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Value-added utilisation of waste glass in concrete

Ahmad Shayan*, Aimin Xu

ARRB Transport Research Ltd., 500 Burwood Highway, Vermont South, Victoria, 3133, Australia

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Abstract

A large proportion of the postconsumer glass is recycled into the packaging stream again, and some smaller proportions are used for a variety of purposes, including concrete aggregate. However, a significant proportion, which does not meet the strict criteria for packaging glass, is sent to landfill, taking the space that could be allocated to more urgent uses. Glass is unstable in the alkaline environment of concrete and could cause deleterious alkali-silica reaction (ASR) problems. This property has been used to advantage by grinding it into a fine glass powder (GLP) for incorporation into concrete as a pozzolanic material. In laboratory experiments, it can suppress the alkali reactivity of coarser glass particles as well as that of natural reactive aggregates. It undergoes beneficial pozzolanic reactions in the concrete and could replace up to 30% of cement in some concrete mixes with satisfactory strength development. The drying shrinkage of the concrete containing GLP was acceptable.

Keywords: Glass aggregate; Glass powder; ASR; Pozzolanic reaction; Strength development

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1. Introduction

Glass is produced in many forms, including packaging or container glass (bottles and jars), flat glass (windows and windscreens), bulb glass (light globes) and cathode ray tube glass (TV screens, monitors, etc.), all of which have a limited life in the form they are produced and need to be reused/recycled to avoid environmental problems that would be created if they were to be stockpiled or sent to landfill. This paper deals with the recycling aspects of container glass, and the term “glass” hereafter refers to this type only.

2. Recycling of glass

Postconsumer glass containers have traditionally been disposed of either in domestic refuse, which ends up in landfill, collected in designated collection spots for reuse/recycling, or collected from kerbside and then transported to collection sites. The major aim of environmental authorities is to reduce, as far as possible, the disposal of postconsumer glass in landfill and diversion to economically viable glass product streams.

Glass is a unique inert material that could be recycled many times without changing its chemical properties. In other words, bottles can be crushed into cullet then melted and made into new bottles without significant changes to the glass properties. Most of the glass produced is in the form of containers, and the bulk of what is collected postconsumer is again used for making containers. The efficiency of this process depends on the method of collecting and sorting glass of different colours. If different colour glass (clear, green and amber) could be separated, then they could be used for manufacturing similar colour glass containers. However, when the glass colours get mixed, they become unsuitable for use as containers and are then used for other purposes or sent to landfill.

Reindl [1] reported the many noncontainer uses of glass cullet, which included road construction aggregate, asphalt paving, concrete aggregate, building applications (glass tiles and bricks, wall panels, etc.), fibre glass insulation, glass fibre, abrasive, art glass, agricultural fertiliser, landscaping, reflective beads, tableware, hydraulic cement, among other applications. The utilisation of glass in concrete is of particular interest for the work reported here.

A major concern regarding the use of glass in concrete is the chemical reaction that takes place between the silica-rich

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* Corresponding author. Tel.: +61-3-9881-1658; fax: +61-3-9803-2611.
E-mail address: ahmads@arrb.com.au (A. Shayan).

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glass particles and the alkali in the pore solution of concrete, i.e., alkali-silica reaction (ASR). This reaction can be very detrimental to the stability of concrete, unless appropriate precautions are taken to minimise its effects. Such preventative actions could be achieved by incorporating a suitable pozzolanic material such as fly ash, silica fume (SF) or ground blast furnace slag in the concrete mix at appropriate proportions.

The susceptibility of glass to alkali implies that coarse glass or glass fibres could undergo ASR in concrete, possibly with deleterious effects. However, it would be expected that fine ground glass (i.e., glass powder, GLP) would exhibit pozzolanic properties such as those of the materials named above and would be an effective ASR suppressant, preventing ASR damage to concrete in the presence of reactive aggregates. Reindl [1] presented a summary of work conducted by other researchers or organisations. For example, he quotes from Boral, Lilesville, NC that ground soda-lime glass of < 100 mesh was effective against ASR and from Clean Washington Centre that glass as fine aggregate (rather than powder) can weaken the concrete matrix due to ASR. He quoted work by Samtur [2] on this issue, which indicated that fine GLP (< 200 mesh or < 75 μm particle size) could act like a pozzolanic material to reduce the tendency of reactive aggregate to undergo ASR. Pattengil and Shutt [3] had apparently also found similar effects. The work of Phillips and Cahn [4] has been quoted to have shown that up to 35% glass cullet could be used in concrete in combination with low-alkali cement, without detrimental effects.

Recently, the New York State Energy Research and Development Authority (NYSERDA) sponsored research on the utilisation of recycled glass for concrete masonry blocks, and it was shown that waste glass can be used as both coarse aggregate and additive, provided that certain conditions are met [5]. Another project dealt with the use of recycled glass and fly ash in precast concrete, and encouraging results were obtained Meyer and Baxter [6].

