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Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs

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Abstract

Earlier laboratory work by the authors indicated satisfactory performance of glass powder (GLP) in concrete as a pozzolanic material. The powder was manufactured from mixed colour waste packaging glass comprising soda-lime glass. In order to investigate the performance of GLP in concrete under field conditions, a field trial was conducted using a 40 MPa concrete mixture, incorporating various proportions of GLP (0%, 20%, and 30%) as cement replacement. Ten mixture formulations, some of which also included sand-size crushed glass aggregate particles, were used to cast ten concrete slabs (1.5 × 2.5 × 0.25 m). Cylinders and prisms were also manufactured from the same batches at the time of casting for the measurement of compressive and splitting tensile strength, flexural strength, shrinkage, expansion, ultrasonic pulse velocity, volume of permeable voids, and chloride permeability. Core samples were drilled from the slabs at various ages for the same tests (except tensile and flexural), as well as for microstructural examination. Results showed that strength gain was slower in GLP-bearing concrete up to 28 days, but at the age of 404 days all the mixtures exceeded the 40 MPa target and achieved about 55 MPa strength.

Mixtures containing GLP also performed satisfactorily with respect to drying shrinkage and alkali reactivity, and there were indications that GLP reduces the chloride ion penetrability of the concrete, thereby reducing the risk of chloride induced corrosion of the steel reinforcement in concrete. The results demonstrated that GLP can be incorporated into 40 MPa concrete at dosage rates of 20–30% to replace cement without harmful effects. The use of GLP provides for considerable value-added utilisation of waste glass in concrete and significant reductions in the production of green house gases by the cement industry.

Keywords: Waste glass; Glass powder; Concrete; Pozzolanic material; AAR

1. Introduction

The term glass comprises several chemical varieties including binary alkali-silicate glass, boro-silicate glass, and ternary soda-lime silicate glass. Most of the packaging glass which is the subject of this paper is of the soda-lime silicate variety. It is manufactured in various colours, mostly green, amber and clear, but waste glass after being collected from the domestic waste stream is of a mixed colour.

Research on the use of crushed glass as a partial replacement for aggregate dates back many decades [e.g., 1–3]. Although work on the use of finely ground glass as a pozzolanic material also started as early as 1970s [4], most of the work in this area is relatively recent [5–9], and has been encouraged as a result of continual accumulation of waste glass and its consequent environmental issues. Moreover, waste glass is potentially a very useful material and appropriate economical applications need to be found for it.

Concerns about the use of glass aggregate in concrete relates to its susceptibility to alkali-aggregate-reaction (AAR) in concrete, and this aspect was also recognised and studied several decades ago, as indicated by the literature cited above or even earlier [10]. It is important to recognise that the reactivity of glass depends on its type and composition and physical features such as the presence of pores and separate solid phases in the glass [11]. For example, binary glasses such as sodium silicate glass behaves differently from soda-lime glass such that the binary glasses cause alkali release and mortar expansion even in combination with low-alkali glass, whereas soda-lime

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glasses require high alkali contents in the mortar or concrete to enable it to react deleteriously and cause expansion [10,11]. Also, glasses containing boron, such as pyrex glass were found to be more reactive than soda-lime silica glasses [11]. Particle size of glass and alkali content of the mortar or cement are two other important factors influencing the reactivity of glass as aggregate [5–7,9,11–14].

Our previous work at ARRB on the utilisation of waste glass in concrete [5,6] had shown that both fine glass powder (GLP) of <10 μm particle size, and crushed glass aggregate could be used in concrete together without adverse effects on concrete durability. In their work the authors concentrated largely on the utilisation of waste glass in the form of GLP as cement replacement material in concrete, which would be of more monetary and environmental value than the use of waste glass as aggregate; the latter being much cheaper than cement. The implication of the work was that considerable amounts of waste glass could be diverted from landfill for utilisation in concrete. Particularly, fine glass powder could be used as a value-added product as it could replace a proportion of expensive concrete ingredients such as cement itself or supplementary cementitious materials such as silica fume and fly ash. This paper reports the results of a field trial on the utilisation of glass powder and glass aggregate in concrete, funded by the Government of NSW through the Waste Reduction Grants Program.

1.1. Location of trial

The field trial was conducted at the VISY Industries Paper Recycling Plant at Smithfield, a western suburb of Sydney. The trial site was in an existing car parking area which had an appropriate base course. Ten slabs, each measuring 1.5×2.5×0.25 m, were cast for ten separate concrete mix formulation. The casting of the concrete slabs was completed in September 2002, the first month of spring in Australia.

2. Materials

The coarse aggregate was a 20 mm Crushed River Gravel, which was used together with coarse and fine sand of the same source. This aggregate is regarded as non-reactive by the concrete industry, but recently cases of AAR have been found in 30-year old concrete piles incorporating this aggregate [15,16]. However, due to age differences, it is not possible to establish that they have exactly the same origin. The cement used was a Blue Circle Southern type GP cement which had a typical chemical composition (%), determined by XRF, of SiO_2 (20.0), Al_2O_3 (4.3), Fe_2O_3 (3.4) TiO_2 (0.24), Mn_3O_4 (0.10), CaO (63.2), MgO (1.36), Na_2O (0.18), K_2O (0.43), calculated Na_2O equiv. (0.46) SO_3 (2.6), Loss on ignition (3), and fineness of 352 m^2/kg. Silica fume from Western Australia was used in two of the mixes, and where appropriate a water reducer (WRG) was employed. The glass products used were:

(a) glass powder of nominal <10 μm particle size. The material consisted of particles which were 88%<10 μm and 12%>15 μm. The surface area of the glass powder was about 800 m^2/kg, which was much finer than the cement (350 m^2/kg).
(b) coarse glass sand (crushed glass particles 0.60–2.36 mm, with modulus of fineness of 3.25).
(c) fine glass sand (crushed glass particles 0.15–0.30 mm, with modulus of fineness of 1.67).

The average composition of the glass material (%) is as follows: SiO_2 (72.4), Al_2O_3 (1.45), Fe_2O_3, (0.48), CaO (11.5), MgO (0.65), Na_2O (13.0), K_2O (0.43), SO_3 (0.09).

2.1. Concrete mixtures

A concrete mix, commonly used in the locality as structural concrete of 40 MPa strength, was chosen for the field trial concrete. This was used as the reference mix and had a cement: aggregate: sand ratio of 1 : 2.68 : 2.02 with a water/cement ratio of 0.49. Other mix proportions were formulated based on this mix to include the glass components mentioned above. The purpose of the trial was to determine the following effects on field concrete.

- the effect of glass powder as a cement replacement material at 20–30% dosage rates
- the effect of glass sand as natural sand replacement, at 40–75% dosage rates

Table 1
Mix proportions based on Grade 40 Concrete Mix (kg/m^3)

Mix number	Description	Cement	SF	GLP	Coarse aggregate	Coarse sand	Fine sand	Crushed glass	Water
Mix 1	Reference mix	380	0	0	1019	576	192	0	185
Mix 2	10% SF in binder	342	38	0	1019	566	189	0	185
Mix 3	20% GLP in binder	304	0	76	1019	564	188	0	185
Mix 4	30% GLP in binder	266	0	114	1019	558	186	0	185
Mix 5	10% SF in binder; 50% CGS[a]	342	38	0	1019	283	94	356	185
Mix 6	20% GLP in binder; 50% CGS	304	0	76	1019	282	94	355	185
Mix 7	30% GLP in binder; 40% CGS	266	0	114	1019	335	112	281	185
Mix 8	30% GLP in binder; 75% CGS	266	0	114	1019	141	47	523	185
Mix 9	No GLP; 50% CGS	380	0	0	1019	288	96	363	185
Mix 10	100% cement; 50% CGS 30% GLP by mass of cement replaced fine sand	380	0	114	1019	288	36	306	185

[a] CGS = crushed glass sand.

