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Studies on concrete containing ground waste glass

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Abstract

The possibility of using finely ground waste glass as partial cement replacement in concrete was examined through three sets of tests: the lime-glass tests to assess the pozzolanic activity of ground glass, the compressive strength tests of concrete having 30% cement replaced by ground glass to monitor the strength development, and the mortar bar tests to study the potential expansion. The results showed that ground glass having a particle size finer than 38 μm did exhibit a pozzolanic behavior. The compressive strength from lime-glass tests exceeded a threshold value of 4.1 MPa. The strength activity index was 91, 84, 96, and 108% at 3, 7, 28, and 90 days, respectively, exceeding 75% at all ages. The mortar bar tests demonstrated that the finely ground glass helped reduce the expansion by up to 50%. A size effect was observed; a smaller glass particle size led to a higher reactivity with lime, a higher compressive strength in concrete, and a lower expansion. Compared to fly ash concrete, concrete containing ground glass exhibited a higher strength at both early and late ages. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Concrete; Ground waste glass; Pozzolan; Compressive strength; Waste management

1. Introduction

Nonrecyclable waste glass constitutes a problem for solid waste disposal in many municipalities. The current practice is still to landfill most of the nonrecyclable glass. Since the glass is not biodegradable, landfills do not provide an environment-friendly solution. Consequently, there is a strong need to utilize waste glasses.

Traditionally, most nonrecyclable mixed-color broken glasses are coming from the bottling industry. In addition, the recently initiated business of recycling mercury-containing fluorescent lamps also produces a large quantity of nonrecyclable waste glass. Processing fluorescent lamps is important because it protects the environment from overexposure to mercury. It reduces the level of mercury content from 1 mg/L before treatment to 0.05 mg/L afterward, which is four times less than the regulated amount of 0.2 mg/L. The fluorescent lamp recycling facility crushes the fluorescent lamps, separates the metal caps, and recovers mercury. For 55,000 tubes recycled, approximately 30 m^3 of waste glass will be generated. In the future, with the environmental law being strictly enforced and with the increasing use of fluorescent lighting systems for energy efficiency, it is expected that more nonrecyclable waste glass will be accumulated from the fluorescent lamp recycling business.

Efforts have been made in the concrete industry to use waste glass as a partial replacement of the coarse or fine aggregates. Due to the strong reaction between the alkali in cement and the reactive silica in glass, the use of glass in concrete as part of the coarse aggregate was not satisfactory because of the marked strength regression and excessive expansion [1]. Recent studies have shown that if the glass was ground to a particle size of 300 μm or smaller, the alkali silica reaction (ASR)-induced expansion could be reduced [2,3]. Partial replacement of fine aggregates in concrete by crushed glass was attempted. The fly ash was effectively incorporated into the 1.5-mm glass concrete to control the expansion [4]. The strength loss due to the sand substitution by the crushed glass was reported to be between 5 to 10% [5].

The successful use of other industry byproducts or wastes, such as fly ash and silica fume, in concrete sets a good example for waste glass to be used in a different way. Fly ash and silica fume have been used as supplementary cementing materials to partially replace cement for many years. Both materials have shown beneficial pozzolanic reaction in concrete, which contributes substantially to concrete's strength and durability [6]. A typical pozzolanic material features three characteristics: it should contain high silica content, be X-ray amorphous, and have a large surface area. Compared to fly ash and silica fume, glass has a suffi-

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Table 1
Chemical compositions of soda-lime glass as well as Class F fly ash and silica fume (by weight percent)

	Soda-lime glass	Class F fly ash	Silica fume
SiO_2	72.8	40.71	96.5
Al_2O_3	1.4	17.93	0.5
Fe_2O_3	–	29.86	2.0
$SiO_2 + Al_2O_3 + Fe_2O_3$	74.2	88.50	99.0
CaO	4.9	2.80	0.80
MgO	3.4	1.09	0.90
SO_3	–	1.27	0.2
K_2O	0.3	1.56	2.0
Na_2O	16.3	0.73	0.40
P_2O_5	–	0.17	–
TiO_2	–	0.85	–
B_2O_3	1.0	–	–
Color	white	grey	dark
Fineness	75 μm < glass < 150 μm 38 μm < glass < 75 μm glass < 38 μm	90% < 45 μm (Mean = 11 μm)	99% < 45 μm (Mean = 0.15 μm)

cient silica content and is amorphous in nature. The glass might satisfy the basic requirements for a pozzolan if it could be ground to a size fine enough to passify the alkali-silica reaction and to activate the pozzolanic behavior.