Bazant et al. [7] found that glass particle size of around 1.5 mm caused excessive expansion whereas particles < 0.25 mm caused no expansion in laboratory tests on concrete. Jin et al. [8] found that glass particles of around 1.2 mm caused the largest mortar bar expansion in the particle size range of 0.15–4.75 mm. They found that the largest expansion resulted when glass particles formed 100% of the aggregate and that green glass containing >1.0% chromium oxide had a beneficial suppressive effect on ASR. Carpenter and Cramer [9] also reported that powdered glass was effective in reducing ASR expansion in accelerated mortar bar tests (AMBT), similar to the effects of fly ash, SF and slag. This is in agreement with the present authors' unpublished results [10], where it was shown that GLP could suppress the ASR expansion caused by natural reactive aggregates and coarse glass particles.

Table 1
Chemical composition of various coloured glass

Composition	Clear glass	Brown glass	Green glass
SiO_2	72.42	72.21	72.38
Al_2O_3	1.44	1.37	1.49
TiO_2	0.035	0.041	0.04
Cr_2O_3	0.002	0.026	0.130
Fe_2O_3	0.07	0.26	0.29
CaO	11.50	11.57	11.26
MgO	0.32	0.46	0.54
Na_2O	13.64	13.75	13.52
K_2O	0.35	0.20	0.27
SO_3	0.21	0.10	0.07

Table 2
Chemical properties of crushed glass, GLP and SF (%)

Composition	Crushed glass	GLP	SF
SiO_2	72.61	72.20	89.75
Al_2O_3	1.38	1.54	0.14
Fe_2O_3	0.48	0.48	0.03
CaO	11.70	11.42	0.38
MgO	0.56	0.79	0.05
Na_2O	13.12	12.85	0.19
K_2O	0.38	0.43	0.34
SO_3	0.09	0.09	0.04
LOI	0.22	0.36	6.54

From the above, it appears that glass could be used in concrete in three forms: as coarse and fine aggregates and in powder form. The coarse and fine glass aggregates could cause ASR in concrete, but the GLP could suppress their ASR tendency, an effect similar to supplementary cementitious materials (SCMs). On a market price basis, it would be much more profitable to use the glass in powder form as a cement replacement material (i.e., as SCM) than as aggregate. This would be a value-added material, produced from contaminated, mixed-colour glass chips that are not useable for packaging purposes. Although such material could also be used as abrasive grit, the volume used for this application is not very high compared with that of SCMs. In the following sections, data are presented in relation to the utilisation of glass in concrete in the three forms mentioned above.

3. Experimental work

Three aspects of glass utilisation in concrete were addressed in the research program undertaken at ARRB. These included coarse glass aggregate, fine glass aggregate and GLP. The particle size range for each of these products is given below:

Product	Particle size range	Designation
Coarse glass aggregate	4.75–12 mm	CGA
Fine glass aggregate	0.15–4.75 mm	FGA
Glass powder	< 10 μm	GLP

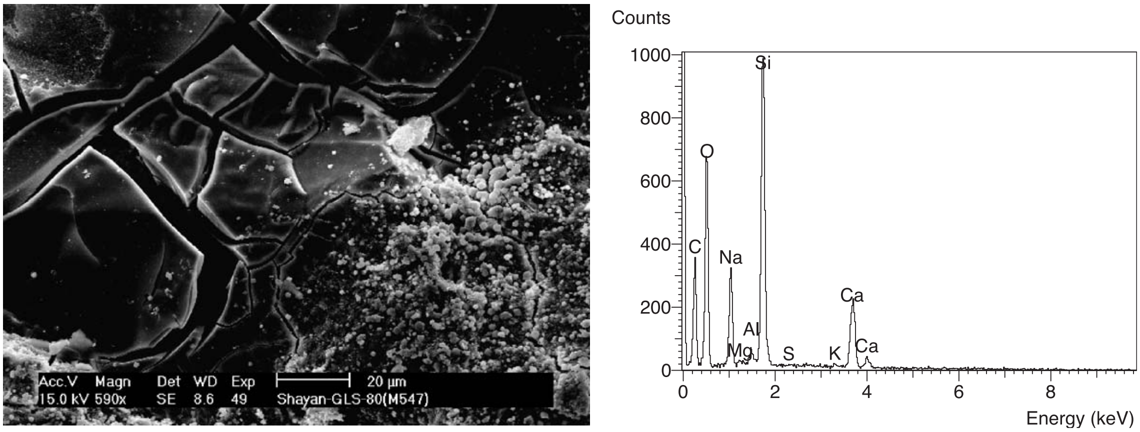

Fig. 1. Site of ASR gel formation in concrete and the composition of the gel.

The chemical compositions of these products are similar for a given type of glass, and typical chemical compositions of the various colour glass have been presented in Table 1.