Table 2
Test program for cast specimens and drilled cores for each mix

Specimen	Number	Tests
Prisms	2	Expansion at 38 °C, 100% RH over 2 years
	2	Shrinkage at 23 °C, 50% RH at 70 days, and flexural strength at 130 days
Cylinders	8	Compressive strength at 7, 28, 90 and 404 days Ultrasonic pulse velocity (UPV) at 28, 90 and 404 days
	2	Tensile strength (splitting) at 28 days
	2	Volume of permeable voids (VPV) 28 days and 404 days
	1	Rapid chloride permeability (RCLP) test at 380 days
Cores from slab	6	Compressive strength test and UPV at 90, 220 and 404 days
	2	Volume of permeable voids (VPV) at 220 and 404 days Rapid chloride permeability (RCLP) at 220 and 380 days Scanning electron microscopy (SEM) on cores at 404 days

In addition to the reference 40 MPa mix, which used the GP cement alone, mixes with silica fume (10% cement replacement) were used for comparison. All other mixes contained either GLP as cement replacement (i.e., as binder), or glass sand as natural sand replacement, or both. No soluble alkali was added to the mixes, to check whether glass powder would release soluble alkali into the concrete pore solution to cause reactive components such as the glass sand (or the natural aggregate) to react. Table 1 gives details of the 10 mixes used in the field trial.

Concrete mixing was conducted at a plant which used an automatic sealed system. All routine ingredients (cement, aggregates, and water) were automatically weighed and placed into the sealed mixer. The other ingredients, including silica fume, glass powder and glass sand, were manually weighed and poured into a mixing truck (with the drum rotating) before it received the mixed ingredients from the sealed mixer.

Mixes 1, 3, 5, 7, 9 were cast on the first day, and the remainder on the second day into bays excavated in the car park for this purpose.

The ratio of coarse to fine glass sand was originally 75:25 and this ratio was used for Mixes 5 and 7, which were found to need more trowelling than Mixes 1 and 3 to smooth the surface. For the other mixes containing glass sand, the ratio of coarse to fine glass sand was made 50:50 to improve workability and finish.

2.2. Specimens

For each mix, a slab (2.5 × 1.5 × 0.25 m), 4 prisms (285 × 75 × 75 mm) and 14 cylinders (100 × 200 mm) were cast all from the same batch. A steel mesh (centre-to-centre spacing 200 mm, made with ϕ8.2 mm bars crossed with ϕ6 mm bars) was placed into the slab to restrain the shrinkage cracking. No specific control was applied to the positioning of the steel mesh. The prisms and cylinders were covered under plastic sheets, stored beside the slabs after casting. After about 24 h, the specimens were removed from moulds, marked and transported to the laboratory for storage in a fog room (21 ± 2 °C, 100% RH) prior to testing at various ages. The ambient maximum and minimum temperatures on the day of casting were 22.0 °C and 12.2 °C, respectively, and the mean relative humidity was 69%. The mean daily max. and min. temperatures over the first four months in the age of slabs were: September (22.7, 12.4 °C) October (24.5, 14.6 °C) November 25.3, 17.2 °C) and December (25.4, 18 °C). The corresponding mean relative humidity for these months were 68.8%, 70.5%, 79.6% and 76%. This weather information shows that the laboratory cured cylinders (wet at 21 ± 2 °C all the time) received a better curing than the field slabs.

2.3. Test program

The tests conducted on the cast specimens included compressive and splitting tensile strength on cores, flexural strength on prisms, drying shrinkage, expansion at 38 °C (100% RH), ultrasonic pulse velocity (UPV), volume of permeable voids (VPV) in accordance with the Australian Standard AS 1011-21, and rapid chloride permeability test (RCLP), using the procedure described in ASTM C-1202.

The compressive strength tests were conducted at 7, 28, and 90 days and at the end of the trial (404 days) for the cylinders maintained in a fog room (21 ± 2 °C, 100% RH). In addition to the cast specimens, the slabs were cored at the ages of 90, 220 and 404 days for compressive strength, UPV, VPV, and examination by the scanning electron microscope (SEM) equipped with an energy-dispersive X-ray (EDX) analytical system to determine the microstructural features of the field concrete and the compositions of the phases identified. Table 2 summarises the test program for each of the mixes.

3. Results

3.1. Properties of fresh concrete

The slump test was conducted on site to record the workability, and the results are presented in Table 3. A slump of 70–80 mm was required for casting of slabs. The change of

Table 3
Slump of fresh concrete and 28-day density of hardened concrete

Concrete	Slump (mm)	28-day density (kg/m^3)
Mix 1	70	2408
Mix 2	75	2340
Mix 3	65	2283
Mix 4	60	2328
Mix 5	65	2326
Mix 6	80	2282
Mix 7	50	2314
Mix 8	50	2232
Mix 9	70	2329
Mix 10	90	2315

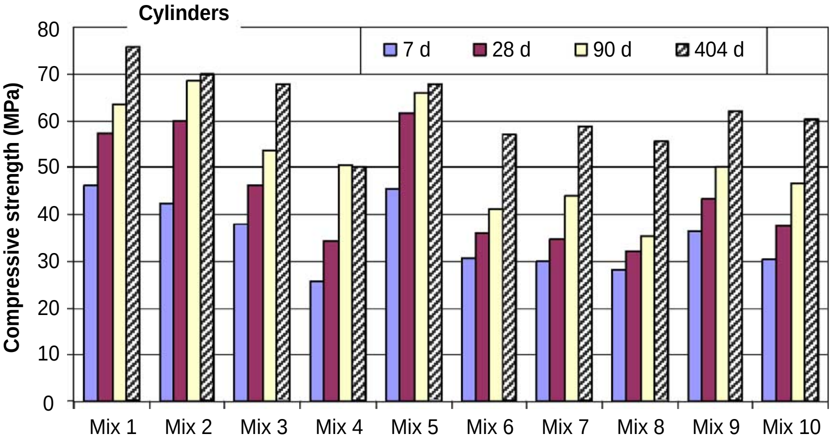

Fig. 1. Graphical presentation of strength development of concrete cylinders.

the ratio of coarse to fine glass sand from 75:25 to 50:50 increased the easiness of achieving a good trowel finish.

Mixes 3, 5, 7, cast on the first day, which contained silica fume or glass powder showed somewhat decreased slump compared to Mix 1. Therefore, a water reducer at dosage rate of 0.3 L per 100 kg cement was used on the second day to bring the slump to 75 mm for Mix 2, but this dosage rate did not work similarly for some other mixes, for example Mix 8 which was a harsh mix and which had a slump of 50 mm. Mix 10 had a slump of 90 mm without the water reducer. Mix 4 was the only mix in which bleeding was evident after casting, which is attributed to the replacement of 30% of the hydraulic cement by the GLP.

3.2. Properties of hardened concrete

3.2.1. Density of concrete

The density of hardened concrete was determined on cylinders at the age of 28 days (Table 3) from their mass and the measured diameter and height. The measured density was generally lower than the theoretical density of the concrete, estimated by assuming 23% water (by mass) for full hydration of Portland cement, and 80% degree of hydration at 28 days. This difference arises because 100% compaction is not usually achieved. The average ratio of measured density to theoretical density was about 0.976, which may be taken to indicate that the concrete contained about 2.4% air as compacted in the cylinders.

