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Characteristics and pozzolanic reactivity of glass powders

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Abstract

This paper deals with the morphology, fineness and pozzolanic activity of four glass powders: one (GP-fine) from the screening of crushed waste glasses, one (GP-dust) from a dust collector for the glass crushing process and two (GP-4000 and GP-6000) from further grinding of the powder from the dust collector in a ball mill. GP-fine and GP-dust consist mainly of large flaky particles, while GP-4000 and GP-6000 consist mainly of small angular particles. The finenesses of these glass powders are measured by particle size distribution and Blaine fineness method. For a similar particle size distribution, ground glass powder has a higher Blaine specific surface area than Portland cement due to the angular morphology of glass particles. Finely ground glass powders exhibited very high pozzolanic activity. The finer the glass powder is, the higher its pozzolanic reactivity is. An increase in curing temperature accelerates the activation of pozzolanic reactivity of both glass powder and coal fly ash in terms of strength development rate. Mortar cube strength results (ASTM C109) indicated that curing temperature has a greater influence on the glass powder than on fly ash. The rapid mortar bar expansion test (ASTM C1260) results indicate that the replacement of Portland cement with ground glass powder also reduces the expansion due to alkali–aggregate reactions, although it is not as effective as coal fly ash.

Keywords: Glass powder; Coal fly ash; Fineness; Pozzolanic reactivity; Alkali–aggregate reaction

1. Introduction

The recycling of waste glass poses a major problem for municipalities nationwide. In 1994, approximately 9.2 million metric tons of postconsumer glass were discarded in the municipal waste stream in the United States. Approximately 8.1 million metric tons or 80% of this waste glass was container glass [1]. New York City alone collects more than 100,000 tons annually and pays material recycling facilities (MRFs) up to $45 per ton for the disposal of the glass. [2]. Use of recycled materials in construction is among the most attractive options because of the large quantity consumptions of the materials, relatively low quality requirements and widespread construction sites. The main applications include a partial replacement for aggregate in asphalt concrete, as fine aggregate in unbond base course, pipe bedding, landfill gas venting systems and gravel backfill for drains [1]. Attempts have been made for a long time to try to use mixed waste glasses as aggregates in cement concrete, but it seems that the concrete with waste glasses always cracks [3–5]. Very limited work has been conducted for the use of ground glass as a cement replacement in concrete [6,7]. Recently, some attempts have been made to use the waste glasses as raw siliceous materials for the production of Portland cement [8,9]. The introduction of waste glasses in cement production will definitely increase the alkali content in the cement. It was also noticed it could result in flash setting due to the high alkali content and the formation of compound $2CaSO_4 \cdot K_2SO_4$ [9].

Glass beads are manufactured by crushing plate glasses and heating the graded particles at about 700 °C. Approximately 25% of the crushed glasses have diameters less than 300 μm. These waste glass powders come from two sources: from the screening of the crushed glasses and from collected dusts during glass

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crushing. They are too fine to be used. The objectives of this work are to investigate and compare the particle morphology of glass powders from different sources, their finenesses and pozzolanic reactivity for use as cement replacements.

2. Experimentation

2.1. Raw materials

2.1.1. Portland cement

A typical commercial Type I Portland cement that complies with the requirements of specification ASTM C 150 was used as a testing cement. Its chemical composition and relevant physical properties, as supplied by the manufacturers, are shown in Tables 1 and 2.

2.1.2. Coal fly ash

A commercial coal fly ash classified as Class F by ASTM C618 [10] was used as a reference material. The chemical composition and the physical properties of the fly ash, as supplied by the manufacturer, are summarized in Tables 1 and 2.

2.1.3. Glass powders

Four glass powders were obtained from a glass beads manufacturer in New York, USA. One is from the screening of crushed glasses (GP-fine), one from a dust collector for the crushing of glasses (GP-dust) and the other two, GP-4000 and GP-6000, from the grinding of GP-dust in a ball mill. Although the four glass powders have different finenesses, they have the same chemical compositions, as shown in Table 1. Compared with the coal fly ash, the glass powder has a higher SiO_2, CaO and Na_2O, but much lower Al_2O_3 contents. According to ASTM C618 and the chemical composition requirement, the coal fly ash can be classified as Class F ash, whereas the glass may be classified as Class N natural pozzolan if Na_2O content in these glass powders is not a concern.