The coarse and fine glass particles are used as replacement for the corresponding size ranges of natural aggregate materials, whereas the GLP has been studied as a pozzolanic material, i.e., the same application as for SF or fly ash. A comparison between the compositions of mixed crushed glass and GLP with that of SF is presented in Table 2, showing the more silica-rich nature of the latter.

The natural materials used in this work were nonreactive, natural, Victorian concrete sand and a crushed basalt coarse aggregate. A reactive greywacke coarse aggregate from NSW was used to assess the effectiveness of GLP in suppressing ASR expansion.

4. Coarse and fine glass aggregates in concrete

The influence of physical properties of glass aggregate such as grading on the properties of the concrete mix is well known. Glass, due to its silica-rich nature and amorphous structure, is susceptible to chemical attack under the high alkali conditions provided by the hydrated cement phase in the concrete. This chemical attack on glass could produce extensive formation of ASR gel (Fig. 1), which is expansive and could cause premature cracking in the concrete, if appropriate precautions are not put in place in the formulation of the concrete mix.

The nature of the glass reactivity has important implications in its utilisation in concrete. For instance, some natural aggregates cause excessive expansion in concrete when used as a small proportion of total aggregate content and some other ones when used at 100% of the total aggregate. The reactivity of aggregate is assessed by AMBT, conducted in 1-M NaOH at 80 °C, according to ASTM C1260 or an Australian method RTA T363 (RTA, NSW Specification B80, Test Method T363). The AMBT results obtained at ARRB have shown that the larger the content of glass in mortar bars, the higher the expansion. Fig. 2 illustrates this effect. The criteria for this test, according to the RTA Test Method T363, are that expansion values smaller than 0.10% at the age of 21 days are associated with nonreactive aggregate (< 0.15% for sand) and expansions greater than 0.10% at 10 days are associated with reactive aggregates. Expansions smaller than 0.10% at 10 days but exceeding 0.10% at 21 days indicate slowly reactive aggregate.

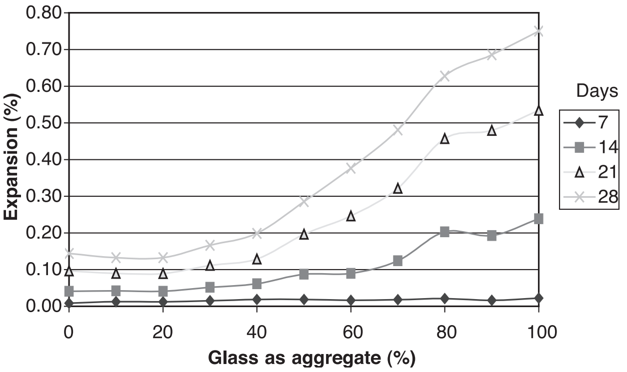

Fig. 2. Expansion as a function of glass content of mortar bars for different ages of storage under the AMBT conditions.

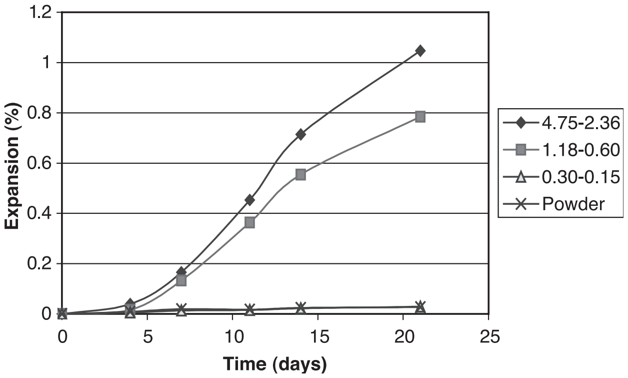

Fig. 3. Expansion curves for mortar bars containing different glass particle sizes.

Table 3
Properties of two concrete mixes containing 50% each of coarse and fine glass

Mix no.	Binder (%)		Glass content (%)		w/b[a]	Slump (mm)	Air (%)	Strength (MPa)		Superplasticiser
	Cement	Fly ash	Coarse	Fine				7 days	28 days	
1	75	25	50	50	0.465	60	1	28.6	39.9	Yes
2	75	25	50	50	0.52	80	2	25.3	35.0	No

[a] Water/binder ratio.

Based on these criteria, Fig. 2 indicates that use of up to 30% glass in the concrete may not cause deleterious effects, particularly if the alkali content of the concrete is low (below 3-kg Na_2O equivalent per cubic meter). At higher alkali contents of concrete, further expansion may result.

In addition to the glass content of mortar bars, the particle size also has an effect on the expansion. This is illustrated in Fig. 3 for four particle size ranges, including powder (< 10 μm), very fine sand (0.15–0.30 mm) and two coarser sand fractions. The results shown in Fig. 3 indicate that glass particle sizes below 0.30 mm would not cause deleterious expansions whereas fractions above 0.60 mm would cause significant deleterious expansions.