This paper presents a preliminary study on the assessment of the pozzolanic activity of ground waste glass as well as its potential use in concrete as a partial replacement of cement. A series of tests were conducted to study the pozzolanic activity and the alkali-silica reaction of the glass; the lime-glass tests were to examine the reaction of ground glass with lime, the compressive strength tests were to monitor the strength development of the concrete containing 30% ground glass as cement replacement, and the mortar bar tests were to investigate the expansion induced by the possible reaction between the alkali in cement and the silica in glass. The particle size effect was evaluated and the comparison of glass concrete with fly ash concrete and silica fume concrete also was made.

2. Methods

2.1. Ground waste glass

The waste glass used in this study was obtained from recycled fluorescent lamps supplied by RLF Canada in Quebec. It was a typical soda lime glass. The chemical composition of the glass was analyzed using an X-ray microprobe analyzer and is listed in Table 1 together with that of Class F fly ash and silica fume for comparison. Although the silica content of glass is higher than fly ash, the equivalent reactive components ($SiO_2 + Al_2O_3 + Fe_2O_3$) is relatively low in glass. The silica fume had the highest percentage of reactive silica among the three. In accordance to ASTM C618, the glass satisfies the basic chemical requirements for a pozzolan and exhibited a favored white color. However, it does not meet the optional requirement for the alkali content because of the high percentage of Na_2O in glass. To satisfy the physical requirement for fineness, the glass has to be ground to pass a 45-μm sieve. This was accomplished by crushing and grinding the glass in a jar mill in the laboratory, and by sieving the ground glass to the desired particle size. To study particle size effect, three different ground glasses were used:

- 150-μm glass: ground glass having particles passing a #100 sieve (150 μm) and retained on a #200 sieve (75 μm);
- 75-μm glass: ground glass having particles passing a #200 sieve (75 μm) and retained on a #400 sieve (38 μm); and
- 38-μm glass: ground glass having particles passing a #400 sieve (38 μm).

According to ASTM C618, the 150-μm glass did not qualify as a pozzolan due to the coarse particle size. The 75-μm glass was marginal, depending on the percent passing the 45-μm sieve. Consequently, only the 38-μm glass satisfied the fineness requirement. The purpose of the study was to examine if the coarse ground glass could still depict certain levels of pozzolanic behavior. The particle size ranges of the three ground glasses as well as that of the fly ash and silica fume are also listed in Table 1. The particle size and the particle shape of the ground glass were analyzed using the scanning electron microscope. Typical micrographs are shown in Fig. 1. The ground glasses exhibited angular shapes. For each glass, the specified particle size was dominant, although there were still large numbers of fines present in the 150- and 75-μm glass. It seemed that more fines were retained in the 75-μm glass than in the 150-μm glass. The crystallinity of the glass was examined using X-ray diffraction technique. The X-ray