3.2.2. Strengths of concrete, UPV and VPV

3.2.2.1. Strength. The results of strength testing of laboratory-cured cylinders and cores drilled from the trial slabs are presented in Figs. 1 and 2. The strength values reported are the average of two test results.

Based on the 28 day strength results, among the mixes that incorporated GLP, only that containing 20% GLP met the strength requirement of a 40 MPa concrete. At the age of 90 days only Mix 8 had remained under-strength and Mix 6 just exceeded the 40 MPa value. Mix 8 had the lowest strength which arose because it contained 75% crushed glass as sand replacement in addition to 30% GLP as cement replacement. The excessive amount of glass sand and reduced cement content had made the mix harsh to work and compact. This also reduced the density of concrete because of the lower specific gravity of glass (2.5) as compared to our natural sand (2.63). It should be

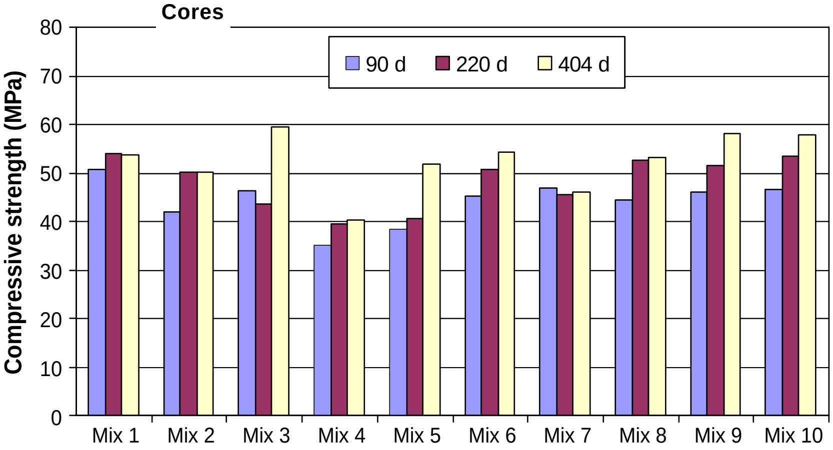

Fig. 2. Compressive strength of core samples.

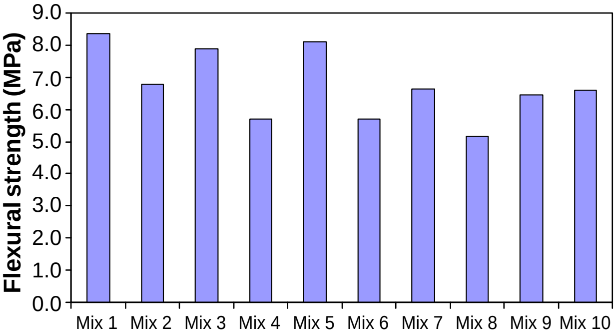

Fig. 3. Flexural strength of concrete prisms at 130 days.

noted that Mix 4, with 30% GLP and without crushed glass, gained significant strength between the ages of 28 and 90 days, from 34 to 50.6 MPa, i.e., 16.6 MPa additional strength. The control mix (Mix 1) gained only 6 MPa and Mix 2 with 10% silica fume 8 MPa over the same period. This shows that significant pozzolanic reaction had taken place in this period of time in the presence of 30% GLP. Continual curing up to the age of 404 days generally resulted (except Mix 4), in significant additional strength gain (up to 60 MPa) for Mixes 3, 6, 7, 8 and 10 which contained GLP. Mixes 2 and 5 which contained silica fume had almost reached their ultimate strength at 90 days. Considering that the mixes containing GLP had only 70–80% of the cement content of Mix 1, their 404 day strength values are considered to be very good.

Mix 9, with no GLP but with 50% crushed glass as sand replacement, met the criteria for a 40 MPa concrete, but this mix would not be advisable when the concrete alkali content is high, as deleterious AAR expansion could take place. The differences in cylinder strength among the various glass-bearing mixes were less prominent at 404 days than at earlier ages, which is attributed to continued hydration reactions in all the mixes.

Comparison of the strength of cores with that of cylinders at ages of 90 and 404 days, shows that for Mixes 1–5 the core strength was significantly lower than their corresponding cylinder strength. For Mixes 6–10, the core and cylinder strengths were closer to each other at 90 days, but cylinder strength exceeded core strength at 404 days, suggesting less effective curing for slabs (field conditions) compared to cylinders (fog-curing). Since the concrete mix composition was the same in both cases, the variation in strength could only be attributed to compaction and curing conditions. Moreover, cores were taken from different locations on the slabs at different ages and could represent somewhat different compaction levels. Results of examination by the scanning electron microscope indicated that good compaction was not achieved in some of the slabs, as suggested by the presence of excessive air voids in the specimens examined.

Comparison of strength results for cores at ages of 90, 220 and 404 days (Fig. 2) generally shows moderate increases in the strength with age, but for some mixes (e.g., [1,4,7]) the strength could statistically be considered to be the same at all these ages. This arose probably due to lack of curing and random variation of compaction within each slab. Cores representing Mix 4, which exhibited bleeding after casting, had the lowest strength, and were revealed by SEM to have a porous mortar phase.

In terms of curing condition, the laboratory cured cylinders were continually subjected to wet conditions at 23 °C. Therefore, cement hydration was probably more complete than that of the slabs, and enhanced strength development. On the other hand, the slabs could have been subjected to a higher temperature for some periods on summer days, but night temperatures were mostly below 18 °C during the year. Curing at higher temperature increases the rate of strength gain, but not necessarily the final strength [17]. Integration of temperature and humidity over one year would certainly favour the fog-cured cylinders compared to the slabs, given average daily temperatures of well below 23 °C for most days. The overall strength would be the result of an interplay between these factors, (compaction, humidity, temperature). It is likely that full attention was not paid to good compaction during casting of slabs.

The flexural strength results determined on concrete prisms at the age of 130 days (average of two results), are graphically presented in Fig. 3. The prisms had been cured in the fog room for 1 week, followed by 10 weeks of drying at 23 °C, 50% RH (to measure drying shrinkage), and subsequent curing in fog room for nearly 9 weeks. Generally, the flexural strength followed the same trend as the cylinder strength. Mix 4, with 30% GLP, and Mix 8, with 30% GLP and 75% crushed glass sand, had the lowest flexural strength. The small differences observed among other mixes probably relate to normal sample variability.

The relative flexural strength of the mixes was similar to that of the splitting tensile strength. Comparison of the flexural strength of concrete prisms with the splitting tensile strength determined on cylinders at 28 days (Fig. 4), shows that the two are linearly correlated over the strength range achieved. The flexural strength (age 130 days) was about 50% higher than the split tensile strength (age 28 days), due to older specimens used in the flexure tests.

The ultrasonic pulse velocity (UPV) was measured on cylinder and core specimens at various ages, and the dynamic modulus of elasticity (E_d) was calculated based on the formula $E_d = \rho V^2 \frac{(1+\nu)(1-2\nu)}{1-\nu}$, where V is the pulse velocity, ρ is the

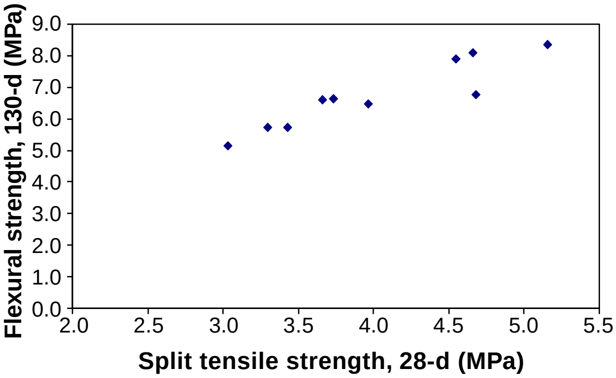

Fig. 4. Relationship of 28-day splitting tensile strength and 130-day flexural strength.