Table 1
Chemical composition of raw materials

Oxide	Percentage by mass (%)		
	Portland cement	Coal fly ash	Glass
SiO_2	20.33	47.8	72.5
Al_2O_3	4.65	23.4	0.16
Fe_2O_3	3.04	15.1	0.2
CaO	61.78	3.36	9.18
MgO	3.29	0.81	3.65
SO_3	3.63	1.33	0.39
Na_2O	0.24	0.72	13.2
K_2O	0.59	1.7	0.12
Density (kg/m^3)	3150	2520	2470

Table 2
Physical properties of Portland cement and Class F fly ash

	ASTM Type I cement	Fly ash	ASTM C 618 for Class F fly ash
Specific gravity	3.15	2.52	–
Fineness			
Passing 325 mesh (%)	96.1	73.6	66 (min)
Specific surface area, Blaine (m^2/kg)	383	–	–
Compressive strength, mortar cubes (MPa)			
1-day	14.3	–	–
3-day	21.8	–	–
7-day	26.1		
28-day		–	–
Strength activity index with Portland cement (%)			
7-day	–	76.7	75 (min)
28-day	–		
Water requirement (% of cement control, max)		97.1	105
Soundness, autoclave expansion or contraction (%)	0.198	– 0.02	0.8 (max)

2.2. Experimental techniques

2.2.1. Examination of glass particle morphology under scanning electron microscope (SEM)

The morphology of glass particles was examined using a Personal SEM manufactured by R J Lee Instruments, USA. Glass powders were spread on a conductive double-edged adhesive tape and stuck to an SEM sample stud. Loose particles were dislodged with a blast of air. The samples were extensively viewed, then representative photographs were taken.

2.2.2. Fineness measurement of glass powders

Two techniques were used to measure the fineness of these glass powders: Blaine air permeability surface area measurement as per ASTM 204 [11] and particle size distribution analysis.

2.2.2.1. Blaine air permeability surface area. The principle of the Blaine air permeability measurement is based on measurement of the resistance of air when it flows through a given thickness of powder. The smaller the particle size of the powder, the narrower the space between the particles and the higher the resistance to air; thus it takes a longer time for air to pass through a layer of fine powder than a layer of coarse powder. According to ASTM C204, the specific surface area can be calculated by using the following equation:

$$S = \frac{S_s \rho_s (b - \varepsilon_s) \sqrt{\varepsilon^3} \sqrt{t}}{\rho (b - \varepsilon) \sqrt{\varepsilon_s^3} \sqrt{t_s}} \tag{1}$$

where S = specific surface area of the test material (m^2/kg); S_s = specific surface area of the standard cement used in calibration of the apparatus (m^2/kg); t = measured time interval of manometer drop for test material (s); t_s = measured time interval of manometer drop for standard cement (s); ε = porosity of a prepared bed of test material; ε_s = porosity of a prepared bed of standard cement; ρ = density of the test material (kg/m^3); ρ_s = density of standard cement (3150 kg/m^3); and b = apparatus constant related to characteristics of the samples tested.

The constant b varies with the nature of the materials tested. For Portland cement, a value of b = 0.9 is recommended in the ASTM C204. Three glass powders, GP-dust, GP-4000 and GP-6000, were used to determine the constant b for glass powder. A standard Portland cement with known specific surface area was tested first as the reference material.

2.2.2.2. Particle size distribution. The particle size distribution of these raw materials was measured by using a laser particle size analyzer.

2.2.3. Pozzolanic reactivity index

The pozzolanic activity of the four glass powders was evaluated based on ASTM C311 test method [12]. In the test mixtures, 20% of the mass of the cement was replaced by glass powder or fly ash. The mixture proportions and water requirements for these mortar mixtures are summarized in Table 3. The water-to-cement ratio for Portland cement is 0.485 as specified in ASTM C311. The water-to-cement ratios for other mixtures containing coal fly ash and glass powders were tested to reach a flow 110 ± 5 as of the control mixture. Since GP-fine is very coarse, it has the lowest water requirement. As the fineness of the glass increases, the water requirement of the mixtures increases. The mixture with fly ash also showed a lower water requirement due to its spherical particles and ball bearing effect of fly ash.