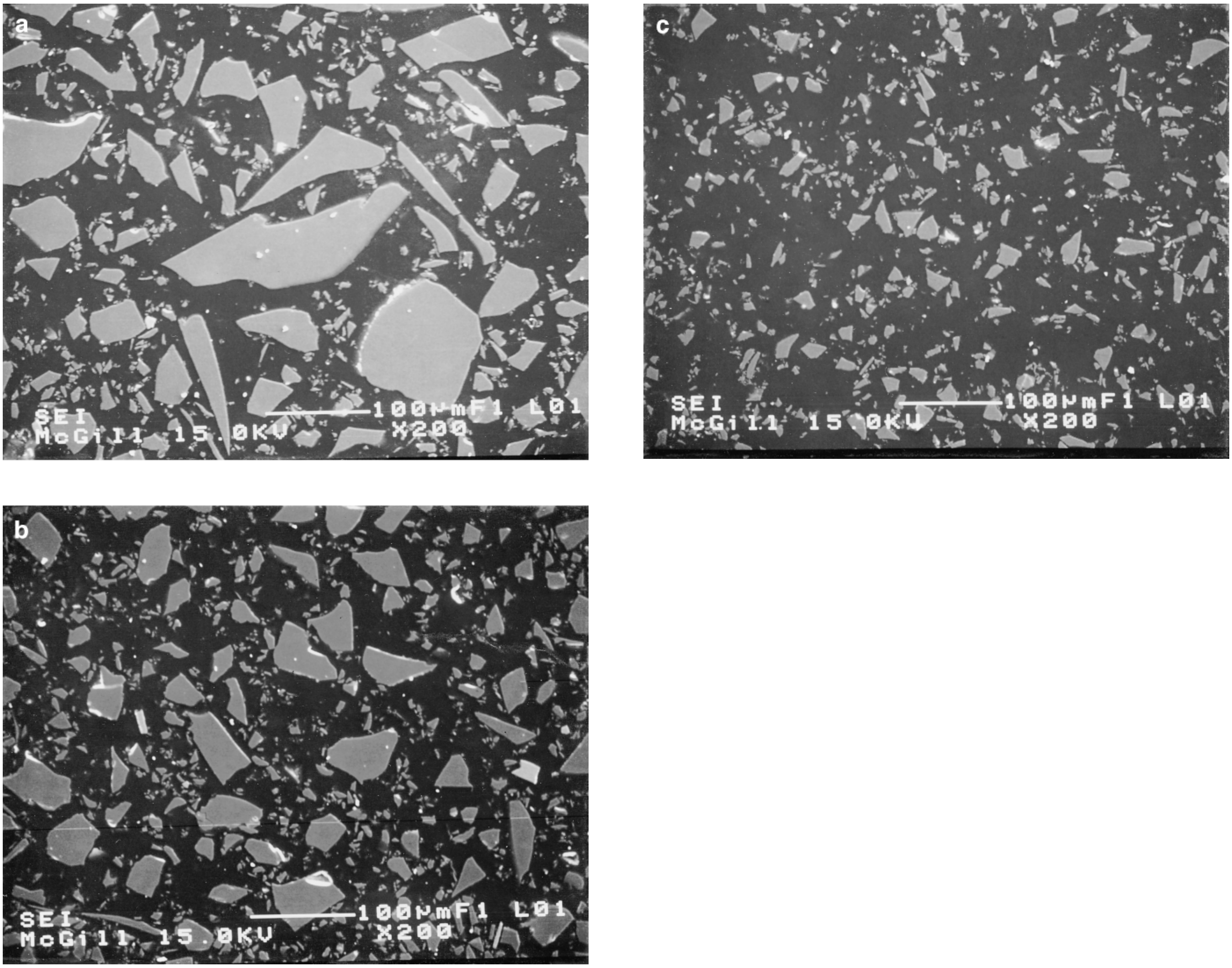

Fig. 1. Particle size and shape of ground waste glass. (a) 150-µm glass; (b) 75-µm glass; (c) 38-µm glass.

spectrum of the glass is presented in Fig. 2. It is evident that soda lime glass is a typical amorphous material.

2.2. Lime-glass test

Lime-glass tests were conducted following ASTM C593 [7]. Five batches of samples with different mineral additives were prepared. Respectively, they contained the Class F fly ash, silica fume, 150-µm glass, 75-µm glass, and 38-µm glass. Both fly ash and silica fume batches were used as control for comparison. The chemical compositions of all additives are listed in Table 1, and the mixture proportions are given in Table 2. The hydrated lime, mineral additives, and graded standard sand were added up to 100% and water was adjusted to achieve a flow of 65 to 75% consistency through a flow table test. The mixture was cast in 50-mm cube molds, wrapped by wet burlap, sealed by plastic bag, and cured at 54°C in an oven. Compressive strength tests of all batches were carried out after 7 days curing at 54°C. At least three samples were tested and averaged for each batch. Cubes with 75-µm glass and 38-µm glass were also tested after an additional 21 days curing at 23°C in water to monitor the long-term strength gain. As recommended by ASTM C593, a satisfactory pozzolanic material should have a minimum compressive strength 4.1 MPa when mixed with lime after 7 days curing at 54°C, and after an additional 21 days curing at 23°C in water.

2.3. Compressive strength test

Compressive strength tests were conducted to study the strength development of concrete containing the ground glass at early and late ages. The cement replacement by the ground waste glass in the concrete was targeted at 30% by volume. The concretes containing the ground glass were compared to the concretes having the same percent replacement of cement by fly ash and silica fume, as well as to the control concrete without any mineral additives. The mixture proportions are shown in Table 3. The six batches were defined as follows:

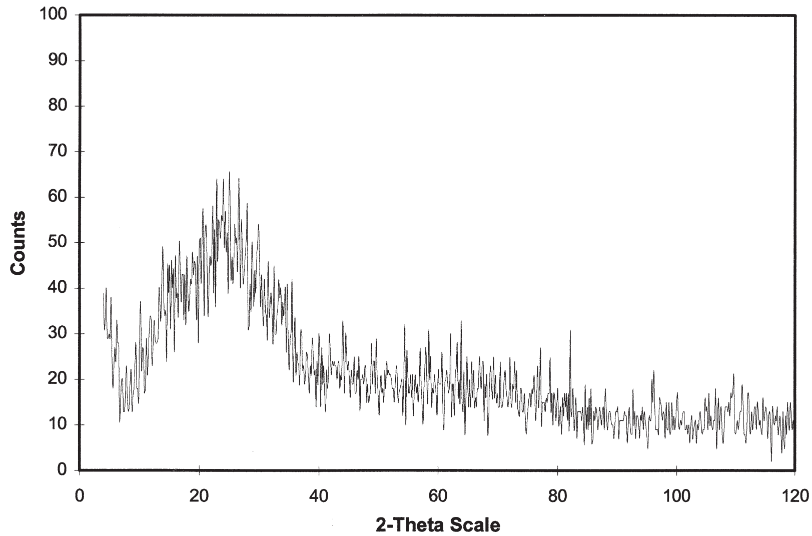

Fig. 2. X-ray spectrum of ground glass.

