properties of the OPC, PFA [20], GGBS [20], MS, MK and GP/AP/FP [21] used in ASR study are shown in Table 2.

Table 1. Details of the glass cullet used in the ASR study

Glass Colour	Particle Size Ranges	Investigation
Green	6-12 mm	Pessimum size, colour effect
	3-6mm	Pessimum size, colour effect
	1-3mm	Pessimum size
	Sub 600 μm	Pessimum size
	Sub 212 μm	Pessimum size
	Sub 35 μm	Pessimum size
Amber	6-12 mm	Pessimum size, colour effect, suppressants
	3-6mm	Pessimum size, colour effect
	1-3mm	Pessimum size
	300-600 μm	Pessimum size
	150-300 μm	Pessimum size
	Sub 90 μm	Pessimum size
Flint	6-12 mm	Pessimum size, colour effect
	3-6mm	Pessimum size, colour effect, suppressants
	1-3mm	Pessimum size
	0.6-1.18 mm	Pessimum size
	300-600 μm	Pessimum size
	150-300 μm	Pessimum size
	Sub 150 μm	Pessimum size
Blue	6-12 mm	Pessimum size, colour effect
	3-6mm	Pessimum size, colour effect, suppressants
	1-3mm	Pessimum size

Table 2. Chemical and physical properties of OPC, ASR suppressants and glass

PROPERTIES		OPC[a]	ASR SUPPRESSANTS				GLASS POZZOLAN		
			PFA	GGBS	MS[a]	MK[a]	GP	AP	FP
Chemical Composition (%)	SiO_2	21.79	48-55	31-36	92	-	71.28	71.52	72.2
	Al_2O_3	4.89	22-29	9-20	1	-	1.63	2.19	1.36
	Fe_2O_3	1.95	8-13	0.5	1	-	0.32	0.21	0.07
	CaO	64.81	1-6	33-45	0.3	-	10.76	10.42	10.98
	MgO	1.12	1-2	4-15	0.6	-	1.57	0.71	1.16
	K_2O	0.71	2-4	<1	0.8	-	0.62	0.16	0.56
	Na_2O	0.15	0.7-1.7	<1	0.3	-	13.12	13.88	13.08
	SO_3	3.01	<0.5	0.5-2	0.3	-	<0.05	0.05	0.1
	Na_2Oeq	0.62	-	-	-	-	-	-	-
	LOI	1.07	1-3	-	-	-	<1	<1	<1
Physical Properties	Colour	grey	grey	off white	dark grey	white	light grey		
	Density (g/cm^3)	3.15	2.3	2.9	1.4	0.3	2.5	2.5	2.5
	surface area (m^2/kg)	350-400	600[b]	375-425	15000-20000	12000[b]	250-350[b]		
	Moisture (%)	-	0.2	-	-	0.5	-	-	-

a - data presented in the table is from the materials supplier; b – data obtained at CCC using a laser particle distribution machine.

2.1.4 Potential ASR Suppressants

A wide range of potential ASR suppressants have been investigated, including BS 3892 PFA, GGBS, MS (micro-silica), MK (Metakaolin) and green/amber/flint glass pozzolan (GP, AP and FP). Typical chemical and physical properties of the OPC, PFA [20], GGBS [20], MS, MK and GP/AP/FP [21] used in ASR study are shown in Table 2.

2.2 Mix Proportions

2.2.1 Effect of Glass Colour

The aim of this investigation was to determine the effect of glass colour on ASR reactivity. BS 812:123 mix proportions were used with 100% coarse glass aggregate (3-6mm and 6-12mm) and normal sand. Details of the BS 812-123 concrete mix proportions are given in Table 3.

2.2.2 Pessimum Glass Particle Size

A range of particle sizes from sub 35μm to 12mm of green, amber, blue and flint glass cullet were used to investigate the effect of glass particle size. BS 812:123 mix proportions (Table 3) were used with 30% glass aggregate replacement for normal coarse and fine aggregate.