Therefore, the magnitude of expansion would depend on the interaction of glass content, particle size and alkali content of the concrete. These results have shown that glass can react and produce ASR gel and that once the particle size is sufficiently reduced, it can act as a pozzolanic material. It is well known that the reactivity of aggregate and its consequent expansion can be suppressed by incorporating appropriate amounts of SCMs such as SF and fly ash. Fine GLP can also act in a similar manner (see later).

So far as utilisation as fine and coarse aggregates is concerned, trial mixes were undertaken with the view of establishing how much fine and coarse glass could be used in concrete mixtures that would be suitable for some structural applications and for concrete pavements. The trials aimed at producing concrete appropriate as VicRoads 32-MPa strength grade. This mixture contained a binder of 255-kg/m^3 cement and 85-kg/m^3 fly ash. The coarse aggregate and sand contents were 1080 and 780 kg/m^3, respectively. After a number of trials, adjusting the properties of fresh and hardened concrete, the following concrete mixture formulations were found to be satisfactory, as detailed in Table 3.

It is evident from the strength results that these mixes easily meet and exceed the requirements of the 32-MPa concrete while incorporating large quantities of waste glass.

For nonstructural applications, where lower strength (e.g., 25 MPa) is required, the same mix without the water reducer or superplasticiser could be used to achieve the required strength. Two mixes containing 50% coarse glass without and with 50% fine glass are detailed in Table 4. Due to the presence of 25% fly, any ASR expansion would be greatly reduced to nondeleterious levels.

The drying shrinkage of the concrete mixes was well below the limit of 0.075% specified by the Australian Standard AS 3600. Fig. 4 shows typical drying shrinkage curves for the concrete specimens with various glass contents.

From the above, it is concluded that up to 50% of each of fine and coarse glass could be used in some structural and nonstructural concrete applications. However, other engineering properties of such concrete mixes also need to be investigated.

5. Incorporation of GLP in concrete

The initial work undertaken by ARRB on the utilisation of glass as a pozzolanic material was partially supported by EcoRecycle Victoria in 1998 and subsequently by VISY Recycling, Glass Division. The following section summarises the results obtained during this research program.

5.1. Effects of GLP on mortar strength

The particle size distribution of the GLP used is as follows:

Particle size (μm)	< 5	5–10	10–15	>15
%	39.0	49.0	4.4	7.6

The specific surface area of the GLP was 800 m^2/kg, which is around double that of most Australian GLP cements (~ 400 m^2/kg).

Table 4
Concrete mixes for 25 MPa concrete (air/entrained)

Mix no.	Binder (%)		Coarse[a] glass (%)	Fine[a] glass (%)	w/b	Slump (mm)	Air (%)	Strength (MPa)	
	Cement	Fly ash						7 days	28 days
1	75	25	50	0	0.54	80	6.1	18.5	28.1
2	75	25	50	50	0.50	75	4.5	19.5	31.2

[a] The remainder of each fraction consists of natural coarse and fine aggregate materials.

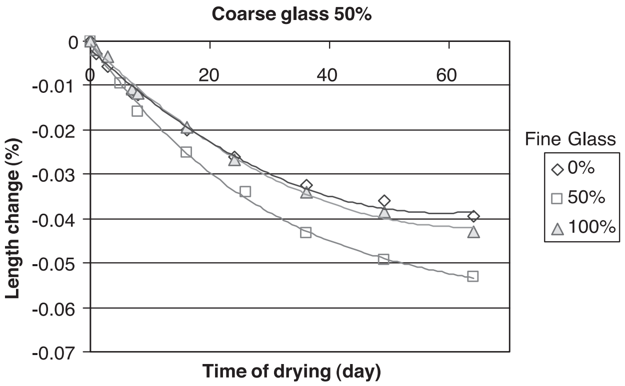

Fig. 4. Drying shrinkage curves for concrete mixes containing 50% coarse glass and various amounts of fine glass.

The effects of cement or sand replacement by GLP on the strength of mortar cubes (aggregate/cement ratio of 2.25 and water/cement ratio of 0.47) are shown in Figs. 5 and 6. In the case of cement replacement, the reduction in the 28-day strength increases with the level of cement replacement and for up to 30% replacement may, to some extent, be a short-term effect because in such short periods the pozzolanic effects would not become evident. Fly ash also exhibits a similar effect when it replaces an equal mass of cement.

Longer-term strength development was studied in comparison with SF. This series consisted of control specimens in which the fine aggregate was a reactive greywacke and other specimens that contained 10% SF, 20% GLP or 30% GLP, each replacing corresponding amounts of the cement. In one case, 30% GLP replaced the aggregate. Fig. 7 shows the strength development of each combination over 270 days.

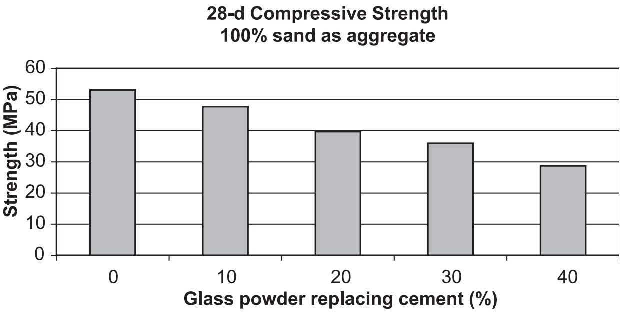

Fig. 5. Effect of GLP replacing cement on strength of mortar made with 100% sand.