- Control concrete: no mineral additives
- Silica fume concrete: 30% by volume of the Portland cement replaced by silica fume
- Fly ash concrete: 30% by volume of Portland cement replaced by fly ash
- 150-μm glass concrete: 30% by volume of Portland cement replaced by 150-μm glass
- 75-μm glass concrete: 30% by volume of Portland cement replaced by 75-μm glass
- 38-μm glass concrete: 30% by volume of Portland cement replaced by 38-μm glass

The hybrid batches with 15% ground glass and 15% silica fume were also prepared to investigate if the highly reactive silica fume could promote the pozzolanic activity of the ground glass in concrete. As a control, concrete with 15% silica fume alone was also tested. The batches were defined as follows and the mixture proportions are shown in Table 4:

- Hybrid 150-μm glass-SF concrete: 30% by volume of Portland cement replaced by 15% silica fume and 15% 150μm glass
- Hybrid 75-μm glass-SF concrete: 30% by volume of Portland cement replaced by 15% silica fume and 15% 75-μm glass
- Hybrid 38-μm glass-SF concrete: 30% by volume of Portland cement replaced by 15% silica fume and 15% 38-μm glass
- 15% silica fume concrete: 15% by volume of Portland cement replaced by silica fume

The control concrete was based on a cement content of 300 kg/m^3 with a target strength of 25 MPa at 28 days. The mate-

Table 2
Mixture proportions for lime tests (by weight percent)

Batches	Silica fume	Fly ash	150-μm glass	75-μm glass	38-μm glass
Lime	9	9	9	9	9
Mineral additives	18	18	18	18	18
Graded sand	73	73	73	73	73
Water/lime + mineral additives	180	64	68	70	76

Table 3
Mixture proportions for concretes containing 30% mineral additives (kg/m^3)

	S.G.	Control concrete	Silica fume	Fly ash	150-μm glass	75-μm glass	38-μm glass
Cement	3.15	300	210	210	210	210	210
Silica fume	2.20	–	62.7	–	–	–	–
Fly ash	2.60	–	–	74.3	–	–	–
Glass	2.40	–	–	–	68.6	68.6	68.6
Coarse aggregate	2.60	1,269	1,269	1,269	1,269	1,269	1,269
Fine aggregate	2.60	681	681	681	681	681	681
Water	1.00	225	204.7	213.2	208.9	208.9	208.9

S.G. = specific gravity.

Table 4
Mixture proportions for hybrid glass-silica fume concretes (kg/m^3)

	S.G.	15% silica fume	Hybrid 150-μm glass-silica fume	Hybrid 75-μm glass-silica fume	Hybrid 38-μm glass-silica fume
Cement	3.15	255	210	210	210
Silica fume	2.20	31.4	31.4	31.4	31.4
Fly ash	2.60	–	–	–	–
Glass	2.40	–	34.3	34.3	34.3
Coarse aggregate	2.60	1,269	1,269	1,269	1,269
Fine aggregate	2.60	681	681	681	681
Water	1.00	214.8	206.8	206.8	206.8

S.G. = specific gravity.

rials used were CSA type 10 (ASTM type I) cement, river sand, and crushed limestone with maximum aggregate size of 10 mm. For all the batches, water-to-cementitious (cement + mineral additive) ratio was 0.75, and the coarse-to-fine aggregate ratio 65 to 35. No other additives were used. Twenty cylinders, 50 mm in diameter and 100 mm in height, were cast for each batch. After 24 h of curing in molds, the samples were demolded and placed in a water bath at room temperature for moisture curing. Five cylinders from each batch were tested at 3, 7, 28, and 90 days, respectively, to obtain compressive strength of the concrete. The strength activity index at a given age is defined in accordance with ASTM C618 [7] as the percent compressive strength with respect to the control. This gives a measure of how close the values are to the control.

2.4. Expansion test

Study of the expansion due to the possible reaction between the alkali in the cement and the silica in the glass was done in accordance with ASTM C1260 [7]. The 25 × 25 × 100-mm mortar bars were made of standard graded river sand, Type 10 Portland cement, and a mineral additive. The water-to-cementitious ratio was 0.47 and the cementitious-aggregate ratio was 1 to 2.25. For the five batches containing mineral additives, 30% by volume of the Portland cement was replaced by the silica fume, fly ash, 150-μm glass, 75-μm glass, and 38-μm glass, respectively. After 24 h of curing, the bars were placed in water at 80°C for another 24 h to gain a reference length. They were then transferred to a solution of 1 N of NaOH at 80°C. Readings were then taken every day for 14 days. The mortar bars without any additives were also tested as control. The comparison with the control is an indication of whether or not the silica in glass is reactive with the alkali in cement and from the solution. It also manifests if the mineral additives used are able to suppress the expansion by consuming more lime in concrete.