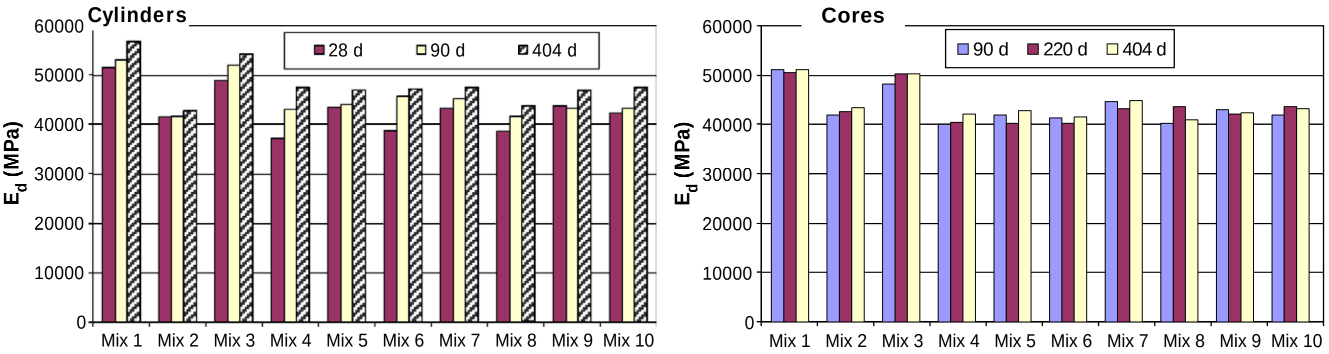

Fig. 5. Dynamic modulus of elasticity of cylinders and cores as indicated.

density of concrete, and v the dynamic Poisson's ratio, assumed to be 0.20. The variation in elastic modulus of cylinders and cores for the various mixes is graphically presented in Fig. 5.

The values of elastic modulus for the cylinders at 404 days are generally higher than those for the cores at the same age, which reflect the trend noted above for the compressive strength.

3.2.2.2. Volume of permeable voids. The volume of permeable voids is an important property of concrete affecting transport mechanisms through the concrete, such as ingress of aggressive gases and solutions. Local authorities require that VPV values for 40 MPa concrete not exceed 14% and 16%, for rodded cylinders and drilled cores, respectively (VicRoads Specification for structural concrete, Section 610.06).

The results of the VPV determinations are presented in Fig. 6. The VPV values of the two strongest mixes, i.e., Mixes 2 and 5, which had 10% silica fume, were higher than the acceptable limit. These mixes probably contained a larger amount of fine interstitial pores (gel pores) than other mixes, which contributed to the higher VPV. The VPV values of the cores were consistently larger than those of the cylinders tested at 28 days, which is expected due to better compaction of cylinders. The VPV of Mixes 2, 4, 5 and 10 exceeded the values specified for both cylinders and cores (except cores from Mix 10), probably indicating that a lower water/binder ratio should be used for these mixes.

3.2.2.3. Drying shrinkage. The results of drying shrinkage measurements are presented in Fig. 7. They indicate that all the mixes have produced acceptable drying shrinkage values below 0.075% at the age of 56 days, as required by the Australian Standard AS 3600. Mix 2, containing 10% SF, showed shrinkage values larger than those of any of the other mixes.

Drying shrinkage as a function of moisture loss (Fig. 8) showed that at the same value of shrinkage, Mix 1 had the lowest water loss, whereas Mix 4 which contained 30% GLP in the binder had the largest water loss. This probably arose because this water was not utilised in the hydration of cement (30% less cement compared to Mix 1). Mix 2 had the highest shrinkage probably because shrinkage is also related to the elastic modulus of concrete, and Mix 2 had the lowest modulus.

3.2.2.4. AAR expansion. All the concrete prisms stored at 38 °C, 100% RH showed insignificant expansion (<0.015%) at the age of 760 days (Fig. 9), indicating that no deleterious AAR expansion took place by that age. In Fig. 9, curves for Mixes 5, 6, 7, 8, 9 and 10 represent mixes in which 40%, 50% or 75% of the natural sand was replaced by glass sand of 0.15–2.36 mm particle size. It has been suggested that for crushed glass, the largest AAR expansion is caused by particles in the size range 1.18–2.36 mm [12]. Other work [13] has shown that glass particles of around 1.5 mm caused excessive expansion, whereas those <0.25 mm caused no expansion in concrete. Our earlier results [5,6] also showed that glass particles of <0.30 mm did not cause expansion in the accelerated mortar bar test (1 M NaOH, 80 °C). Therefore, the trial concrete mixes contained glass particle sizes that were capable of AAR expansion.

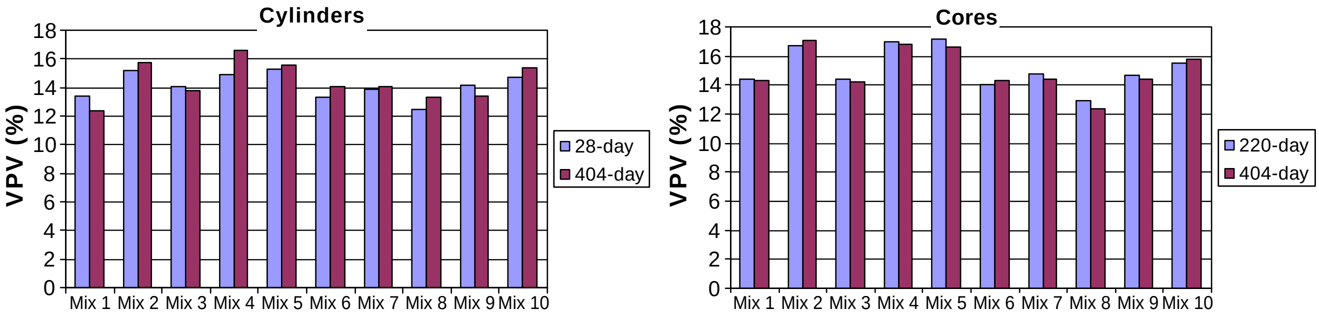

Fig. 6. Volume of Permeable Voids (VPV) for cylinders and cores as indicated.

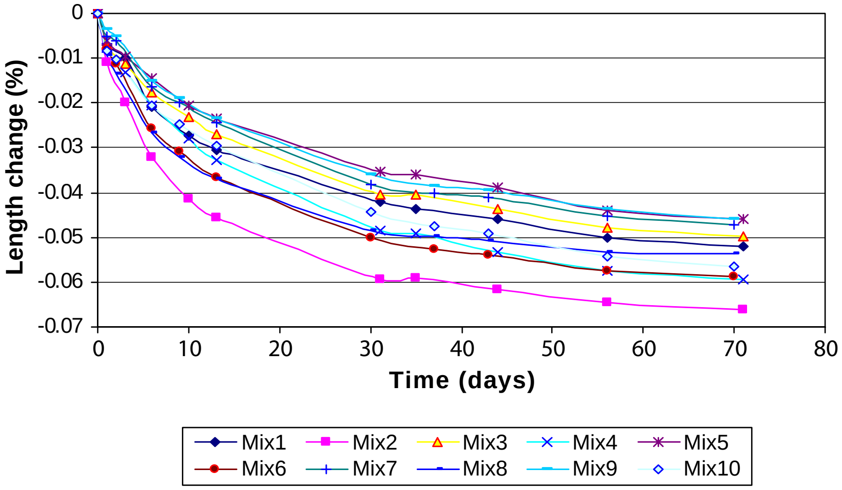

Fig. 7. Drying shrinkage of concrete prisms.