2.2.3 ASR Suppressants

White cement, PFA, SPFA, GGBS, MS, MK and AP/GP/FP were used selectively as ASR suppressants in combination with the worst-case glass particle sizes. BS 812:123 (Table 3) mix proportions were used with 100% coarse glass

Table 3. Mix proportions by volume for ASR study (BS 812-123)

Materials	Cement	Aggregates			water (free)
		5-10mm	10-20mm	sand	
Proportions (% by volume)	22.2	22	16.5	16.5	22.8

aggregate (3-6mm blue and 6-12mm amber) and normal sand

2.3 Sample Preparation

46 concrete mixes were prepared in accordance with BS 812-123. 3 concrete prisms (40×40×160 mm) were cast for each mix at room temperature and cured for (24±2) hours at 20°C in plastic bags with a relative humidity around 100%. After demolding, the prisms were stored at 80°C in tap water for another 24 hours and then immersed in 1 N NaOH at 80°C until testage.

2.4 Test Procedures

The length change of the prisms was measured using a length comparator to BS 812-123. An initial reading was taken after demolding and a zero reading after storing in tap water at 80°C for 24 hours. The prisms were then immediately transferred to a 1N NaOH solution at 80°C. Two glass concrete samples containing 3-6mm flint glass aggregate (OPC/Flint and OPC/MK20/Flint) were examined using optical microscopy (OM) to see if ASR gel was formed after these samples were immersed in 1N NaOH solution for 4 months.

3. RESULTS AND DISCUSSION

3.1 Effect of Glass Colour on ASR

Expansion results (the average of 3 prisms) of concrete using 3-6mm and 6-12mm green, amber, flint and blue glass coarse aggregate are shown plotted in Figs. 1-2.

It should be noted that measurement of the PC/Blue 3-6mm, PC/Amber 6-12mm and PC/Flint 6-12mm mixes was halted after 28 days in 1N NaOH solution at 80°C because of the large expansions measured. Others were tested up to 91 days (well beyond the ASTM C1260 recommended 14 days test during). As expected, all glass aggregates tested were reactive, but the rate of reaction varied with glass colour and particle size. For the 3-6mm size range, blue is the most reactive glass colour while green, amber and flint show similar but lower expansion rates. For the 6-12mm size range, the expansion rates of amber and flint are much higher than those of green and blue glass aggregate Results of previous research studies [7, 8, 13] in USA on the effect of glass colour on ASR show that clear (flint) glass causes most expansion, amber glass is considerably less reactive whilst green glass appears not only to be not reactive, but also reduce the expansion of slightly reactive normal sand. Meyer and Jin [7, 13] also suggested that glass colour effect on ASR was due to small quantities of colour-controlling oxides and that especially for non-expansive green glass, a strong relation was found between expansion and Cr_2O_3, which is typically added to the glass for the green colour. Results from this research seem to be different and the authors feel that chromium may not the chemical component which influences ASR expansion dramatically. As can be seen from Table 2, the chemical compositions of different colours of glass are very similar, and it is unlikely that very small quantities of colouring oxides can affect ASR expansion significantly. Moreover, results in Figs. 1-2 also show that different particle sizes