3. Results and discussion

3.1. Activity of ground glass with lime

The compressive strengths of the lime-glass mixtures as well as that of the controls made of lime-silica fume and lime-fly ash are shown in Fig. 3. The 38-μm glass satisfied the minimum strength requirement at 7-day test, and attained an increase in strength after additional 21 days of curing in water. The strength of 150-μm glass mixture was far below the limit because the size of the glass was too

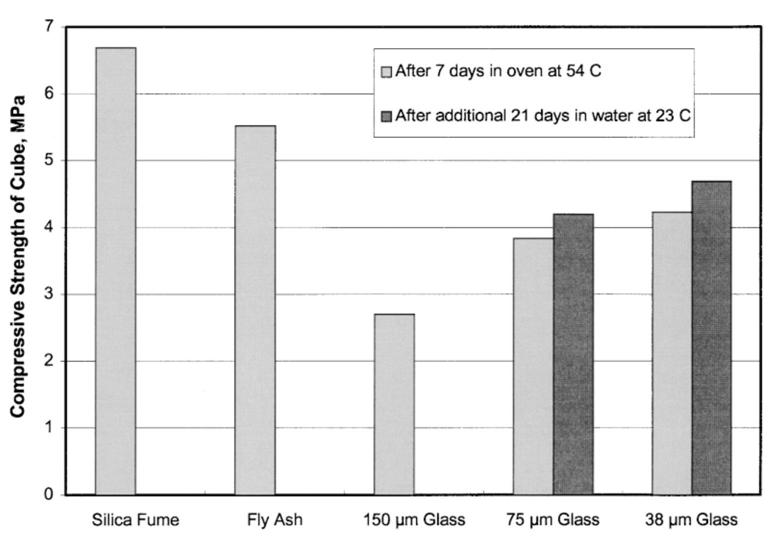

Fig. 3. Compressive strength of lime-mineral additive mixtures.

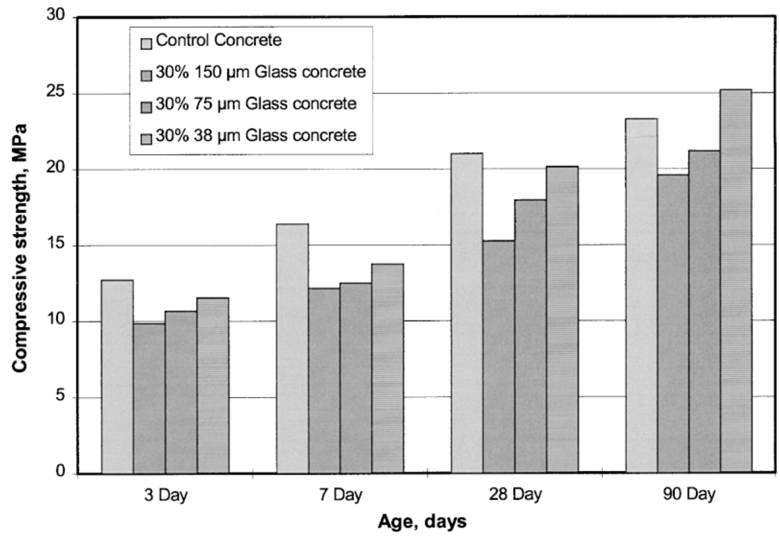

Fig. 4. Compressive strength of concretes containing 30% ground glass.

coarse to serve as a pozzolan. The 75-μm glass performed marginally. Its 7-day strength was slightly lower than the threshold value, while its additional 21-day curing in water enhanced the strength to a satisfactory level. As controls, both lime-fly ash and lime-silica fume mixtures exhibited high pozzolanic activity. The relatively low percentage of components, $SiO_2 + Al_2O_3 + Fe_2O_3$, in glass (Table 1) made the ground glass less reactive. The size effect of the ground glass on the pozzolanic activity was observed. The smaller the particle size, the more reaction of the glass with the lime.

Water-to-lime + additive ratio from the flow table tests (Table 2) was an indication of workability. To keep the same consistency, the ground glass required slightly higher water content than the fly ash, suggesting that the workability of the glass concrete was decreased. This reduction was about 18% if 38-μm glass was compared with fly ash. The angular shape of the glass particles (Fig. 1) could be the direct cause for this reduction. Relatively speaking, the smaller particle size of glass required more water to keep the same workability. Overall, the use of silica fume doubled water content to maintain the consistency.