To understand the effect of curing temperatures on the strength activity index, elevated curing temperatures at 35 and 65 °C were also used for the samples made with GP-4000, in addition to the standard curing temperature of 23 °C.

Table 3
Mixing proportions and water-to-cementing material ratio for specified flow

Mixing batch	Cementing material	Water/cement ratio	Cement /sand ratio
PC	100% Portland cement	0.485	2.75
GP-fine	80% Portland cement + 20% GP-fines	0.465	2.75
GP-dust	80% Portland cement + 20% GP-dust	0.471	2.75
GP-4000	80% Portland cement + 20% GP-4000	0.480	2.75
GP-6000	80% Portland cement + 20% GP-6000	0.485	2.75
Fly Ash	80% Portland cement + 20% fly ash	0.471	2.75

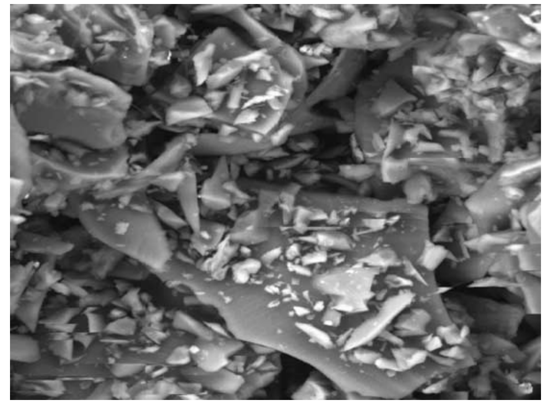

Fig. 1. Particle morphology of glass powders from a dust collector (× 1000).

2.2.4. Alkali–aggregate reaction (AAR) expansion

The effect of ground glass powder and fly ash on AAR expansion was evaluated by following ASTM C1260—an accelerated mortar bar method [13]. A known highly reactive siliceous limestone sand from Spratt quarry in Ottawa, Ontario, was used as AAR reactive aggregate in the test.

Three 25 × 25 × 275-mm mortar bars were cast for each batch. The mortar mixtures had an aggregate-to-cementitious material ratio of 2.25 and a water-to-cementitious material ratio of 0.47. Immediately after casting, the specimens with moulds were taken into a moisture room at 23 ± 2 °C and covered with a plastic sheet. They were demolded 24 ± 2 h after the casting and preconditioned for a further 24 h in water maintained at 80 ± 2 °C. The lengths of these mortar bars after immersion in the hot water were measured as initial lengths, and then the mortar bars were subsequently transferred to 1 M NaOH solution maintained at 80 ± 2 °C. The lengths of these mortar bars during immersion in the NaOH solution were periodically measured for 21 days. Presented length

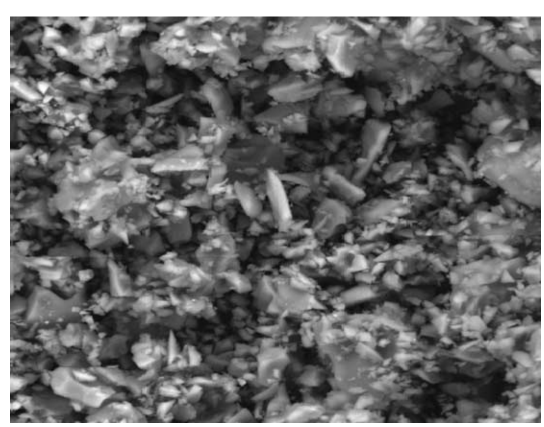

Fig. 2. Particle morphology of ground glass powder (× 1000).

Table 4
Data for the determination of Blaine fineness apparatus constant b for glass powders