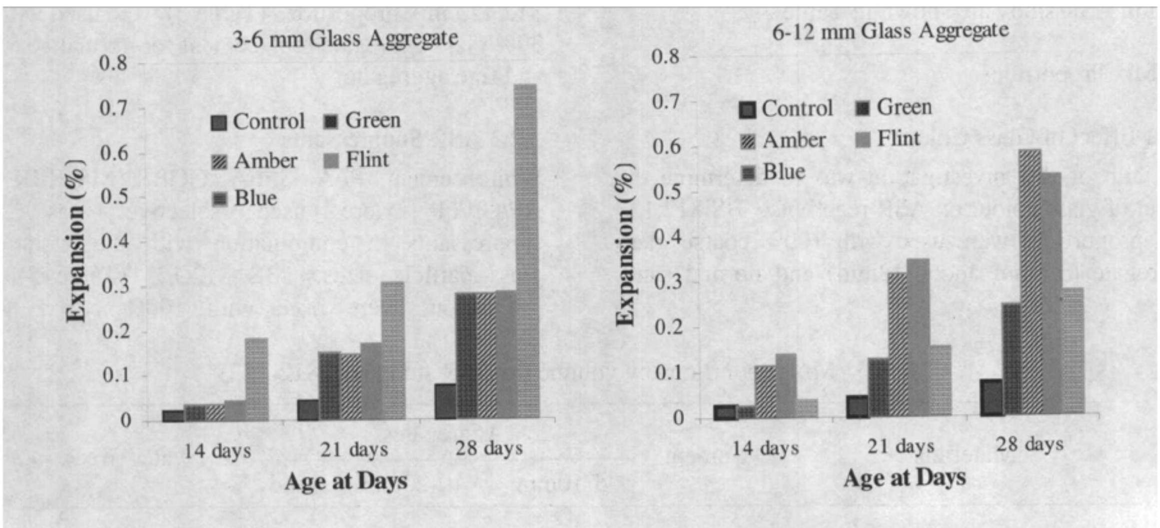


Fig.1. Effect of glass colour on ASR up to 28 days

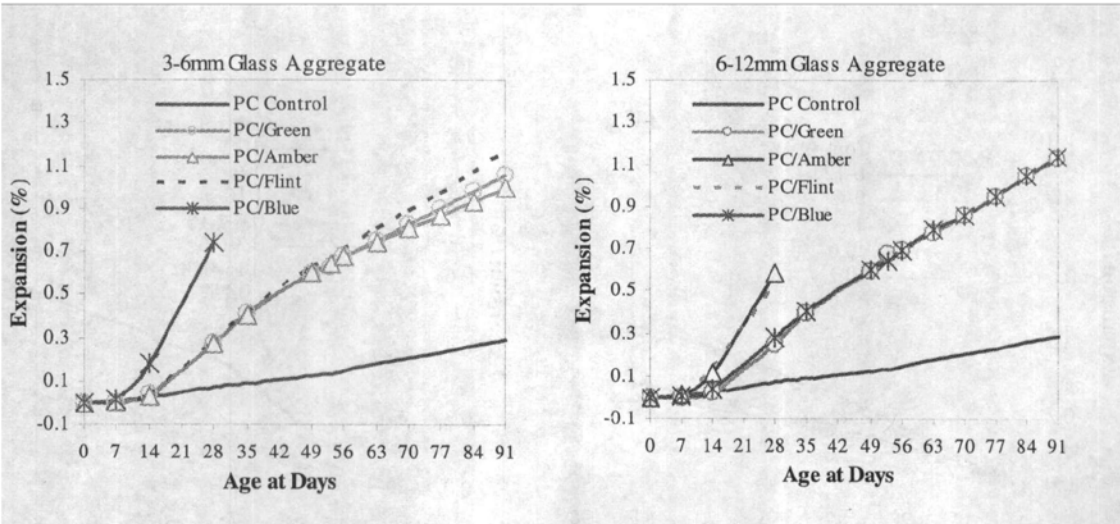


Fig.2. Effect of glass colour on ASR up to 91 days

of the same colour glass has different trend of colour reactivity, suggesting that other factors rather than colour play an important role on the ASR expansion rate of glass aggregate. Further research needs to be done on the mechanism of glass colour reactivity

3.2 Effect of Glass Particle Sizes on ASR

Summary ASR expansion results up to 91 days (35 days for 1-3mm blue glass) for a range of particle sizes from <35μm to 12mm, Table 1, of green, amber, flint and blue glass used as aggregate in concrete are shown plotted in Figure 3.

It can be seen clearly from Figure 3 that 1-3mm blue glass is the most reactive size range among the various glass colours and particle sizes tested (expansion is 0.732% for 1-3mm blue at 35days and 0.721% for 6-12mm amber at 42 days). Results also show that concrete made with green and amber glass particles < 0.6mm and flint glass particles <1.18mm exhibits less expansion than the control mix, which implies a degree of ASR mitigation for these particle size ranges, while ASR expansion rates increase with particle size above 1mm for green and amber and 1.18mm for flint. However, the size effect on ASR of blue glass aggregate shows contradictive trend compared with that of green, amber and flint glass aggregate. ASR expansion rates of blue glass aggregate decrease with the increase of particle size ranges from 1-3 to 6-12mm. In general, expansion rate increases with glass particle sizes. These findings are contradictive to that of Meyer and Jin [7, 13] which showed that for clear (flint) soda-lime glass, Pyrex glass and fused silica, the pessimum sizes of ASR expansion were appeared to be 1.18mm, 150μm and 75μm respectively. Further investigation on the chemistry of glass and the effect of crushing process needs to be carried out to understand why such variability occurs.

3.3 Effectiveness of ASR Suppressant Materials

The ASR expansion results of concrete made with a range of potential pozzolanic ASR suppressants and 3-6mm flint and 6-12mm amber glass aggregate are shown plotted in Figures 4-5. These show that metakaolin (MK) and pulverized-fuel ash (PFA) can totally mitigate ASR in both glass aggregate cases. Other materials tested including ground granulated blast-furnace slag (GGBS), white Portland cement, micro-silica (MS) and amber (AP), green (GP) and flint (FP) ground glass powder at around $300m^2/kg$ fineness, can also reduce ASR significantly, but are less effective than PFA and MK.