No soluble alkali had been added to the concrete in order to check whether the GLP would release sufficient amounts of alkali that could induce deleterious AAR expansion in the presence of the reactive glass particles in the sand fraction. If the GLP (13% Na_2O content) were able to release sufficient amounts of alkali to cause deleterious AAR expansion, then this effect should have been evident for Mixes 3, 4, 6, 7, 8, 10, which also contained reactive aggregate particles, particularly for Mix 10, which had no cement replacement as well as 30% GLP as fine sand replacement. Even in the presence of a highly reactive natural aggregate, the GLP per se did not release alkali to cause deleterious expansion [6]. Work on the binary glass, however, had led to the suggestion that binary glasses corrode in concrete to provide both silica and alkali to cause deleterious AAR expansion regardless of the alkali content of concrete [11]. Therefore, the soda-lime glass used here behaved very differently from the binary glasses used in other work [10,11], and unlike them did not cause deleterious AAR expansion, in the absence of high alkali content in the concrete. Moreover, results shown in Fig. 9 and laboratory evidence from previous work indicate that GLP was an effective suppressor of AAR in concrete.

3.2.2.5. Rapid chloride penetration (ASTM C-1202). In this test, the passage of electrical current through a circular slice of concrete is measured under a 60 V potential gradient. The concrete slice, 50 mm thick, is cut from a cylinder or a core and placed as a membrane between two liquid cells. One cell contains 0.3 M NaOH and the other 3% NaCl. The 60 V potential difference is applied across the concrete slice for 6 h, and the amount of charge passed measured in coulombs. ASTM C-1202 categorises the chloride penetrability of concrete based on the amount of charge passed. The test is assumed to determine the resistance of concrete to chloride penetration, but this is somewhat controversial [18]. It is clear that the test measures movement of charge related to all ionic species and not just chloride ions.

Fig. 10 presents the results obtained on the cores and cylinders at the ages indicated. The “chloride penetrability” of Mixes 3, 4, 6, 7, 8 and 10 which contain glass powder was

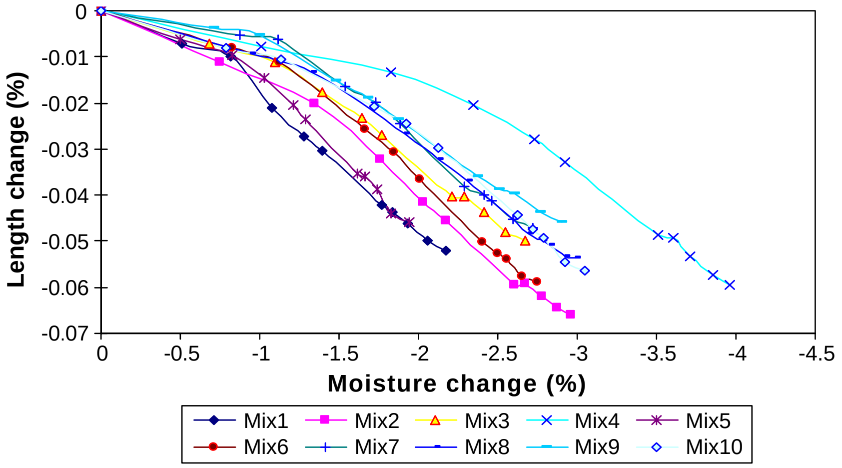

Fig. 8. Shrinkage against moisture loss of the concrete prisms, 23 °C 50% RH.

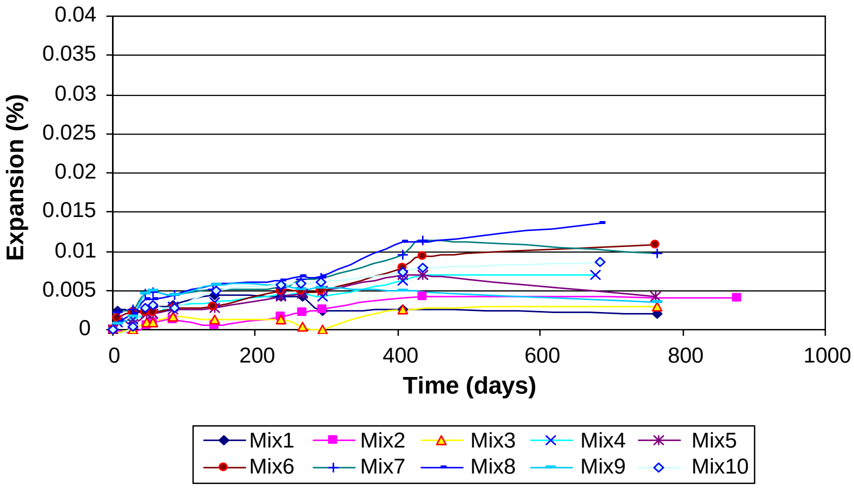

Fig. 9. Expansion of concrete prisms, 38 °C 100% RH.

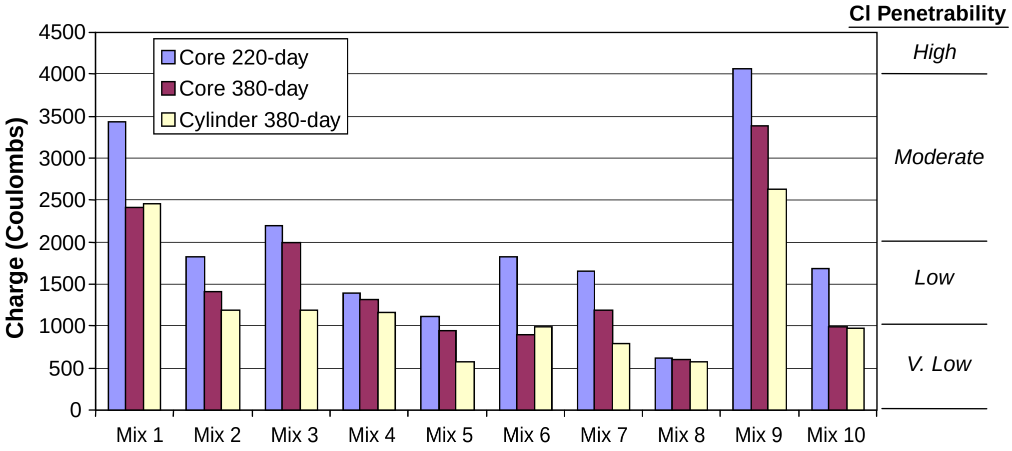

Fig. 10. Results of the rapid chloride penetration test (ASTM C-1202 method).

significantly lower than that of Mix 1 (reference), and comparable to or lower than that of Mixes 2 and 5, which contained silica fume.

Moreover, the moist-cured cylinders exhibited lower "chloride permeability" than the cores (external exposure), indicating that GLP may be very beneficial under submerged marine exposure conditions against chloride-induced corrosion of reinforcement in concrete. The relation between VPV and the "chloride penetrability" was poor, indicating that the latter was mainly influenced by the concrete composition and pore solution chemistry rather than by relatively small differences in the VPV.