Sample	Density, ρ (kg/m^3)	Desired porosity, (ε)	Mass of sample, W (g)	Recorded time, t (s)	$\sqrt{\varepsilon^3 t}$	Regression equation and specific surface area
GP-dust	2470	0.591	1.96	14.12	1.705	
		0.559	2.11	20.27	1.883	$\varepsilon = -0.2140\sqrt{\varepsilon^3 t} + 0.957$
		0.540	2.2	23.56	1.928	$\times\ (R^2 = 0.9791)$
		0.530	2.25	26.64	1.991	$S = 264$ m^2/kg
GP-4000	2470	0.559	2.11	29.45	2.269	
		0.530	2.25	41.59	2.488	$\varepsilon = -0.1251\sqrt{\varepsilon^3 t} + 0.843$
		0.501	2.39	60.43	2.754	$\times\ (R^2 = 0.9977)$
		0.469	2.54	85.61	2.975	$S = 467$ m^2/kg
GP-6000	2470	0.559	2.11	46.61	2.855	
		0.530	2.25	66.04	3.135	$\varepsilon = -0.0938\sqrt{\varepsilon^3 t} + 0.825$
		0.501	2.39	93.95	3.434	$\times\ (R^2 = 0.997)$
		0.469	2.54	140.55	3.812	$S = 582$ m^2/kg

change is an average of three identical mortar bars at each age.

3. Experimental results and discussion

3.1. Morphology of glass powders

SEM examinations indicated that the glass powders from the screening process or from a dust collector consist mainly of coarse and angular flaky particles with a broad particle size range, as shown in Fig. 1, whereas ground glass powders consist mainly of fine angular particles with a narrow particle size range, as shown in Fig. 2. Thus, glass powders have very different particle morphology from fly ash particles, which are mainly spherical. ASTM Type F fly ash particles have a clean surface, whereas there are deposits of various condensates, such as alkalis and sulphates, on the surface of Type C fly ash particles [14,15].

3.2. Fineness measurement of glass powder

3.2.1. Blaine fineness

The test data of Blaine are listed in Table 4. If the bed porosity ε is plotted vs. $(\varepsilon^3 t)^{1/2}$, three straight lines are obtained as shown in Fig. 3; the constant b for each pozzolan is the intercept of the relevant line. The results in Fig. 3 indicated that the two ground glass powders showed very close intercepts, whereas the intercept of the dust is significantly different from the two glass powders. The difference may be contributed to the use of the same density for all the three materials. Usually, coarse materials have a lower measured density than fine materials due to the possible entrapped air in coarse particles. Thus, the intercept from the dust was used as the b for the calculation of the Blaine fineness of the material, which is 264 m^2/kg. The average of the intercepts from the two ground glass powders was used as the b for the calculation of Blaine fineness of the two fine powders, which are 467 and 582 m^2/kg, respectively.

3.2.2. Particle size distribution

Fig. 4 shows the particle size distribution of the four glass powders. The particle size distributions of the ASTM Type I Portland cement and the coal fly ash are also plotted for comparison. It can be seen that the GP-fine from the screening process is very coarse and contains particles with size ranges from 40 to 700 μm. The GP-dust from the dust collector is finer than GP-fine, but still much coarser than Portland cement. Portland cement contains about 40% of particles smaller than 10 μm, while the GP-dust contains

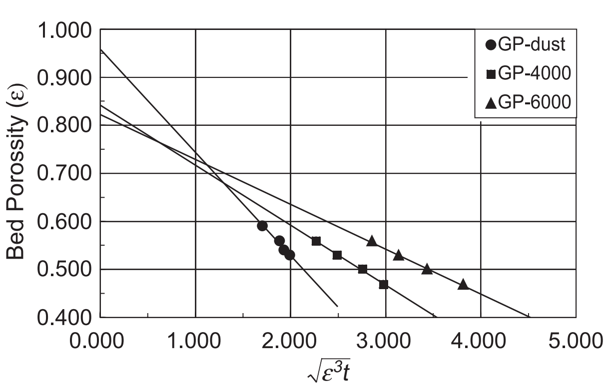

Fig. 3. Determination of apparatus constant b for glass powders.

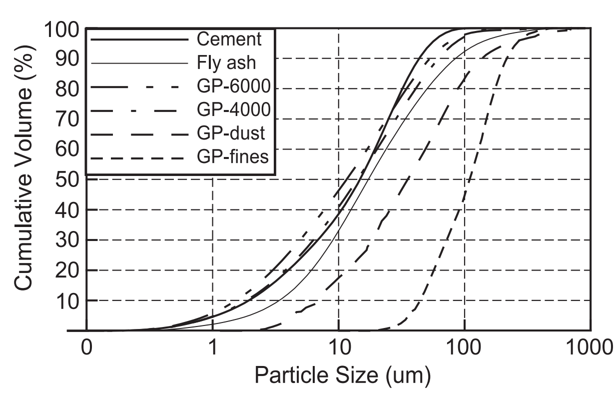

Fig. 4. Particle size distribution of glass powders and Portland cement.