3.2. Compressive strength development

The compressive strength of each batch at a particular age was an average of five tests. The maximum standard deviation of all the tests was 10%. The comparison of concretes containing ground waste glass with control concrete is shown in Fig. 4. All batches of glass concretes had lower strengths than the control at the ages of 3, 7, 28, and 90 days, except that the strength of the concrete containing 38-μm glass exceeded that of control by 8% after 90 days of curing. It seemed that there existed a competition in strength development between the 30% 38-μm glass in glass con-

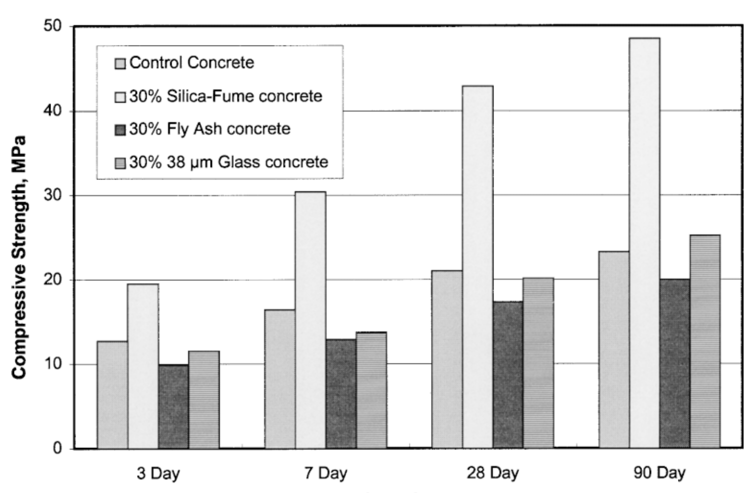

Fig. 5. Comparison of 38-μm glass concrete with silica fume concrete and fly ash concrete.

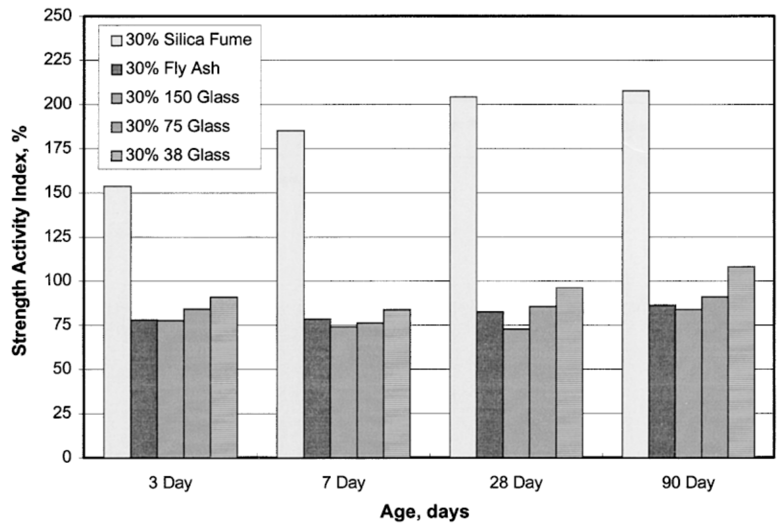

Fig. 6. Strength activity index of concretes containing 30% mineral additives.

crete and the same amount of cement in control concrete. The size effect was observed again. The smaller the particle size of the glass, the higher the strength of the glass concrete. Fig. 5 compares 38-μm glass concrete with silica fume concrete and fly ash concrete at the same percent of cement replacement. The 38-μm glass concrete exhibited a strength higher than the fly ash concrete at all ages, but only half that in silica fume concrete. The strength activity indexes of all the five concretes containing 30% mineral additives are presented in Fig. 6. ASTM C618 recommends that a pozzolan have a minimum strength activity index of 75% for it to benefit concrete. As a consequence, the activity index of 150-μm glass did not always satisfy the criteria. On the other hand, 75- and 38-μm glasses were not only very suitable, but directly comparable to fly ash concrete at all ages. The relatively higher early strength index of 38-μm glass concrete could be attributed to the high content of Na_2O in glass. It was generally accepted that alkalis in concrete could act as catalysts in forming calcium silicate hydrate at early age, and promoting early strength development [8]. It was also reported that high content of alkalis in cement could result in a decrease of 28-day strength in concrete [8]. For glass containing concretes in the presence of 16% Na_2O from the soda lime glass, the early strength increase was observed. However, the late strength decrease was not noticed. Silica fume concrete showed a superior performance. It was the submicron particle size and the high silica content in silica fume that played a critical role in strength development. The effect of glass particle size on the concrete strength is summarized in Fig. 7. A smaller size of ground glass led to a higher compressive strength, especially at a late age.