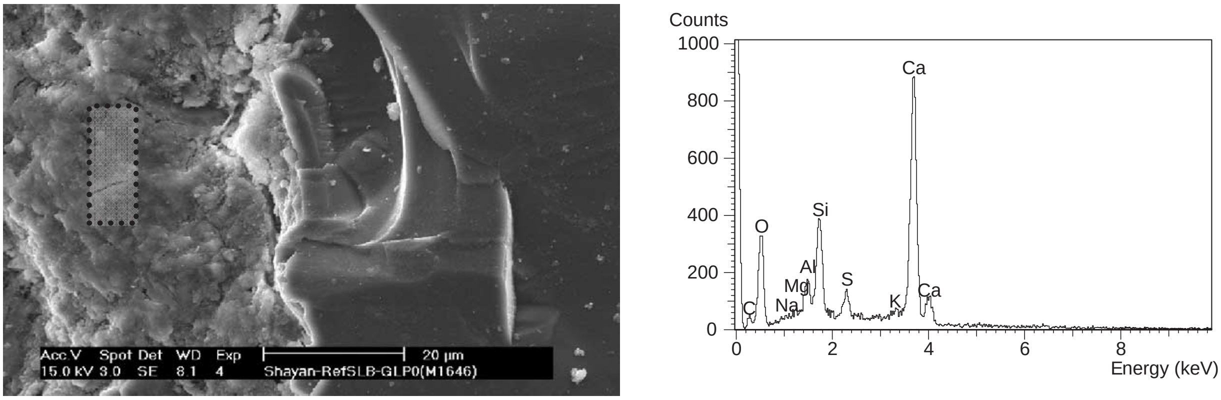

Fig. 11. SEM view of cement paste near a glass particle in Mix 1 (reference), and its EDX spectrum.

4. Microstructural examination of concrete cores

Scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) analysis were used to examine the nature of the hydrated binder and the binder-aggregate interfacial zones. The locations of the EDX analyses are marked on each SEM image. Note that the peak height in the EDX spectra is proportional to the amount of element present. A brief summary of SEM/EDX analysis is given below.

Fig. 11 shows the typical composition of the hydrated paste in Mix 1 (reference) and its interface with an aggregate. The paste in Mix 2, which contained 10% silica fume was found to have been enriched with silica, as expected (Fig. 12).

The composition of the paste in Mix 3 (20% GLP) also showed enrichment in silica, and assimilation of fine glass

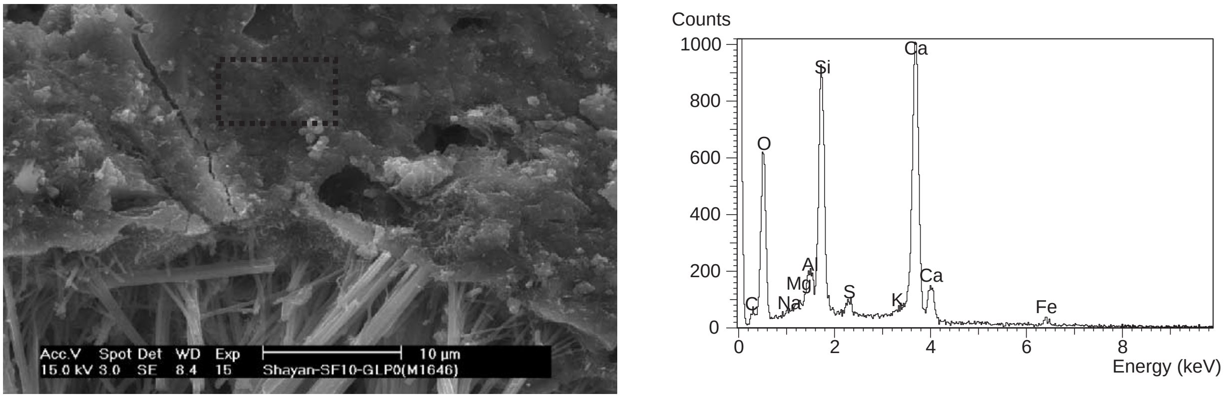

Fig. 12. SEM view and EDX composition of paste in Mix 2 which contained 10% silica fume.

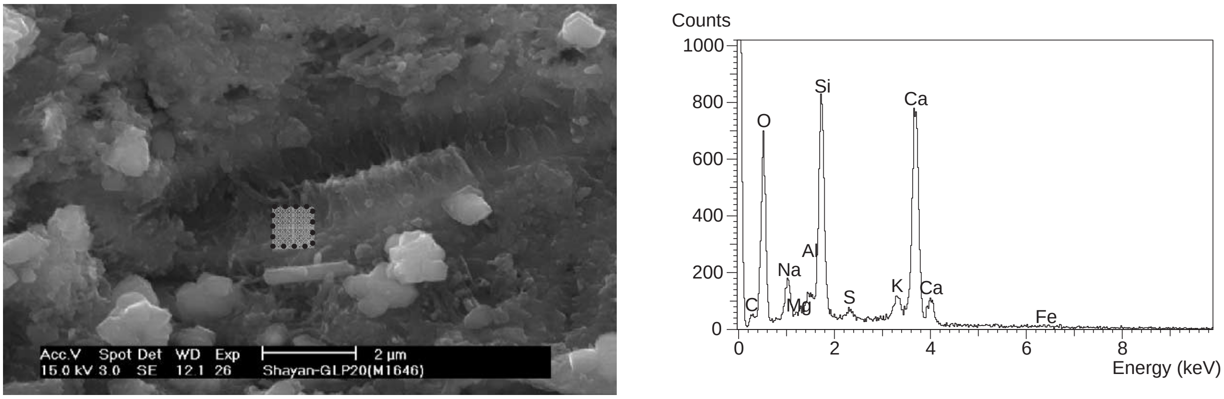

Fig. 13. SEM view and EDX composition of a reacted glass shard assimilated into the paste (Mix 3).

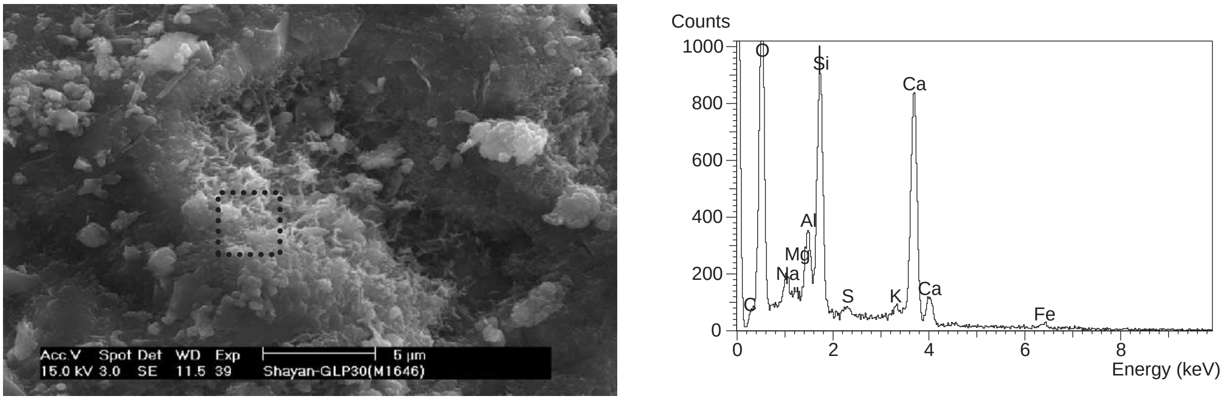

Fig. 14. SEM view and EDX composition of paste near a reacted glass particle in Mix 4.

particles into the paste was clearly noted (Fig. 13). This feature was also noted in Mix 3 which had 30% GLP (Fig. 14), and in both cases the reaction sites indicated high Na contents. Occasional round particles in Mix 4, about 20 μm diameter, appeared to have reacted in the concrete (Fig. 15), but the reaction product had small amounts of Na and large amounts of Ca. The compositions mentioned above were different from that of unreacted or partially reacted glass (Fig. 16), and may reflect the composition of the pozzolanic reaction product.

