# Value-added Utilisation of Waste Glass in Concrete

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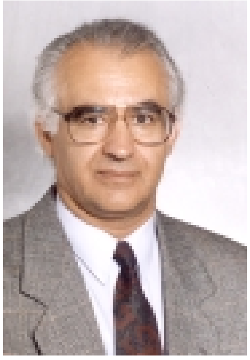


Ahmad Shayan is a Chief Scientist at ARRB Transport Research. He has over 22 years of experience in the assessment of concrete deterioration and its prevention, and also utilisation of waste materials in concrete and recycling. He has published around 110 papers and written 185 technical reports on these issues. He is a member of several national and international committees.

## Summary

A large proportion of the post consumer glass is recycled into the packaging stream again, and some smaller proportion is 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 problems. This property has been used to advantage by grinding it into a fine glass powder (GLP) for incorporation into concrete as a pozzolonic 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 pozzolonic 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; pozzolonic reaction; strength development.

## 1. Introduction

Glass is produced in many forms, including packaging of container glass (bottles, jars), flat glass (windows, windscreens), bulb glass (light globes), 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 in order 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.

### 1.1 Recycling of glass

Post-consumer 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 post-consumer 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 post-consumer 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, 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.

Rindl (1998) reported the many non-container 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 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 pozzolonic material such as fly ash, silica fume, 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), would exhibit pozzolonic 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. Rindl (1998) presented a summary of work conducted by other researchers or organisations. For example, he quotes from Boral company, Lilesville**,** North Carolina 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 (1974) on this issue, which indicated that fine glass powder (< 200 mesh, or < 75 μm particle size), could act like a pozzolonic material to reduce the tendency of reactive aggregate to undergo ASR. Pattengil (1973) had apparently also found similar effects. The work of Phillips and Cahn (1973) 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, 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 as additive, provided that certain conditions are met (NYSERDA, 1997). Another project dealt with the use of recycled glass and fly ash in precast concrete and encouraging results were obtained (NYSERDA, 1998).

Bazant et al. (1998) 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, Meyer and Baxter (2000) 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 more than 1.0% chromium oxide had a beneficial suppressive effect on ASR. Carpeneter and Cramer (1999) also reported that powdered glass was effective in reducing ASR expansion in accelerated mortar bar tests, similar to the effects of fly ash, silica fume and slag. This is in agreement with the present authors' unpublished results Shayan and Xu, (1998), where it was shown that glass powder could suppress the ASR expansion caused by natural reactive aggregates and coarse glass particles.

From the above it appears that glass could be used in concrete in three forms; as coarse and fine aggregate, and in powder form. The coarse and fine glass aggregates could cause ASR in concrete, but the glass powder 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 an SCM), than as aggregate. This would be a value-added material, produced from contaminated, mixed-colour glass chips which are not useable for packaging purposes. Although such material could also be used as abrasive grit, although the volume used for this application is not very high compared to 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.

## 2. 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 glass powder. The particle size range for each of these products is given below:

| Product | particle size range | designation |
|---|---|---|
| coarse glass aggregate | 12 mm – 4.75 mm | CGA |
| fine glass aggregate | 4.75 mm – 0.15 mm | FGA |
| glass powder | < 10 µm | GLP |

The chemical composition 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.

*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 |

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

*Table 2 – Chemical properties of crushed glass, glass powder and silica fume (%)*

| Composition | Crushed glass | Glass powder | Silica fume |
|---|---|---|---|
| $SiO_2$ | 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 |
| L.O.I. | 0.22 | 0.36 | 6.54 |

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

## 3. 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 AAR gel (Figures 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.