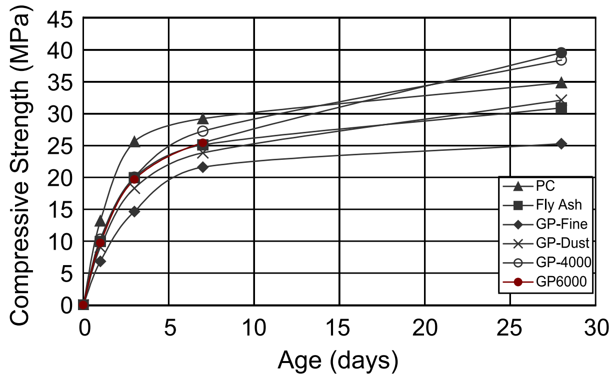

Fig. 5. Strength development of cement mortars at 23 °C.

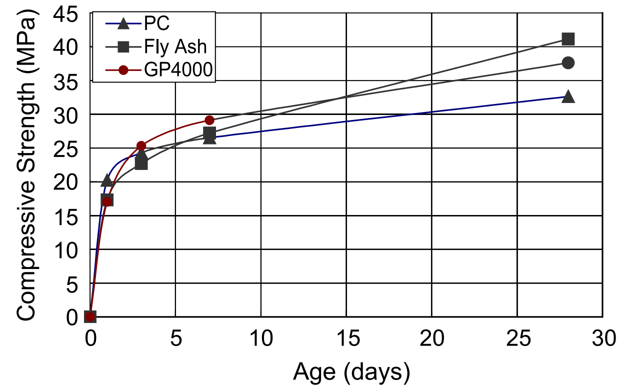

Fig. 7. Strength development of cement mortars at 35 °C.

only about 20% particles smaller than 10 μm. The particle size distribution curve of the fly ash is very similar to but slightly coarser than that of GP-4000.

The particle size distribution of GP-4000 is almost the same as that of Portland cement when particles are smaller than 30 μm. GP-4000 shows a coarser distribution than the Portland cement in size smaller than 30 μm. One obvious factor is that GP-4000 still contains some particles larger than 100 μm, whereas Portland cement does not.

Portland cement has a Blaine fineness of 383 m^2/kg, whereas GP-4000 has a Blaine fineness of 467 m^2/kg. The difference in Blaine fineness and particle size distribution may be attributed to the particles' shape rather than the size. Since glass is more brittle than Portland cement clinker, it is expected that ground glass contains more elongated particles than Portland cement does. This is probably why GP-4000 shows much higher Blaine fineness than Portland cement.

GP-6000 has finer particle size distribution than GP-4000 as expected. Compared with Portland cement, GP-6000 shows a finer particle size distribution in the portion of particles smaller than 50 μm, but a slightly higher portion of particles larger than 60 μm than Portland cement.

3.3. Pozzolanic activity of glass powders

The strength and strength activity index of these glass powders and coal fly ash at 23 °C are plotted in Figs. 5 and 6. It can be observed that GP-fines showed the lowest strength and the lowest pozzolanic strength activity index among the materials tested due to its coarse particles. Its pozzolanic strength activity index values were around 70% to 74% at 7 and 28 days, which are slightly lower than the minimum of 75% as specified in ASTM C618 for pozzolanic materials.

Although the particle size of GP-dust is much coarser than that of the fly ash, the pozzolanic strength activity index of the GP-dust was only slightly lower at 1 to 7 days, but higher at 28 days than the fly ash. It had a pozzolanic strength activity index of 82% at 7 days and 92% at 28 days. From strength aspect, it can be regarded as a good pozzolanic material. The only concern for using this material as a cement replacement in concrete is the potential alkali–aggregate reaction when an alkali reactive aggregate is used.