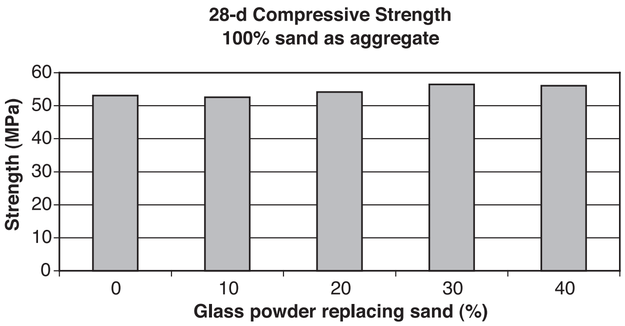

Fig. 6. Effect of GLP replacing aggregate on the strength of mortar made with 100% sand.

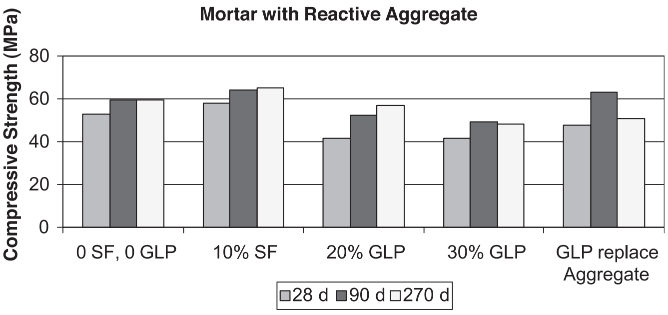

Fig. 7. Strength development of mortar with reactive aggregate.

These results indicate that 10% SF replacement produces higher strength than the GLP replacements, but they also show that mortar specimens containing GLP continue to develop further strength with time, indicating pozzolanic reactivity. It should be noted that when 30% sand was replaced by GLP, the 90-day strength was the same as that of the SF-bearing specimens.

To verify the positive effect on strength of aggregate replacement by GLP, two additional tests were conducted on mortar cubes, cured for up to 270 days. In one set of specimens, 20% cement was replaced by GLP, and in the other set, in addition, 10% of aggregate was also replaced by GLP. Fig. 8 confirms that this replacement is beneficial, probably due to improvement in the particle packing as well as the pozzolanic reaction. It should be noted that the strength achieved with 30% GLP replacing 20% cement and 10% aggregate exceeds that of the SF-containing mix.

The apparently larger effect of SF on strength gain compared with GLP is exaggerated in these tests, because those with SF have 90% cement whereas those with GLP have 80% and 70% cement. For a comparison based on similar cement contents, mortar strength tests were conducted on two further sets of specimens that contained crushed, graded glass as the fine aggregate (80%

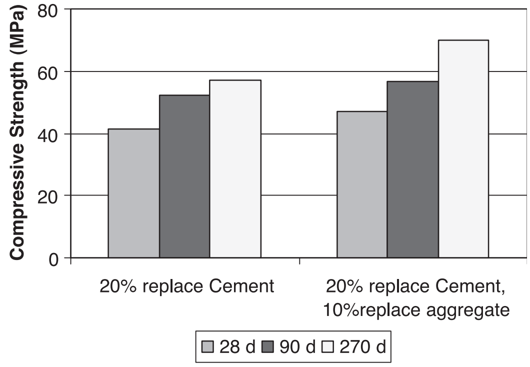

Fig. 8. Strength development of reactive aggregate with additional GLP.

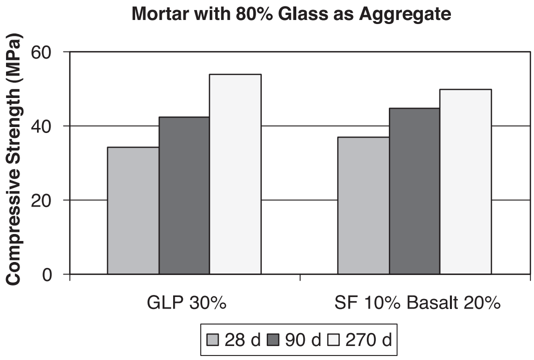

Fig. 9. Comparison between SF and mortar GLP with 30% reduction in cement content.

glass + 20% natural sand) and in which 30% of the cement was replaced by other materials. In one set, 30% of cement was replaced by GLP, and in the other set, cement was replaced by a mixture of 10% SF + 20% pulverised basalt powder (nonpozzolanic). This made the cement content of the two sets the same. Fig. 9 shows the strength results for the two sets to be very similar. It should be noted that the strength results presented in Figs. 7 and 9 are not comparable due to completely different aggregates in the mortar mixes.