It is known that the pozzolanic reaction at room temperature is slow and therefore a long curing period is needed to observe its positive benefits. Studies had found that if the low reactive pozzolan, such as fly ash, was used together with a high reactive pozzolan, such as silica fume, the pozzolanic activity of the low reactive pozzolan could be pro-

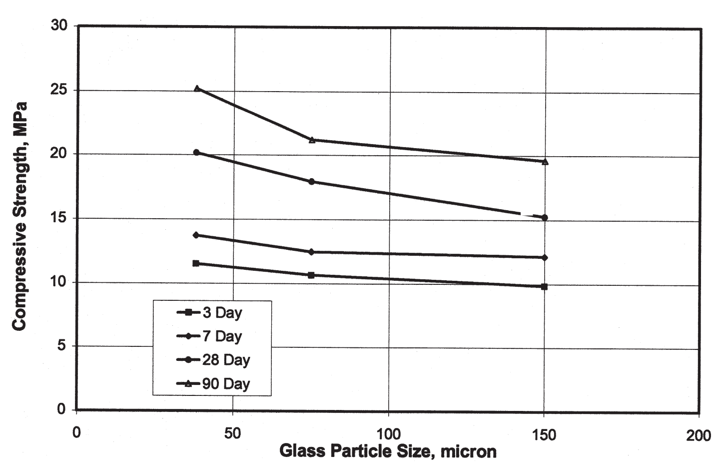

Fig. 7. Particle size effect on compressive strength of concrete containing 30% ground glass.

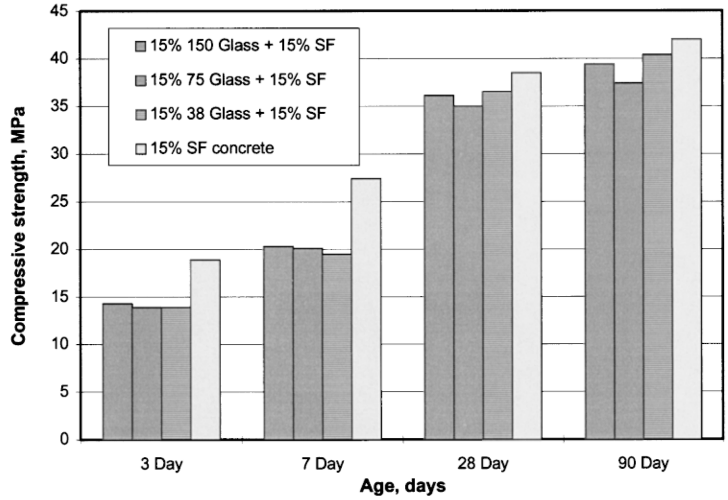

Fig. 8. Compressive strength of concretes containing 15% glass and 15% silica fume.

moted [9]. This phenomenon was also studied in glass concrete. Hybrid batches with 15% ground glass and 15% silica fume were prepared and tested, together with a reference batch containing only 15% silica fume. Consequently, the 15% ground glass in hybrid batches was competing with the same amount of cement in the reference batch in the presence of 15% silica fume. The results of the compressive strength tests are shown in Fig. 8. In the early age (3- and 7-day) tests, all hybrid batches had lower strengths than the reference batch. As hydration progressed, the strength of hybrid concretes approached that of the reference, the 15% silica fume concrete, but had never exceeded that value, even at 90 days. The activity indexes of hybrid batches were computed as the strength ratio of hybrid concrete to the 15% silica fume concrete, and are plotted in Fig. 9. At the ages of 3 and 7 days, the activity indexes were about the same as or even lower than that of the 30% glass concrete without silica fume (Fig. 6). This was indicative of low activity of glass at early ages in the presence of the silica fume. The activity index of concrete containing 15% 38-μm glass was 95% at 28 days and 96% at 90 days. The former was slightly higher than that in 30% glass concrete, while the latter was lower. Size effect of ground glass in hybrid concretes was not as apparent as that observed in glass concrete without silica fume at a late age. The hybrid concrete with 150-μm glass had exhibited an increased activity index, which was close to that with 38-μm glass (Fig. 9). It implies that the activity of ground glass has not been enhanced substantially by the highly reactive silica fume and that the strength gain in hybrid concrete is attributed mainly to silica fume, not to ground glass.

3.3. Expansion due to alkali-silica reaction

The percent expansions of the mortar bars with and without mineral additives are shown in Fig. 10. Each measure at

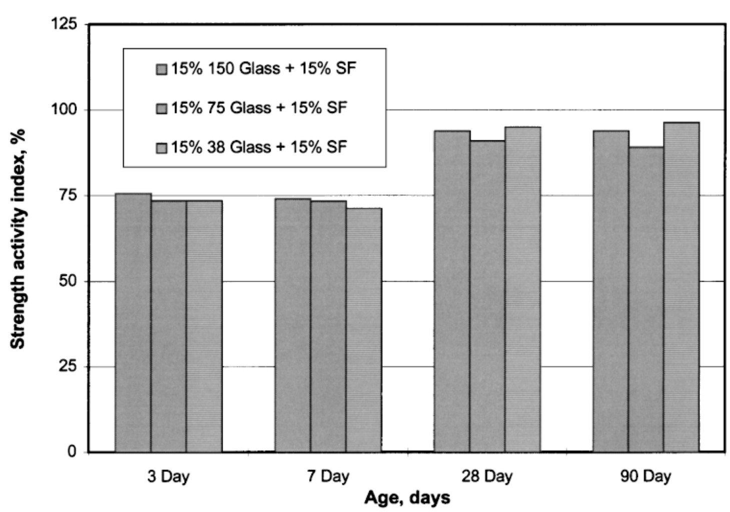

Fig. 9. Strength activity index of concretes containing 15% glass and 15% silica fume.