Mixes 5 and 6 exhibited features similar to those of Mixes 2 and 3, respectively. Fig. 17 shows the paste in Mix 7, next to a glass particle (lower left), which is greatly enriched in Si and Na. The small elongated crystals may be ettringite or some other calcium sulfoaluminate, as indicated by the small sulphur peak in the EDX spectrum. Many other sites showed relics of fine GLP particles which were evidently consumed by the paste, and EDX showed that the particles had been converted to Si- and Ca-rich phases which also retained large amounts of Na (Fig.

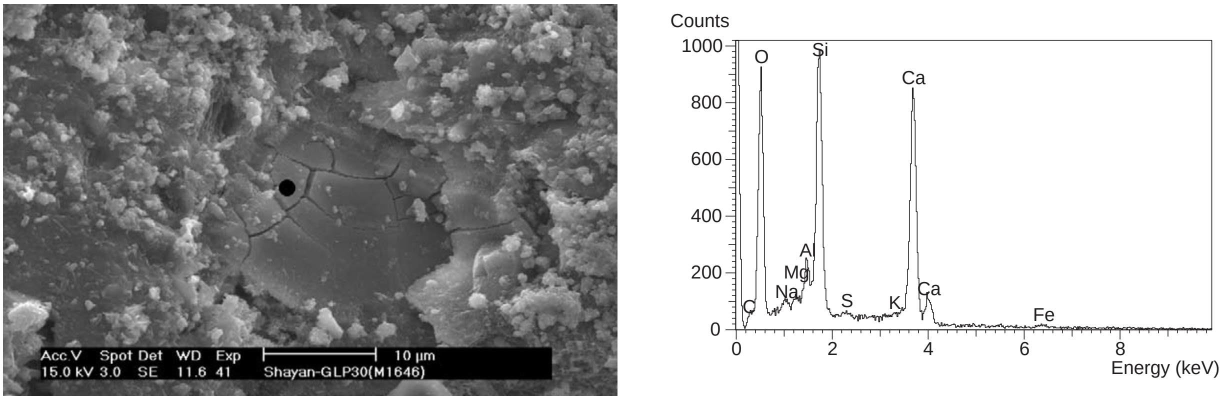

Fig. 15. SEM view and EDX composition of reacted glass forming a Ca-rich gel (Mix 4).

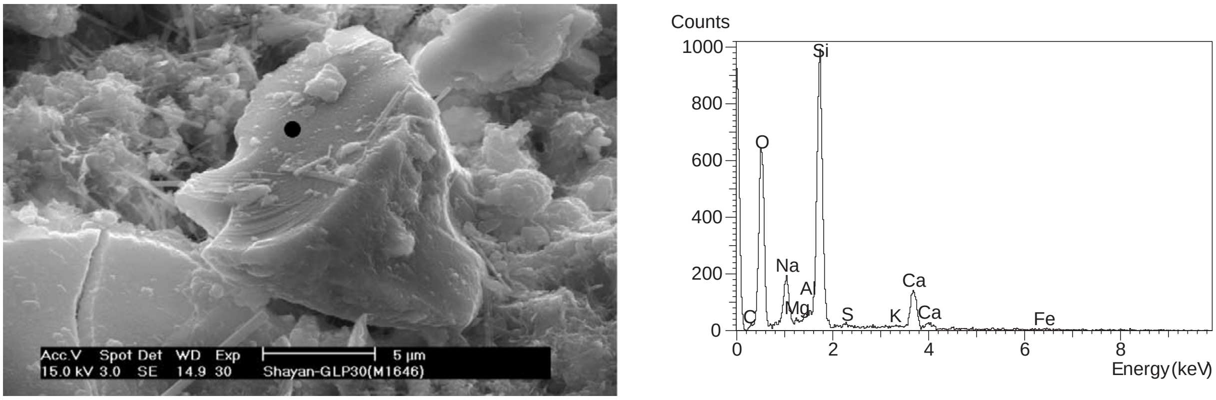

Fig. 16. SEM view and EDX composition of unreacted portion of a glass particle (Mix 4).

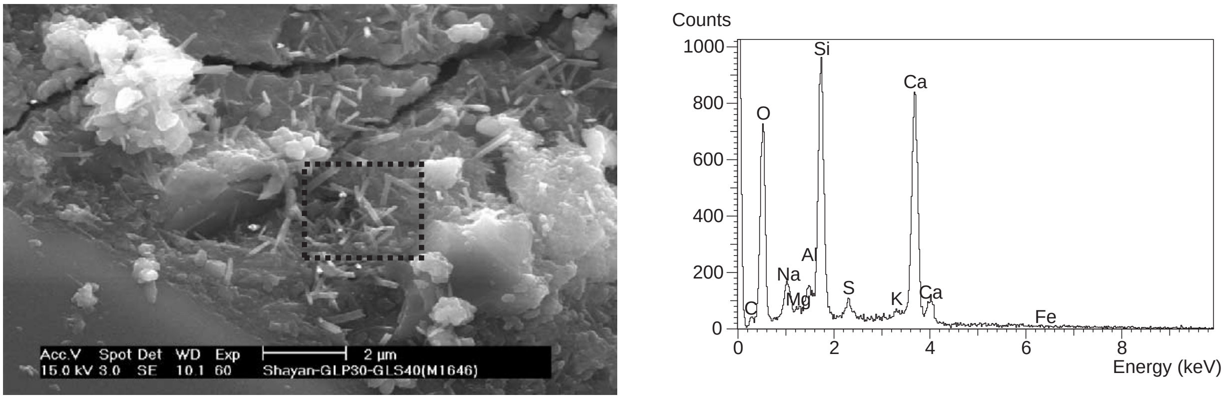

Fig. 17. SEM view and EDX composition of paste in Mix 7, near a glass particle (lower left).The fine needle-shaped crystals in the paste are probably ettringite.

18). The enrichment of paste with Si would considerably increase its capacity to bind K and Na ions, which would then not allow the alkali ions to remain in solution to react with the reactive particles.

Needle-shaped crystals were also noted at some sites of pozzolanic reaction of GLP in Mix 7 (Fig. 19), where large amounts of alkali were retained. It is possible that reaction of glass can ultimately lead to the formation of a poorly crystalline Na-bearing phase, and this may be another reason why the Na content of glass did not contribute to AAR expansion in the presence of reactive aggregate.