Therefore, it is confirmed that the reduced strength observed in Fig. 7 for the mix containing GLP is due to the lower cement content rather than the nature of the GLP. In the case where GLP replaces aggregate, without reduction in the cement content, the resulting strength is greater than those of specimens containing SF. The above indicates the favourable effects of GLP on strength development of mortar specimens containing it.

5.2. Effect of GLP on mortar expansion

As shown in Figs. 2 and 3, coarse sand size particles of glass can cause deleterious ASR expansion, particularly at high glass contents in the AMBT. Therefore, six sets of mortar bars were made to contain 80% glass particles in the aggregate phase as the reactive component. The control set contained the aggregate and plain cement, and in the other five sets, the cement was replaced by 5% SF, 10% SF, 10% GLP, 20% GLP and 30% GLP. Figs. 10 and 11 show the expansion results for these combinations and indicate that both SF and GLP are effective in suppressing ASR expansion when used in sufficient amounts (10% SF and >20% GLP). These results indicate the efficiency of 20% and 30% GLP in suppressing ASR expansion to be better than 10% SF.

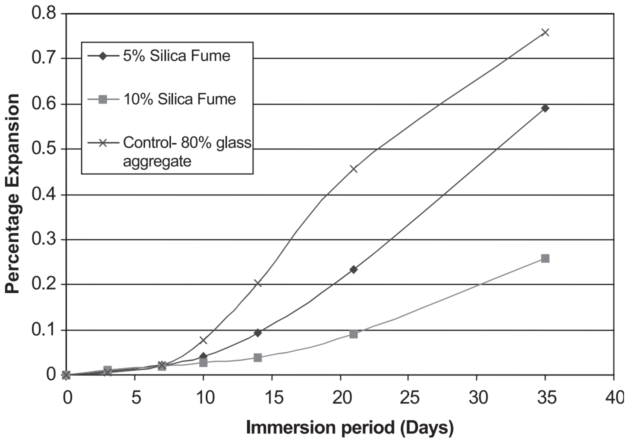

Fig. 10. AMBT results. Effects on SF expansion of mortar bars containing reactive aggregate.

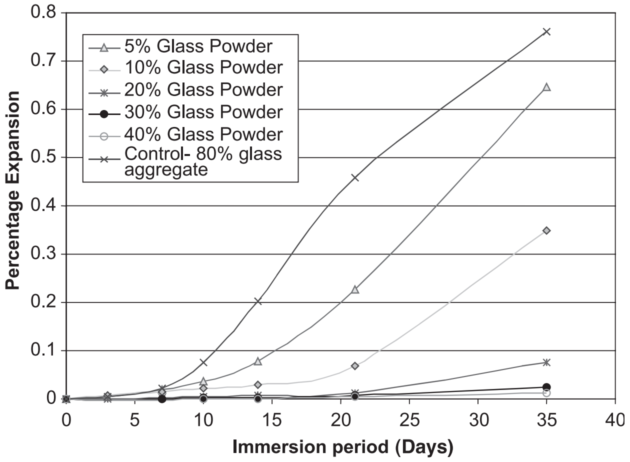

Fig. 11. AMBT results. Effects of GLP on expansion of mortar bars containing reactive aggregate.

Due to the large soda content of the glass (around 13%), it is important to find out whether or not the GLP itself could cause long-term mortar bar expansion or trigger the expansion of reactive aggregates if present in the specimen. Long-term mortar bar expansion testing, conducted at 38 °C, 100% RH, were undertaken in combination with nonreactive and reactive aggregates and with the same levels of cement replacement as mentioned above. The cement alkali level used was 0.63% Na_2O equivalent in the case of the reactive aggregate to find out whether the GLP would release sufficient amounts of alkali to cause deleterious ASR expansions greater than

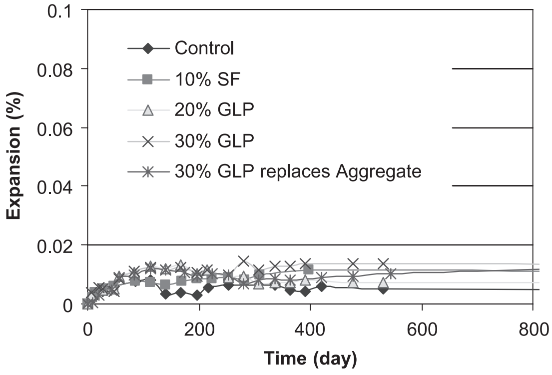

Fig. 12. Expansion curves for mortar bars containing nonreactive aggregate and 30% GLP.