Although GP-6000 is finer than GP-4000, there is only marginal difference in pozzolanic strength activity index between them. However, GP-4000 and GP-6000 had pozzolanic strength activity index similar to or slightly higher than that of the fly ash from 1 to 7 days. At 28 days, the

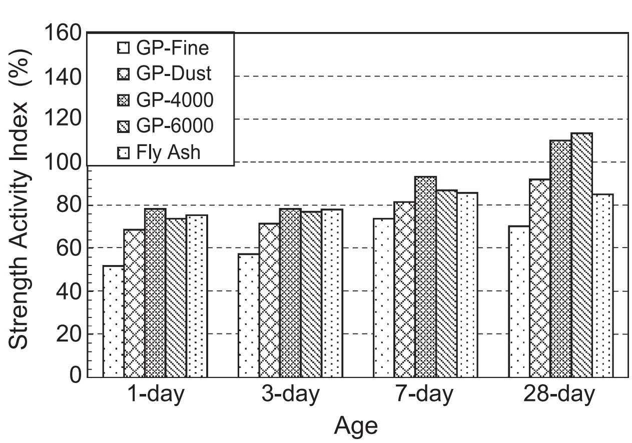

Fig. 6. Strength activity index of glass powders and fly ash at 23 °C.

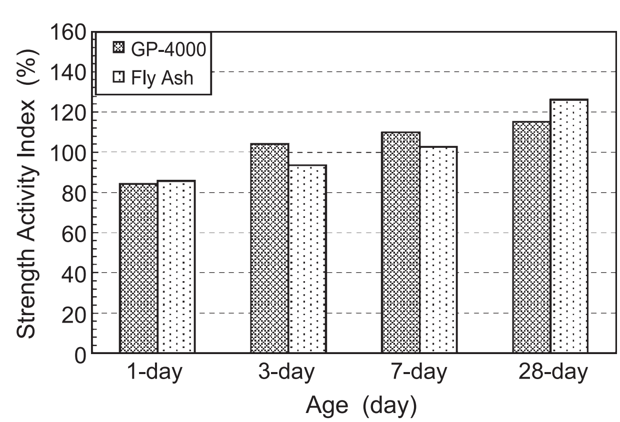

Fig. 8. Strength activity index of glass powder GP-4000 and fly ash at 35 °C.

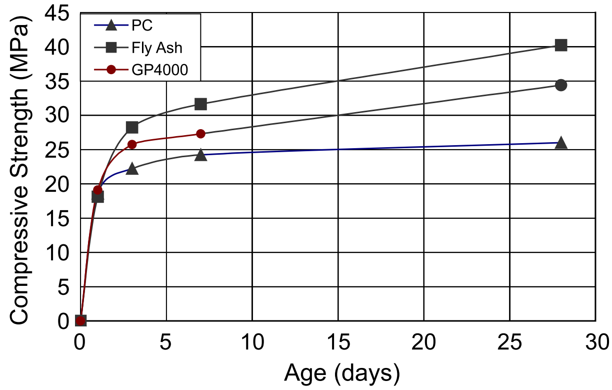

Fig. 9. Strength development of cement mortars at 65 °C.

pozzolanic strength activity index of GP-4000 and GP-6000 went up to around 110%, which is much higher than that of the fly ash (85%). This indicates that these two glass powders have very high pozzolanic reactivity; a replacement of 20% cement with ground glass powder can develop higher strength than 100% Portland cement at 28 days. Previous research has indicated that only a very small portion of fly ash is reacted in the Portland cement system during the first 90 days at room temperature [16,17]. The results here indicate that ground glass powders start to hydrate very significantly after 7 days at room temperature.

When the curing temperature is elevated to 35 or 65 °C, the pozzolanic strength activity index of both GP-4000 and fly ash increased significantly from 1 to 28 days, as shown in Figs. 7–10. The strength of the cement containing 20% fly ash or glass can develop strength similar to or even higher than 100% Portland cement at 7 days at 23 °C. Compared with the results at 23 °C, this means that elevating temperature is very beneficial in increasing the early strength of the cement or concrete containing coal fly ash and glass powders. This can be attributed to the higher apparent activation energy for the pozzolanic reactions between pozzolan and lime than that for the hydration of Portland cement.