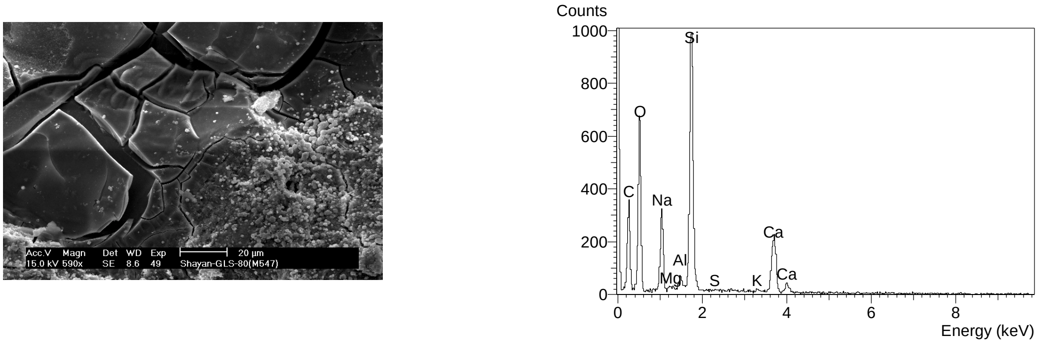


*Fig. 1 Site of AAR gel formation in concrete and the composition of the gel.*

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 accelerated mortar bar testing (AMBT), conducted in 1M NaOH at 80$^{o}$ 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. Figure 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 non-reactive aggregate (smaller than 0.15% for sand), and expansions greater than 0.10% at 10 days associated with reactive aggregates. Expansions smaller than 0.10% at 10 days but exceeding 0.10% at 21 days indicate slowly reactive aggregate.

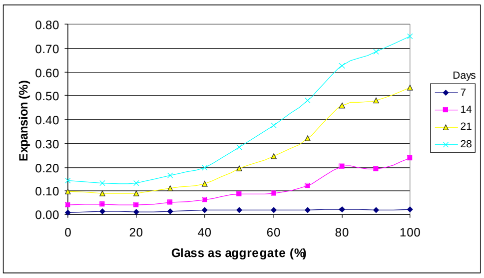


*Fig. 2 Expansion as a function of glass content of mortar bars for different ages of storage under the accelerated mortar bar test conditions.*

Based on these criteria, Figure 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 Figure 3 for four particle size ranges, including powder (<10 µm), very fine sand (0.30–0.15 mm) and two coarser sand fractions. The results shown in Figure 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.

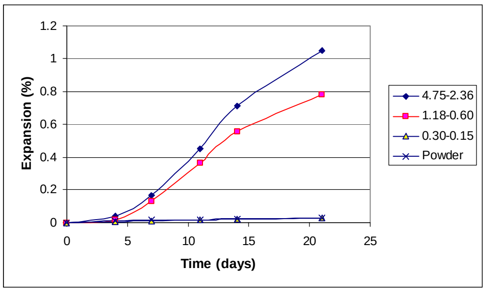


*Fig. 3 Expansion curves for mortar bars containing different glass particle sizes.*

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 AAR gel, and that once the particle size is sufficiently reduced, it can act as a pozzolonic material. It is well known that the reactivity of aggregate and its consequent expansion can be suppressed by incorporating appropriate amounts of supplementary cementitious materials such as silica fume and fly ash. Fine glass powder can also act in a similar manner (see later).

So far as utilisation as fine and coarse aggregate 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 mix 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 mix formulations were found to be satisfactory, as detailed in Table 3.

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

| Mix No. | Binder (%) | | glass content (%) | | w/b* | slump (mm) | air (%) | Strength (MPa) | | super-plasticiser |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cement | fly ash | coarse | fine | | | | 7-day | 28-day | |
| 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 |

* water/binder ratio

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 non-structural 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 ash these mixes would remain free of ASR.

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

| Mix No. | binder | | coarse * glass % | fine * glass % | w/b | slump (mm) | air (%) | strength (MPa) | |
|---|---|---|---|---|---|---|---|---|---|
| | cement % | fly ash % | | | | | | 7-day | 28-day |
| 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 |

* The remainder of each fraction consists of natural coarse and fine aggregate materials.

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

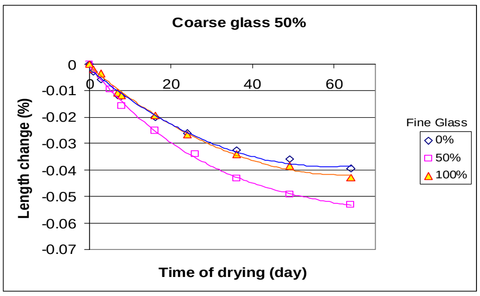


*Fig. 4 Drying shrinkage curves for concrete mixes containing 50% coarse glass and various amounts of fine glass*

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

### 3.1 Glass powder

The initial work undertaken by ARRB on the utilisation of glass as a pozzolonic 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.