The use of pozzolanic materials including PFA, GGBS and MS to control ASR in concrete is the common mitigation method used in concrete construction. Among them, PFA is the most commonly used worldwide because of its economic and technical benefits [22]. As ASR suppressant, the factors affect the efficacy of a given PFA including: i) content (usually as a mass replacement of cement); ii) chemical composition (especially CaO and Na_2Oe content); iii) reactivity of the aggregate and iv) alkali content of the concrete (mainly from Portland cement). Perhaps the most important parameter is the CaO content of the PFA [22], and generally, lower-lime PFAs are more effective than higher-lime PFAs in controlling ASR. As for 6-12mm amber glass aggregate tested in this study, a 30% replacement of cement by PFA can totally mitigate ASR up to test duration of 17 weeks (4 months) for a very reactive 6-12mm amber glass aggregate as 100% coarse aggregate in concrete.

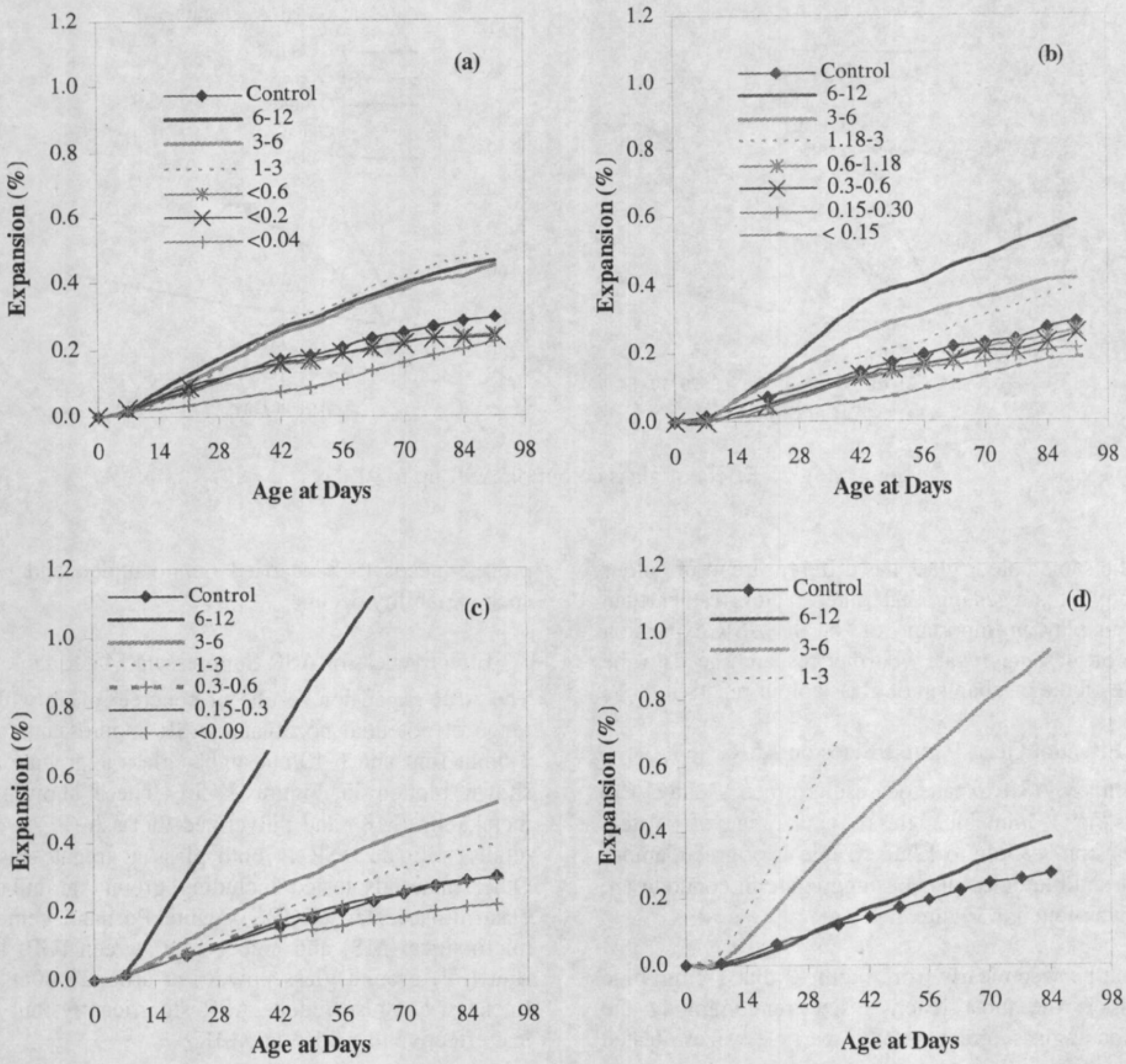


Fig.3. Effect of glass particle size on ASR in concrete for (a) green, (b) flint, (c) amber and (d) blue

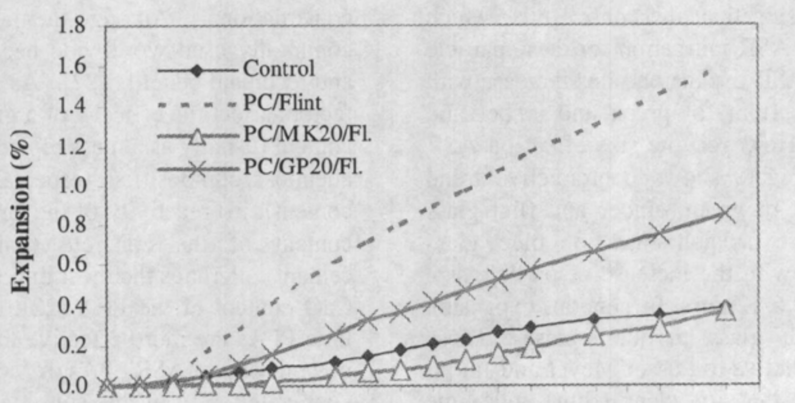


Fig.4. Effect of MK and green glass pozzolan on ASR of 3-6mm flint glass aggregate

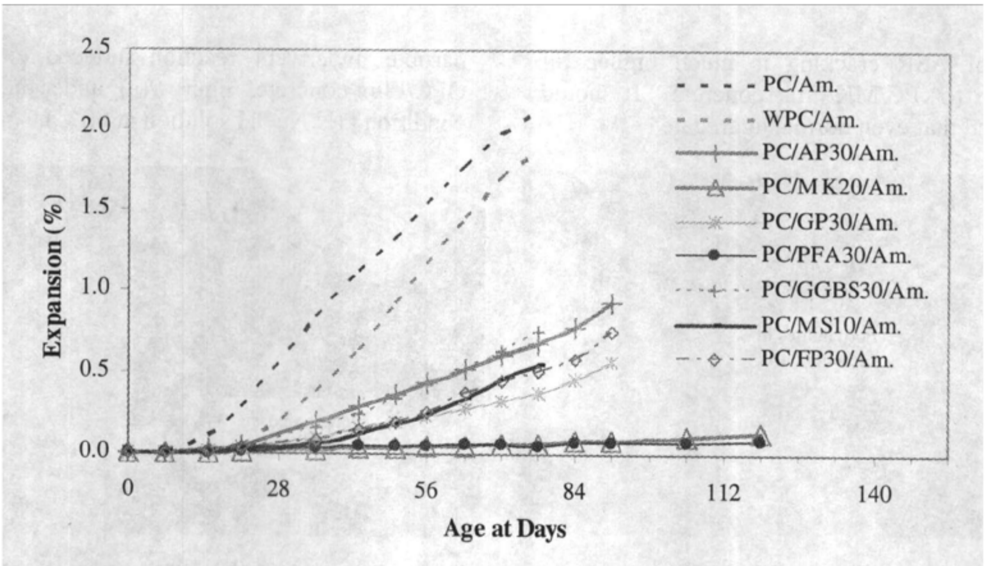


Fig.5. Effect of a range of potential pozzolanic materials on ASR of 6-12mm amber glass aggregate

This is may be due to its lower CaO content (Table 2) and the ability of producing a C-S-H structure with a lower Ca/Si ratio thereby increasing the proportion of bound alkalis, leading to a reduction in the alkalis dissolved in the pore solution [22].