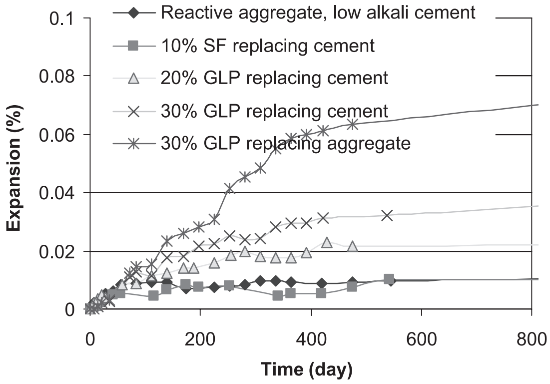

Fig. 13. Expansion curves for mortar bars containing low-alkali cement reactive aggregate and 30% GLP, replacing cement.

0.10%. Expansion values less than 0.1% at 1 year indicate innocuous combinations.

Fig. 12 shows that the GLP itself does not cause any expansion when the aggregate is nonreactive. Moreover, Fig. 13 (where a low-alkali cement was used as the binder) shows that when the aggregate is reactive, the presence of even 30% GLP does not release sufficient amounts of alkali to trigger the reactivity of the very susceptible aggregate used. Even when the cement is not replaced, and GLP has replaced the aggregate, still the 30% GLP does not cause deleterious mortar bar expansion. The data indicate that GLP could be used without fear of harmful effects.

5.3. GLP in concrete

The efficiency of GLP was also assessed in concrete expansion tests. A very reactive aggregate was employed in the concrete prism test conducted according to the RTA T364 Test Method (similar to ASTM C1293). Deleterious expansions are considered to be above 0.03% or 0.04% in 1 year. Fig. 14 shows that even 40% GLP, which has the potential to release more alkali than 30% GLP, has effectively suppressed the enormous expansion of the very reactive aggregate in the concrete (80% reduction). For less reactive aggregates, the expansion would have been completely suppressed. This confirms the beneficial effects of GLP in improving the durability properties of concrete.

When various proportions of GLP were used with nonreactive aggregate in concrete of raised alkali level (5.8-kg Na_2O equivalent per cubic meter), the material itself did not cause deleterious expansion, as shown in Fig. 15. The latter results also confirm that GLP would not cause harmful expansion in concrete.

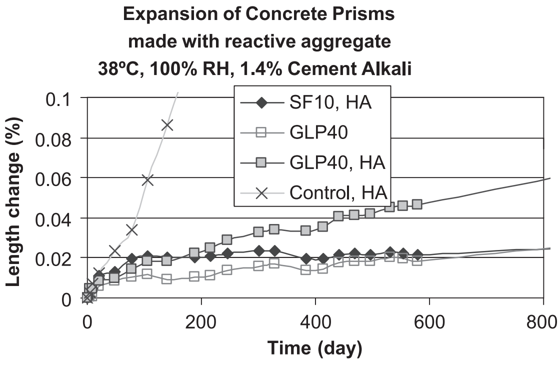

Fig. 14. Expansion curves for concrete prisms containing a very reactive coarse aggregate in combination with the materials indicated. (HA denotes 1.4% cement alkali. GLP40 denotes mixture with low-alkali cement.)

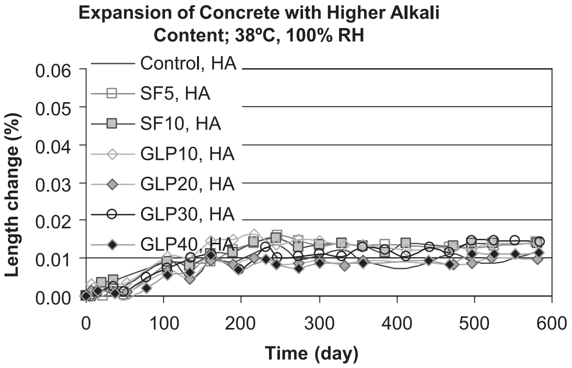

Fig. 15. Concrete expansion curves for the combination of nonreactive aggregate and various amounts of GLP and SF in the presence of 5.8-kg Na_2O equivalent per cubic meter.

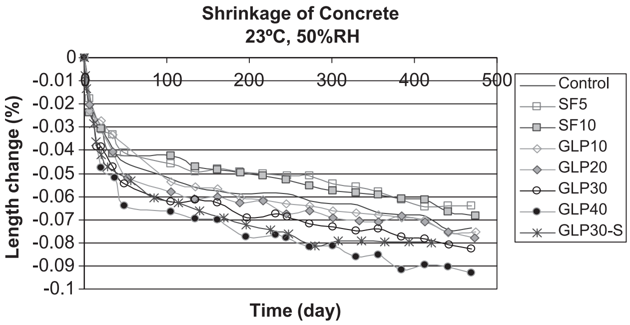

Fig. 16. Drying shrinkage of the various concrete mixtures containing low-alkali contents (no additional alkali).