## 4. Effects of glass powder (GLP) on mortar strength

The particle size distribution of the glass powder (GLP) used is as follows:

| Particle size | : | <5 µm | 5-10 µm | 10-15 µm | >15 µm |
|---|---|---|---|---|---|
| % | : | 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 GP cements (~ 400 $m^2$/kg).

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

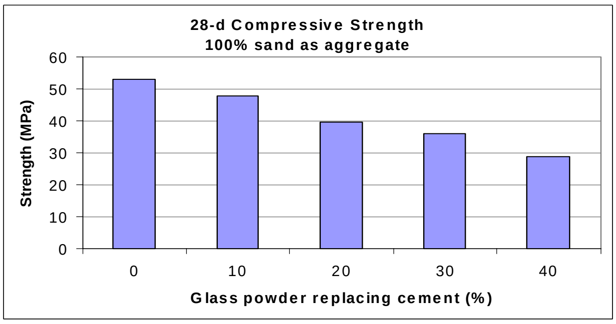


*Fig. 5 Effect of glass powder replacing cement on strength of mortar made with 100% sand.*

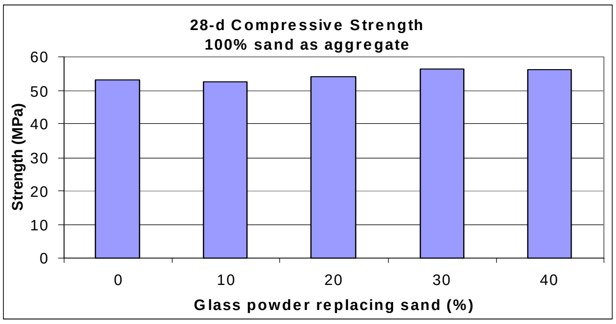


*Fig. 6 Effect of glass powder replacing aggregate on the strength of mortar made with 100% sand.*

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

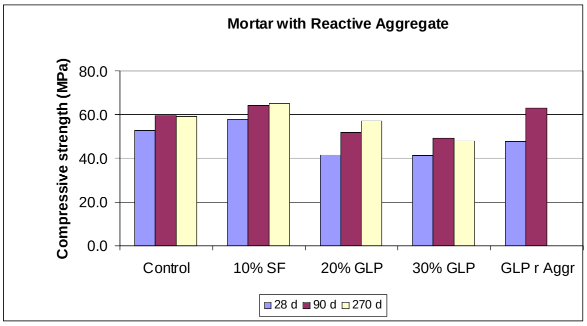


*Fig. 7 Strength development of mortar with reactive aggregate.*

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

The apparently larger effect of SF on strength gain compared to glass powder, is exaggerated in these tests, because those with SF have 90% cement, whereas those with glass powder 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% 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 glass powder, and in the other set by a mixture of 10% silica fume plus 20% pulverised basalt powder (non-pozzolonic). This made the cement content of the two sets the same. Figure 9 shows the strength results for the two sets to be very similar. It should be noted that the strength results presented in Figures 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 Figure 7 for the mix containing glass powder, is due to the lower cement content rather than the nature of the glass powder. In the case where glass powder 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 glass powder on strength development of mortar specimens containing it.

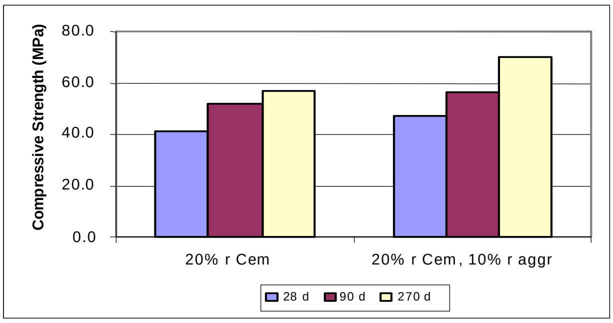


*Fig. 8 Strength development of reactive aggregate with additional Glass Powder.*

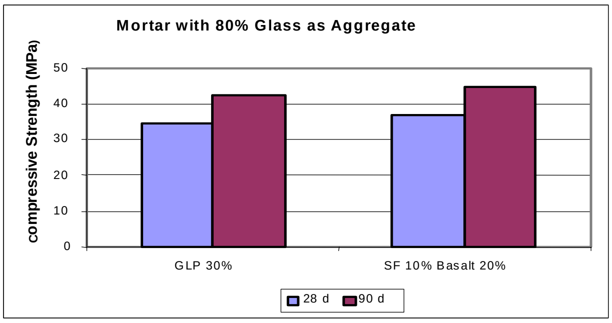


*Fig. 9 Comparison between SF and mortar with GLP with 30% reduction in cement content.*