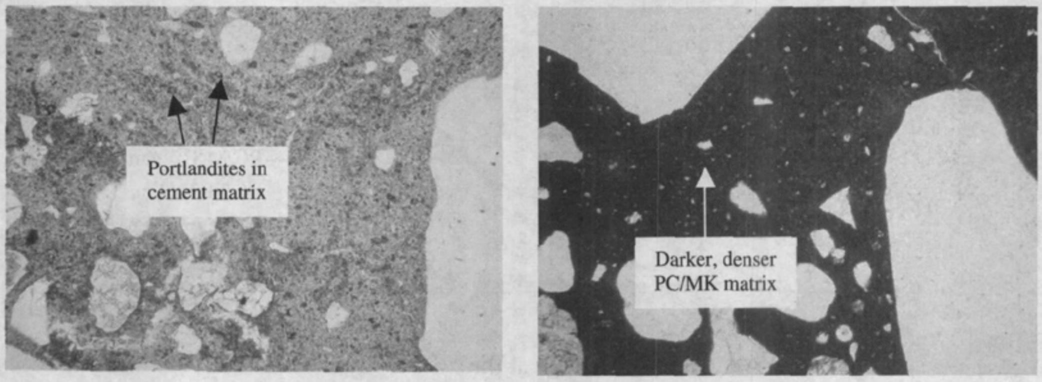
GGBS is also used commonly to mitigate ASR at a higher dosage than PFA, generally 35-50% by mass of cement [22]. Results show that at a 30% replacement level of cement, GGBS can't effectively mitigate ASR of 6-12mm amber glass aggregate. Compare the CaO content of GGBS with that of PFA (Table 2), it is clear that a higher replacement level is needed when GGBS is used as ASR suppressants.

MS has not been used as frequently as PFA and GGBS to control ASR and there exists a paradox that MS might induce ASR rather than mitigating it [23]. Results show that 10% replacement of MS is not as effective as 30% PFA in mitigating ASR of 6-12mm amber glass aggregate. Taking into account of its cost and availability, MS is not a common choice as an ASR suppressant.

As a mineral admixture, MK is relatively new to the concrete industry of its potential for improving the durability of concrete. Meyer [7] reported that 20% of MK could totally mitigate ASR of post-consumer glass. Ramlochan et al [24] concluded that 10-15% of MK might be sufficient to control deleterious expansion of alkali-silica reaction in concrete, depending on the nature of the aggregate and the likely suppressing mechanism appeared to be entrapment of alkalis by the supplementary hydrates of MK with porlandite and a consequent decrease in the pH of pore solution. In this study, a 20% replacement of MK appears to be very effective in mitigating ASR of both glass aggregates tested. An optical microscopy examination was conducted of glass concrete to investigate the micro structure changes with and without MK in the following section.

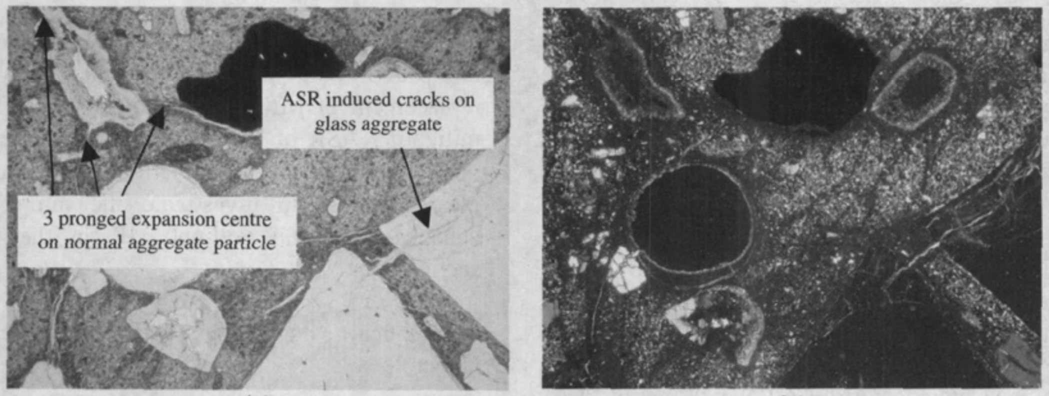
3.5 Optical Microscopy (OM) Analysis of Glass Concrete