The results here also suggest that coal fly ash and glass powders are very effective in enhancing the strength of cement and concrete, especially at elevated temperatures. As curing temperature was increased from 23 to 65 °C, the 7-day strength value of the pure Portland cement was decreased from 29 to 24 MPa, whereas GP-4000 increased from 27 to 30 MPa and fly ash changed from 25 to 32 MPa. The 28-day strength value changed from 35 to 26 MPa for cement control mixture, from 38 to 34 MPa for GP-4000 and from 30 to 40 MPa for fly ash, respectively. It was obvious that higher curing temperatures are deleterious for Portland cement, are more beneficial for glass powder only at early ages, but for the fly ash at all ages.

At 35 °C, GP-4000 showed similar pozzolanic strength activity index at 1 day, but higher at 3 and 7 days and lower at 28 days than the fly ash. As the temperature was further increased to 65 °C, GP-4000 only showed higher pozzolanic strength activity index at 1 day, and lower than the fly ash thereafter.

3.4. AAR expansion

Fig 11 shows the AAR-induced expansion results. Note that the replacement of Portland cement with 20% glass powder or Class F fly ash significantly reduced expansion. The control batch exhibited an expansion of 0.50% at 14 days. The replacement of cement with 20% GP-4000 reduced the expansion to around 0.20%, which is considered to be the upper limit of expansion for "potentially reactive" aggregate, whereas the replacement of cement with 20% fly ash decreased the expansion to less than 0.2% at 14 days. It is obvious that use of the fly ash is more effective in reducing the AAR expansion than GP-4000. Results have indicated 20% replacement of cement with coal fly ash is usually not enough to control deleterious expansion with reactive aggregate [18], but a minimum of 30% Class F fly ash is generally required [19]. Detailed laboratory studies [20] have confirmed that a minimum of 50% cement replacement with GP4000 is required to control deleterious expansion of mortars with reactive aggregates.

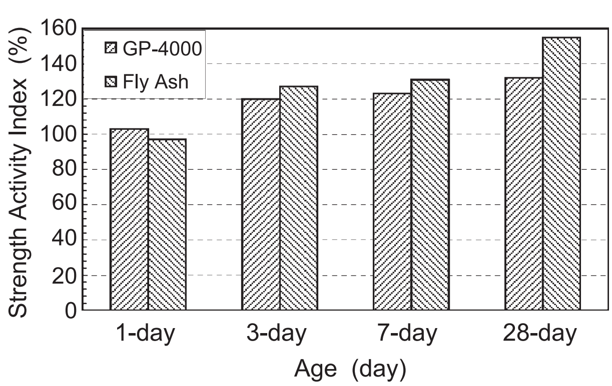

Fig. 10. Strength activity index of glass powder GP-4000 and fly ash at 65 °C.

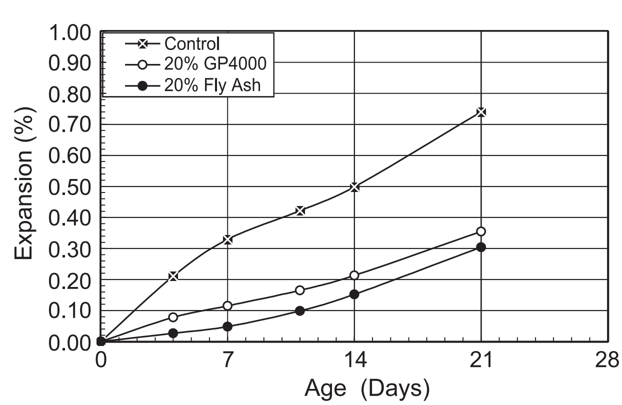

Fig. 11. AAR expansion of mortar bars.

4. Conclusions

Glass powders from crushing process consist mainly of large flaky particles, whereas glass powders from grinding process consist mainly of smaller angular particles. For a similar particle size distribution, ground glass powder showed an obvious higher Blaine specific surface area than Portland cement due to the angularity of the glass particles.

Finely ground glass powders exhibited very high pozzolanic activity. The finer the glass powder is, the higher its pozzolanic activity is.

An increase in curing temperature accelerates the activation of pozzolanic activity of both glass powder and coal fly ash. Mortar strength testing results indicated that curing temperature has a greater influence on the pozzolanic activity of glass powder than on that of fly ash.

Results from ASTM C1260 testing indicated that the replacement of Portland cement with ground glass powder also reduces the AAR-induced expansion, although it is not as effective as coal fly ash.

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