## 5. Effect of glass powder on mortar expansion

As shown in Figures 2 and 3 coarse sand size particles of glass can cause deleterious AAR expansion, particularly at high glass contents in the accelerated mortar bar test. 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%, 20% and 30% GLP. Figures 10 and 11 show the expansion results for these combinations and indicate that both SF and GLP are effective in suppressing AAR expansion when used in sufficient amounts (10% SF and >20% GLP).

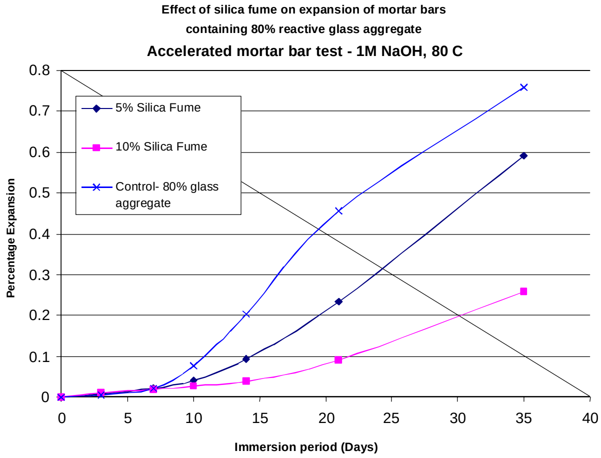


*Fig. 10 Effects of SF on expansion of mortar bars containing reactive aggregate.*

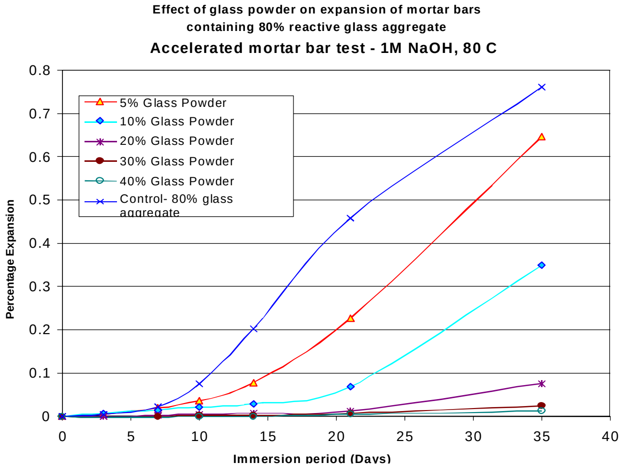


*Fig. 11 Effects of GLP on expansion of mortar bars containing reactive aggregate.*

These results indicate the efficiency of 20% and 30% GLP in suppressing AAR expansion to be better than 10% SF.

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 non-reactive and reactive aggregates, and with the same levels of cement replacement as mentioned above. Expansion values less than 0.1% at 1 year indicate innocuous combinations.

Figure 12 shows that the GLP itself does not cause any expansion when the aggregate is non-reactive. Moreover, Figure 13 shows that when the aggregate is reactive, the presence of even 30% GLP does not 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.

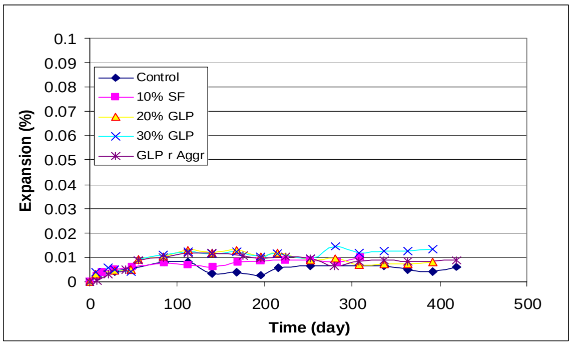


*Fig. 12 Expansion curves for mortar bars containing non-reactive aggregate and 30% GLP.*