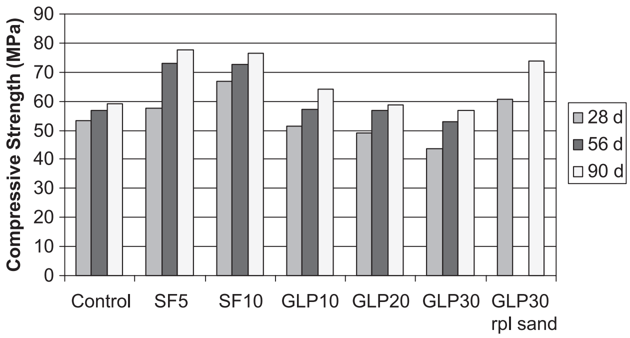

Fig. 17. Strength of concrete cylinders containing GLP and SF compared with the control cylinders.

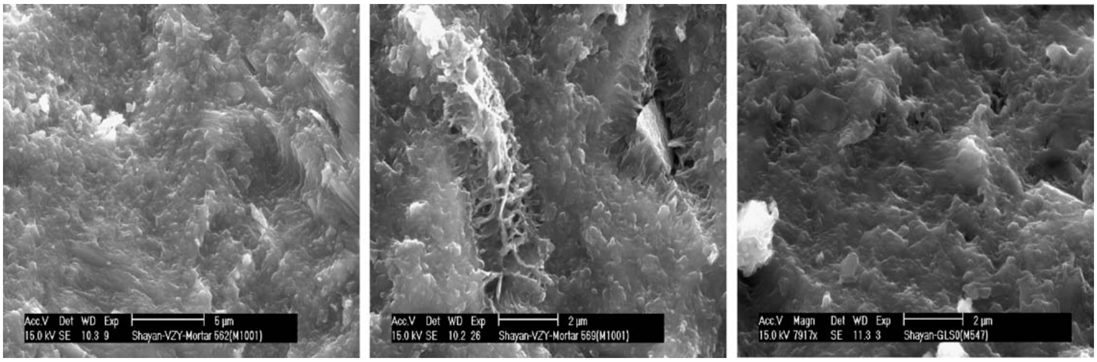

Fig. 18. SEM views of the fracture surface of mortar specimen containing 30% GLP (left and middle) showing its dense microstructure and pozzolanic reaction with cement. These are similar to the SEM view of the mortar without GLP (right).

Moreover, the curve for GLP40 in Fig. 14, related to low alkali concrete (2.65 kg Na_2O/m^3) indicates that the 40 % GLP, replacing cement, did not release sufficient alkali into concrete to cause deleterious AAR expansion in the presence of the very reactive aggregate used. This is despite the fact that this amount of GLP adds about 22.7 kg alkali per cubic meter of concrete, and that the aggregate needs only 5.8 kg Na_2O/m^3 to produces excessive AAR expansion. Therefore, it appears that the alkali contained in the glass powder is not easily available to promote AAR in the presence of reactive aggregates.

5.4. *Effects of GLP on concrete shrinkage and strength*

Concrete specimens corresponding to those represented in Fig. 15 but of lower alkali content were employed for determining the drying shrinkage of concrete containing various amounts of GLP and SF. Long-term data presented in Fig. 16 show that the drying shrinkage of the various mixtures are not excessive and they easily meet the requirements of AS 3600, being values less than 0.075% at 56 days.

The strength properties of the concrete mixtures represented in Fig. 16 are given in Fig. 17. As in the case of mortar specimens, although the concrete mixtures containing GLP have lower initial strength values due to significantly lower cement content, they keep developing strength with time under moist curing conditions and approach the strength of the control mixture. Particularly when GLP replaces sand, the strength is significantly greater than that of the control mixture. These observations indicate the beneficial pozzolanic reaction of the GLP in concrete.

6. Microstructure of mortar phase containing GLP

The mortar specimens containing GLP, which had 270 days of moist curing, were examined by scanning electron microscopy (SEM). These mortar specimens would also represent similar concrete of the same history. Fig. 18 shows the dense microstructure that has developed in mortar incorporating 30% GLP and illustrates the consumption of fine glass particles by their pozzolanic reaction with cement. For comparison, the SEM view of the mortar without GLP is also shown. In both cases, fracture surfaces of the mortar specimens were indicative of a compact microstructure.

7. Conclusions

The data presented in this paper show that there is great potential for the utilisation of waste glass in concrete in several forms, including fine aggregate, coarse aggregate and GLP. It is considered that the latter form would provide much greater opportunities for value adding and cost recovery, as it could be used as a replacement for expensive materials such as SF, fly ash and cement. The use of GLP in concrete would prevent expansive ASR in the presence of susceptible aggregate. Release of alkali from GLP did not appear to be sufficient to cause deleterious ASR expansion. Strength gain of GLP-bearing mortar and concrete is satisfactory. Microstructural examination has also shown that GLP would produce a dense matrix and improve the durability properties of concrete incorporating it.

It has been concluded that 30% GLP could be incorporated as cement or aggregate replacement in concrete without any long-term detrimental effects. Up to 50% of both fine and coarse aggregates could also be replaced in concrete of 32-MPa strength grade with acceptable strength development properties.

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