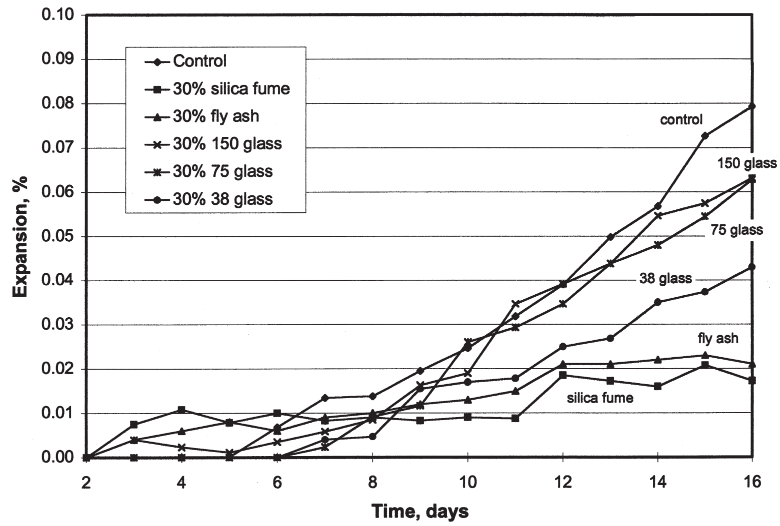

Fig. 10. Expansion of mortar bars with and without mineral additives.

a particular day was an average of three samples. It was evident that batches with 30% cement replaced by mineral additives had expansions less than that of the control. Silica fume mortar had the least expansion, followed by the fly ash batch. While both the 150- and 75-μm glass batches experienced a similar amount of expansion, the 38-μm glass reduced the expansion to half of the control. All batches had expansions below 0.1% and therefore, according to ASTM C1260 specifications, the expansion was within an acceptable limit. The expansion tests showed that not only was the ground glass not expansive as was expected due to the possible alkali-silica reaction, but it actually helped hinder the expansion as compared to the control. This is also an indication of pozzolanic activity. Again, the size effect of ground glass was observed. The finer the particle size, the less the expansion. This phenomenon was also reported in other studies [2,3].

4. Conclusions

Waste glass, if ground finer than 38 μm, did exhibit a pozzolanic behavior. The compressive strength of lime-glass mixture was higher than the threshold limit of 4.1 MPa. The strength activity indexes of the concrete with 30% cement replaced by 38-μm glass were 91, 84, 96, and 108% at 3, 7, 28, and 90 days, respectively, exceeding the 75% as recommended by ASTM C618. The expansion of the mortar bar with 30% cement replaced by the 38-μm glass was reduced to half of that in control. The lime activity, strength development, and reduction in expansion were indicative of pozzolanic activity.

Compared to fly ash concrete, glass concrete had a higher early strength as well as a higher late strength. The high early strength could be attributed to the high alkali content in soda-lime lamp glass. Nevertheless, the high alkali content in mixture did not deteriorate the strength of the concrete at a late age. Instead, a gradual increase in strength was observed. The concrete with 38-μm glass attained a 120% increase in strength from the age of 3 to 90 days. This rate was higher than 102%, the strength increase in fly ash concrete during the same period of time. The presence of silica fume in hybrid concrete with 15% silica fume and 15% glass did not significantly promote the pozzolanic activity of ground glass in concrete.

The size effect of ground glass on the performance of concrete was apparent. A smaller particle size of the ground glass resulted in a higher activity of glass with lime, a higher compressive strength in concrete as well as a lower expansion. It is expected that if the glass can be ground even finer, its pozzolanic activity can be remarkably improved. Further research is necessary to study the effect of high Na_2O content on the alkali aggregate reaction when reactive aggregates are used in concrete. The optimal particle size distribution of glass also needs to be determined to trade off the cost and performance in glass concrete.

The use of ground waste glass as a high volume cement replacement in concrete seems feasible. The purpose of the study is to protect the environment by saving more landfills, to increase the cement plant capacity by using more beneficial additives, and to reduce CO_2 emission per ton of cement by consuming less cement.

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