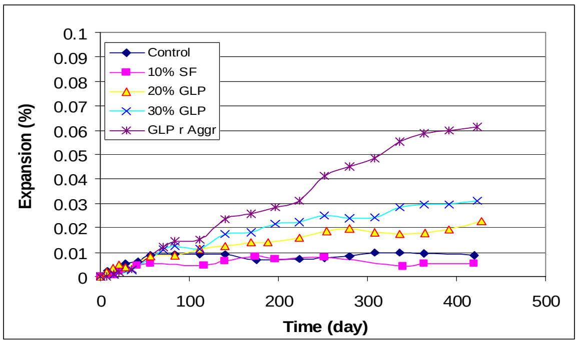


*Fig. 13 Expansion curves for mortar bars containing reactive aggregate and 30% GLP.*

## 6. Glass powder in concrete

The efficiency of glass powder 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 one year. Figure 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.

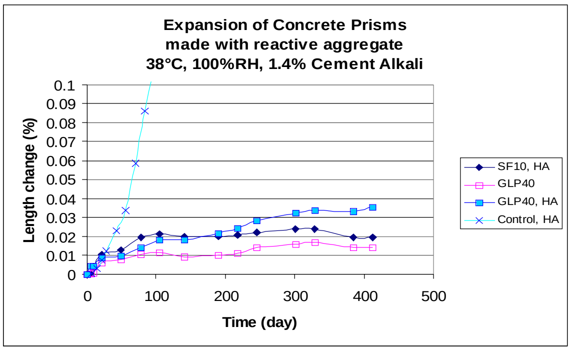


*Fig. 14 Expansion curves for concrete prisms containing a very reactive coarse aggregate in combination with the materials indicated.*

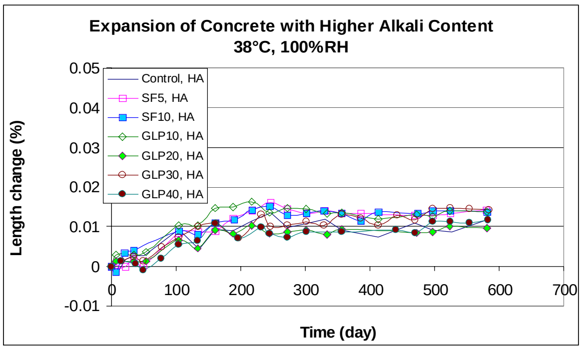
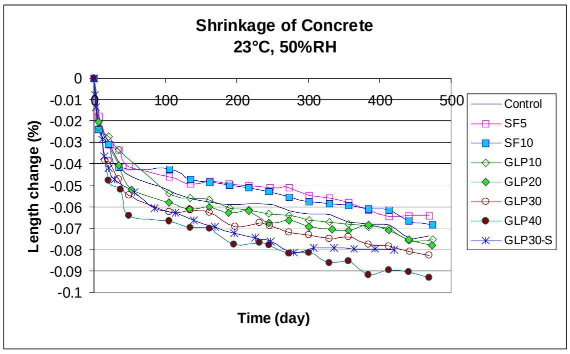


*Fig. 15 Concrete expansion curves for the combination of various amounts of GLP and silica fume in the presence of 5.8 kg $Na_2O$ equivalent./$m^3$.*

When various proportions of GLP were used with non-reactive aggregate in concrete of raised alkali level (5.8 kg $Na_2O$ equivalent/$m^3$), the material itself did not cause deleterious expansion as shown in Figure 15. The latter results also confirm that GLP would not cause harmful expansion in concrete.

### 6.1 Effects of glass powder on concrete shrinkage and strength

Concrete specimens corresponding to those represented in Figure 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 Figure 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.



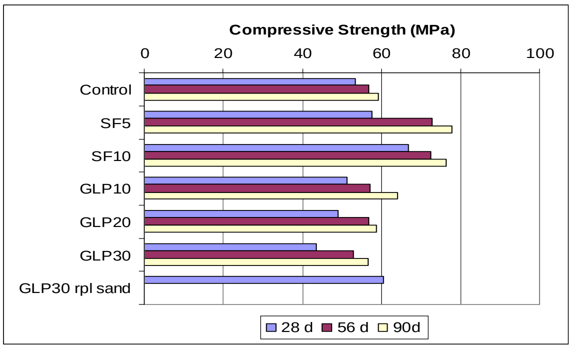


*Fig. 16 Drying shrinkage of the various concrete mixtures containing low alkali contents (no additional alkali).*

*Fig. 17 Strength of concrete cylinders containing glass powder and silica fume, compared to the control cylinders.*

The strength properties of the concrete mixes represented in Figure 16 are given in Figure 17. It is seen that although the mixes 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 mixes. Particularly when GLP replaces sand, the strength is significantly greater than that of the control mixture. The continued strength development clearly indicates the beneficial pozzolonic reaction of the GLP in concrete.