OM images of concrete made with OPC, 3-6mm flint glass aggregate and OPC with 20% replacement of MK and 3-6mm flint glass aggregate are shown in Figures 8-10. It can be seen from Figure 8(a) the existence of fine portlandites within the cement paste matrix of PC/Flint concrete, whilst these were consumed by MK and absent in matrix of PC/MK/Flint concrete as shown in Figure 8(b). It was also observed that the PC/MK cement paste is much denser and darker than that of the merely PC concrete, indicating the use of MK and its pozzolanic reaction in concrete had distinct advantages for durability. The pozzolanic nature of metakaolin and its capability of reacting with portlandite to form supplementary calcium-silicate-hydrate similar in composition and structure to those obtained from Portland cement has been reported [24, 25], and is confirmed in this study by the absence of portlandite in OPC/MK matrix. However in both samples (Figures 9-10), ASR gel was observed on glass aggregate unsurprisingly because of the longer treatment (4 months) of the concrete in 1N NaOH solution at 80°C. However, it was also observed that the degree of ASR cracking is much higher for PC/Flint than for PC/MK/Flint concrete. It should also be noticed that even normal aggregate particle underwent reaction induced expansion in OPC/Flint concrete, Figure 9(a), under the severe test condition (1N NaOH solution at 80°C).



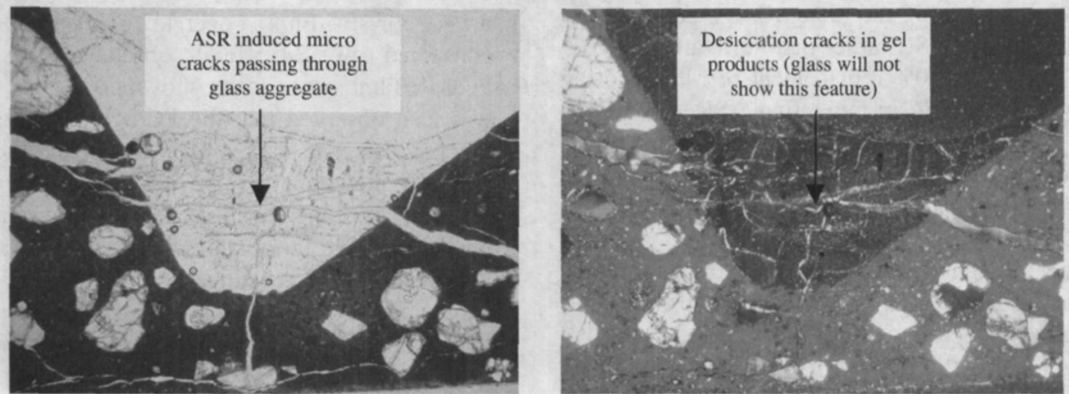
(a) (b)

Fig.8. OM images under plane polarized light (PPL) (after 4 months in 1N NaOH solution at 80°C). Width of fields 3.5mm. (a) PC/Flint 3-6mm; (b) PC/MK/Flint 3-6mm



(a) (b)

Fig.9. OM image of PC/Flint 3-6mm (after 4 months in 1N NaOH solution at 80°C). Width of fields 1.84mm. (a) plane polarized light (PPL); (b) cross polarized light (CPL)



(a) (b)

Fig.10. OM images of PC/MK20/Flint 3-6mm (after 4 months in 1N NaOH solution at 80°C). Width of field 0.9mm. (a) plane polarized light (PPL); (b) cross polarized light (CPL)

4. CONCLUSIONS

1) When used as a concrete aggregate in normal Portland cement concrete, glass aggregate will, with no doubt, react with the alkalis in cement system. The rate of reaction varies with glass colour and particle sizes.
2) The pessimum particle size for ASR reaction appears to vary with glass colour, but in general and very significantly, a reduction in ASR expansion is observed when glass particles with size less than 0.6mm for amber and green and 1.18mm for flint are used.
3) PFA, GGBS, MS, MK and glass powder as cement substitutes all reduce the rate of ASR reaction. PFA and MK at replacement levels of 30% and 20% respectively are by far the most effective suppressants tested.
4) OM study suggests that MK has pozzolanic reactivity and consumes portlandite in cement matrix, thus effectively mitigates ASR expansion.

4. ACKNOWLEDGMENTS

i) The authors are grateful to The Waste & Resources Action Programme for the funding for this research work and to Ted Sibbick of the Building Research Establishment for the Optical Microscopy work.
ii) Mr Kieran Nash is acknowledged for his extensive technical support on this wide research study.