In Mix 8 (30% GLP, 75% glass sand), some GLP particles showed a hydration layer at the transition zone in contact with the paste (Fig. 20). The composition of the layer indicated consumption of lime at the transition zone, judged by the much increased Ca content compared to the composition of unreacted glass. Mix 9 (no GLP, 50% glass sand) had a paste phase which was only slightly enriched in Si, perhaps due to the reaction of

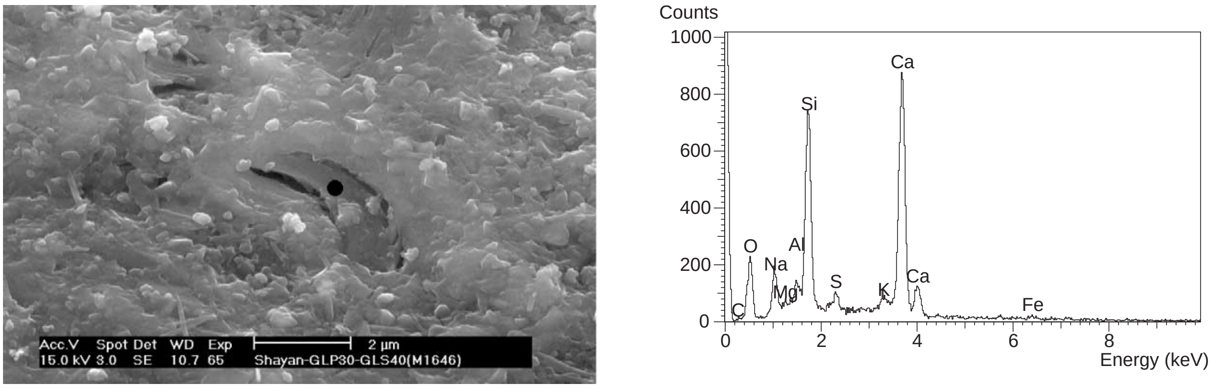

Fig. 18. SEM view and EDX composition of the relics of a very fine glass particle in Mix 7, reacted with cement to form a CSH-like material. Note high Na and K contents.

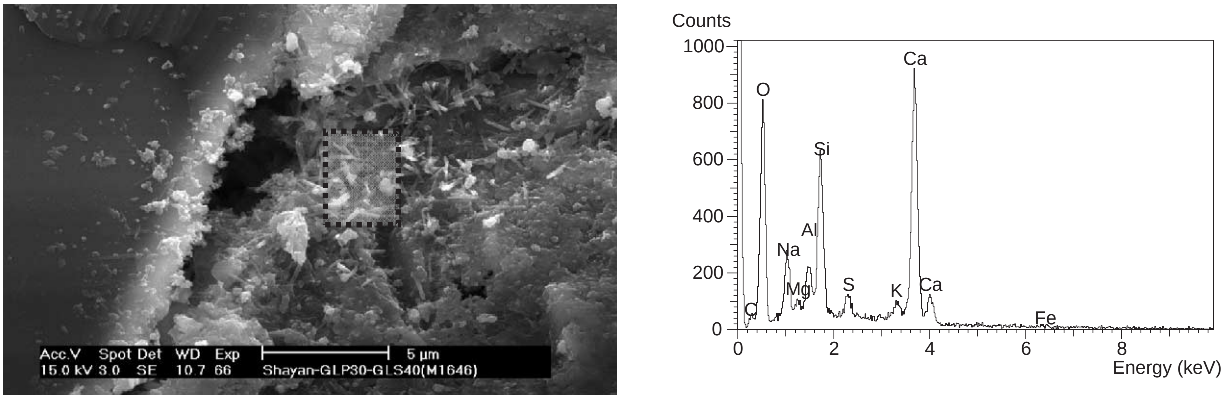

Fig. 19. SEM view and EDX composition of a region of paste in Mix 7, near a glass particle. Note high alkali content in the region of needle-shaped crystals analysed.

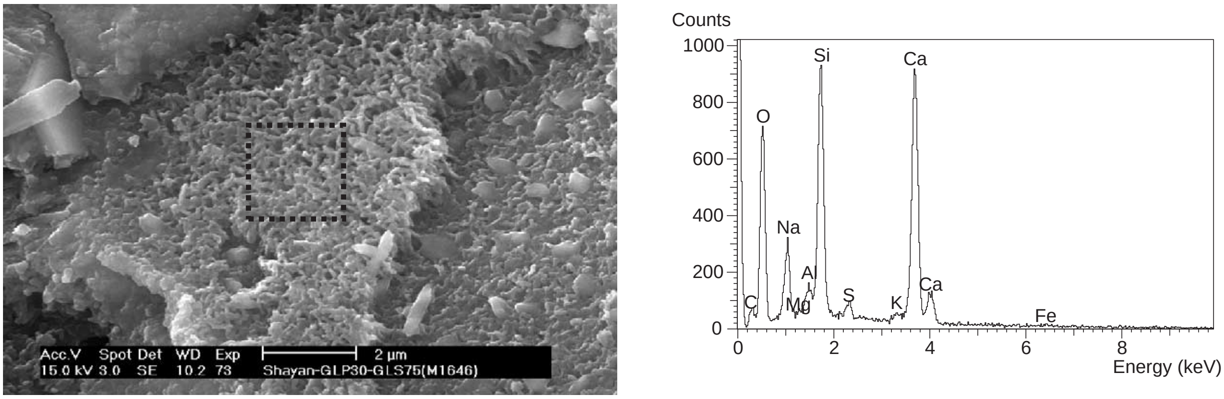

Fig. 20. SEM view and EDX composition of the reacted surface of a GLP particle In Mix 8. Note Na from original glass remaining at the reaction site.

the fine portion of the glass sand. Mix 10 showed features similar to Mixes 3 and 7.

Overall, the SEM/EDX examination showed no deleterious reaction of either GLP or glass sand in the concrete mixes due to insufficient alkali content of the concrete and because GLP did not contribute alkali to the pore solution. Evidence for this was noted from features such as those seen in Figs. 13 and 14, in which glass powder particles appeared to have been assimilated into concrete without forming deleterious AAR gel, and also from the observation that larger glass particles were free of alkali attack and without forming AAR gel in concrete (Fig. 20). Moreover, SEM/EDX observations suggested that the alkali originally contained in the glass was bound in the paste and crystalline materials that resulted from the pozzolanic reaction of GLP ((Figs. 13, 14, 17, 18, 19 and 20) such that it may no longer be available for reaction with reactive aggregate particles.

5. Summary and conclusions

Data has been provided on 10 concrete mixes of various compositions which incorporated glass powder as cement replacement, and glass sand as natural sand replacement. At 28 days, only Mix 3, containing 20% GLP, had met the strength requirement for 40 MPa concrete. However, at 404 days all the other mixes containing 30% glass powder caught up and approached 55 MPa strength, despite 30% reduction in cement content, indicating further strength development due to pozzolanic reaction between GLP and cement. The results also indicated that 40–50% of natural sand could be replaced by crushed glass sand. The strength of cores drilled from the slab was lower than that of the cast cylinder, which has been attributed to less efficient curing under field conditions than laboratory fog curing, and also to less effective compaction of the slabs compared to the cylinders.

The drying shrinkage values of all the mixes were below 0.075% and met the requirements of the Australian Standard AS 3600. There were indications that GLP reduced the chloride ion penetrability of the concrete, thereby reducing the risk of chloride-induced corrosion of the steel reinforcement in concrete, but this issue needs further electrochemical investigation.

No deleterious AAR expansion was noted in the concrete prism test, indicating that AAR would not be a problem in the presence of GLP. This may have arisen because the pozzolanic reaction of GLP with cement appeared to enhance the binding of alkali, making it unavailable for reaction with reactive aggregate.

These results provide ample evidence that both GLP and glass aggregate can be used together in 40 MPa concrete without any adverse reaction. The utilisation of these materials in concrete is strongly recommended, and would provide considerable economic and environmental benefits to the community.

Acknowledgments

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