## 7. 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. Figure 18 shows the dense microstructure that has developed in mortar incorporating 30% GLP, and illustrates the consumption of fine glass particles by their pozzolonic reaction with cement. In both cases fracture surfaces of the mortar specimens were indicative of a compact micro structure.

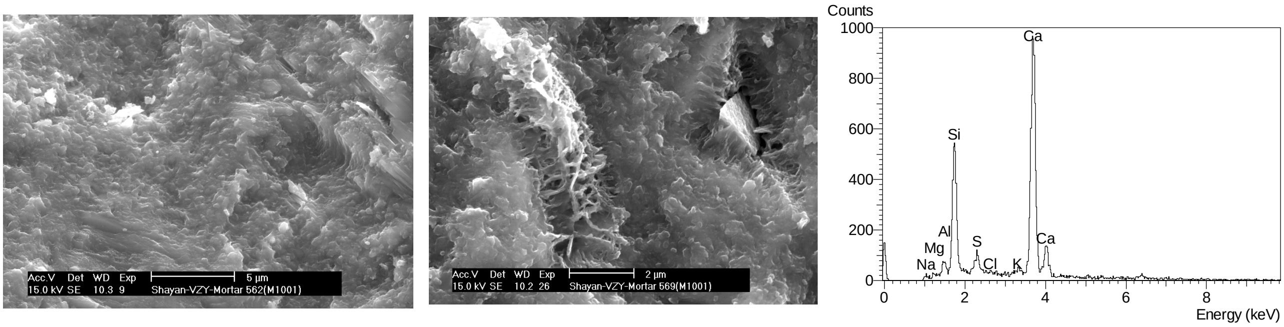


*Fig. 18 SEM views of the fracture surface of mortar specimen containing 30% glass powder showing its dense microstructure, and pozzolonic reaction with cement.*

## 8. 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 glass powder. 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 silica fume, fly ash and cement. The use of glass powder in concrete would prevent expansive ASR in the presence of susceptible aggregate. 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 aggregate could also be replaced in concrete of 32 MPa strength grade with acceptable strength development properties.

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## 10. References

[1] RINDL, J. *Report by Recycling Manager*, Dane County, Dept of Public Works, Madison, USA, August 1998.

[2] SAMTUR, H.R. *Glass Recycling and Reuse,* University of Wisconsin, Madison Institute for Environmental Studies, Report No. 17, March 1974.

[3] PATTENGIL, M. *Glass as a Pozzolan,* Albuquerque Symposium on Utilisation of Waste Glass, Second Prod. 1973.

[4] PHILLIPS, J.C. and CAHN, D.S. *Refuse Glass Aggregate in Portland Cement.* Proc. 3rd Mineral Waste Utilisation Symposium, 1973, pp. 385-390.

[5] NYSERDA. *Use of Recycled Glass for Concrete Masonry blocks.* Report 97-15, Nov. 1997.

[6] NYSERDA. *Use of Recycled Glass and Fly Ash for Precast Concrete.* Report 98-18, Oct. 1998.

[7] BAZANT, Z.P., JIN, W. and MEYER, C. *Fracture Mechanics of Concrete Structures*, Proc. FRA MCOS – Vol. 3, 1998, pp. 1687-1693.

[8] JIN, W., MEYER, C. and BAXTER, S. *ACI Materials Journal*, Vol. 97, March-April 2000, pp. 208-213.

[9] CARPENTER, A.J. and CRAMER, S.M. *Mitigation of ASR in Pavement Patch Concrete that Incorporates Highly Reactive Fine Aggregate.* Transportation Research Record 1668, Paper No. 99-1087, 1999, pp. 60-67.

[10] SHAYAN, A. and XU, A. *Utilisation of Glass as a Pozzolonic Material in Concrete.* ARRB TR Internal Report RC91132, November 1999, 11 pp.