5. REFERENCES

[1] Shao YX, Lefort T, Moras S and Rodriguez D. Studies on concrete containing ground waste glass. Cement and Concrete Research, 30(2000), pp 91-100.

[2] European Parliament and Council Directive 1999/31/EC on the landfill of waste. Official Journal L 182/1, 16.7.1999.

[3] The Landfill Tax Regulations 1996. The Stationery Office Limited, Statutory Instrument 1996 No. 1527, http://www.hmso.gov.uk/si/si1996/Uksi_19961527_en_2.htm, 18/06/2003.

[4] The Producer Responsibility Obligations (Packaging Waste) Regulations 1997. The Stationery Office Limited, Statutory Instrument 1997 No. 648, http://www.legislation.hmso.gov.uk/si/si1997/1970648.htm, 18/06/2003.

[5] Enviros. Recycled Glass Market Study & Standard Review- 2003 Update. WRAP, 2003.

[6] Byars EA. Use of Ground Cullet as a Cement Replacement Material, Sheffield Technopole Final Report, University of Sheffield, August 1997.

[7] Meyer C and Baxter S. Use of Recycled Glass for Concrete Masonry and Blocks, Columbia University Final Report to New York State Energy Research and Development Authority, Rep. No. 97-15, Nov. 1997.

[8] Meyer C and Baxter S. Use of Recycled Glass and Fly Ash for Precast Concrete, Columbia University Final Report to New York State Energy Research and Development Authority, Rep. No. 98-18, Oct. 1998.

[9] Meyer C. Development of Glass Concrete Products, Columbia University Final Report to New York Empire State Development, March 1999.

[10] Byars EA and Morales B. ConGlassCrete II Project Interim Progress Report. www.wrap.org.uk/conglasscrete/cgc_reports.asp, December 2003.

[11] Byars EA, Morales B and Zhu HY. Waste Glass as Concrete Aggregate and Pozzolan – Laboratory and Industrial Projects. Concrete, Vol. 38, No. 1, January 2004, pp 41-44.

[12] Jin W. Alkali-Silica Reaction in Concrete with Glass Aggregate – A Chemo-Physico-Mechanical Approach. PhD Dissertation, Columbia University, New York, 1998.

[13] Jin W, Meyer C and Baxter S. Glasscrete – Concrete with Glass Aggregate. ACI Materials Journal, Mar - April, 2000, pp208-213.

[14] Byars EA, Meyer C and Zhu HY. Use of Waste Glass for Construction Products: Legislative and Technical Issues. Proceedings of the International Symposium on Recycling and Reuse of Waste Materials, Dundee, 2003, pp827-838.

[15] Byars EA and Zhu HY. ConGlassCrete I Project Interim Progress Report. www.wrap.org.uk/conglasscrete, November 2003.

[16] West G. Alkali-Aggregate Reaction in Concrete Road and Bridges. Thomas Telford, 1996.

[17] Concrete Society. Technical Report No. 30, Alkali-Silica Reaction: Minimising the Risk of Damage to Concrete. 3rd Edition, 1999.

[18] American Society of Testing and Materials. Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method). C 1260-01, Annual Book of ASTM Standards, Vol. 04.02, 2003.

[19] British Standard Institution. Testing Aggregate: Method for Determination of Alkali-silica Reactivity – Concrete Prism Method. BS 812-123, BSI, London, 1999.

[20] Hewlett P C (editor). Lea's Chemistry of Cement and Concrete, Fourth Edition. Butterworth-Heinemann, UK, 1998.

[21] Hollands L. Summary Report on ConGlassCrete Projects, Report Z950/1. Glass Technology Services, 2003.

[22] US Department of Transportation Federal Highway Administration. Guidelines for the Use of Lithium to Mitigate or Prevent ASR. Publication No. FHWA-AD-03-047, January, 2003. http://www.tfhrc.gov/pavement/pccp/pubs/03047, May 2003.

[23] Diamond S. Alkali Silica Reaction - Some Paradoxes. Cement and Concrete Composites, 19, 1997, pp 391-401.

[24] Ramlochan T, Thomas M and Gruber KA. The effect of Metakaolin on Alkali-Silica Reaction in Concrete. Cement and Concrete Research, 30, 2000, pp 339-344.

[25] Silva PS and Glasser FP. Pozzolanic Activity of Metakaolin. Advanced Cement Research, 4 (16), 1992, pp 167-178.