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Article

Comparison of Properties of Fresh and Hardened Concrete Containing Finely Ground Glass Powder, Fly Ash, or Silica Fume

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Abstract. Waste glass has potential for use in building materials, for example, as an aggregate replacement, a filler in concrete, or a cement replacement. Finely ground glass powder (particle size of less than 38 μm) can be used as a pozzolan material in concrete because of its high reactive silica content. This paper studied the properties of concrete containing finely ground glass powder (approximate particle size, 12 – 15 μm) of admixture Type D following ASTM C494. The fresh concrete's compressive strength, ability to resist chloride penetration, and free drying shrinkage were evaluated. The experiment showed that using 10% or 20% glass powder reduced the workability of fresh concrete and accelerated its setting time. However, concrete containing 10% finely ground glass powder exhibited greater compressive strength and improved resistance to the penetration of chloride ions than normal concrete and concrete containing fly ash at the same replacement level. Concrete with 10% glass powder also had lower shrinkage than normal concrete and concrete containing fly ash but higher shrinkage than concrete with 10% silica fume.

Keywords: Finely ground glass powder, free shrinkage, chloride resistance, fly ash, silica fume compressive strength development.

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1. Introduction

Pozzolan is an additive used in concrete to improve its quality, for example, to improve the workability, reduce the temperature rise during initial hydration, and improve the strength development and durability of concrete materials [1–4]. Several types of pozzolan are widely used, such as natural pozzolan, fly ash, blast furnish slag, and silica fume (microsilica) [4].

Many studies have shown that waste glass has potential for use in building material, for example, as an aggregate replacement, a filler in concrete, or a cement replacement [5–13]. Specifically, finely ground glass powder (particle size of less than 38 μm) has potential for use as pozzolan, and glass powder has more reactive silica than fly ash, which is the most commonly used pozzolan in Thailand [14]. In addition, glass powder tended to improve the compressive strength more if it was more finely ground [6].

In Thailand in 2009, there were almost 1.76 million metric tons of waste glasses in the waste system, and only 1.28 million metric tons, or 73%, were reused and recycled [15]. Not all of the waste glass can be recycled because of impurities or mixed colors, and the remainder of the waste glass was mostly land-filled. [7]. Systems for collecting, cleaning, sieving, and recycling waste glass exist in Thailand, and many recycling companies are located throughout the country [11]. The use of waste glass in concrete as an additive material can reduce the amount of waste glass in the waste system and increase the available pozzolanic materials in the country.

This research studies the properties of concrete made with 10% or 20% finely ground glass powder (average particle size, 12–15 μm) and compares them with those of concrete containing 10% or 20% fly ash and 10% silica fume by testing the setting time, slump, and compressive strength development of concrete at 1, 3, 7, 14, and 28 days and the durability of concrete, including its ability to resist chloride penetration and free drying shrinkage.

2. Material Properties

2.1. Cement

Type I ordinary Portland cement conforming to ASTM C150 was used in this study. The physical properties and chemical composition of the cement materials are shown in Tables 1 and 2, respectively. The shape of the cement particles is shown in Fig. 1(a).

2.2. Additive Materials

2.2.1. Glass Powder

The waste glass used in this study was soda-lime clear glass from used soda bottles. Crushed waste glass 2.5 cm in size was ground in a ball mill grinder until the mean particle size, as measured by a particle size distribution machine, was between 12 and 15 μm. The particle size was calculated using Fraunhofer's equation with the D(4, 3) method.

2.2.2. Fly Ash

The fly ash used in this study was obtained from the Mae Moh electrical power plant in the north of Thailand.

2.2.3. Silica Fume

The silica fume used in the study is the densified type following ASTM C1240-05 [16].

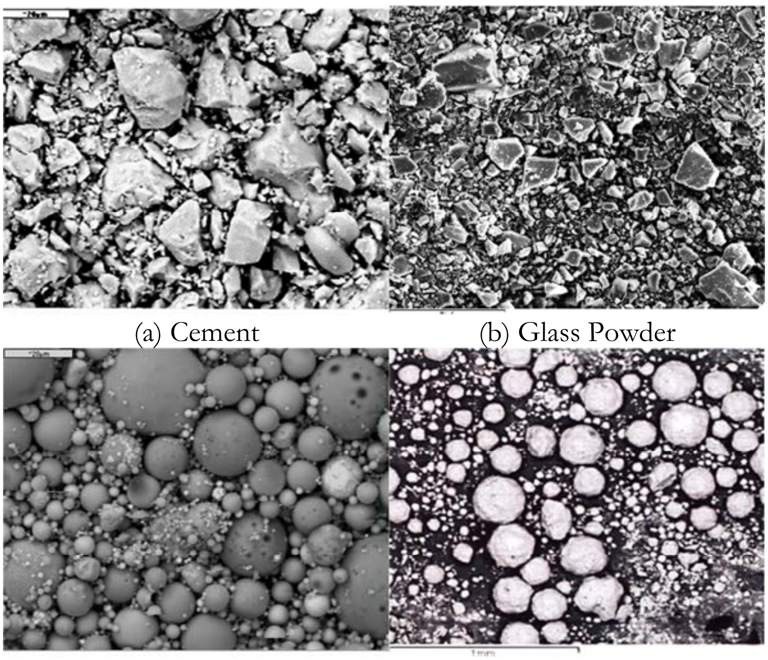
The physical properties and chemical composition of the additive materials are shown in Tables 1 and 2, respectively. The shapes of the additive materials are shown in Fig. 1(b)–1(d).

Table 1. Physical properties of ordinary Portland cement (OPC), glass powder (GP), fly ash (FA), and silica fume (SF) used in this study.

Physical properties	**OPC**	**GP**	**FA**	**SF**
Specific Gravity	3.15	2.51	2.36	2.28
Mean Diameter (μm)	26.06	12.3	26.39	234.48
Wet Sieve Passing 325 Mesh (% mass)	-	100	66.2	92.1

Table 2. Chemical composition of cement, glass powder, fly ash, and silica fume used in this study obtained by X-ray fluorescence spectrometry.

Oxide % By Weight	**OPC**	**GP**	**FA**	**SF**
SiO_2	19.74	65.66	41.18	87.34
Al_2O_3	5.14	1.32	22.06	0.77
Fe_2O_3	3.15	0.14	12.03	4.09
CaO	64.95	11.42	14.89	1.03
MgO	0.90	1.98	2.69	1.18
SO_3	2.51	0.21	2.52	0.35
LOI	2.47	-	0.21	3.53
Na_2O	0.13	18.87	1.15	0.02
K_2O	0.52	0.25	2.33	0.93
Free CaO	0.71	-	0.22	0.01



(a) Cement (b) Glass Powder

(c) Fly Ash (d) Silica Fume

Fig. 1. Scanning electron microscopy images showing particle shapes of (a) cement, (b) glass powder, (c) fly ash, and (d) silica fume.

2.3. Aggregate

The coarse aggregate used in this study was crushed limestone with a maximum nominal size of 19 mm. The coarse aggregate absorption was 0.75%. The fine aggregate was natural river sand with a fineness modulus of 2.65. The maximum size was 4.75 mm. The aggregate absorption value was 0.51%.

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2.4. Chemical Admixture

This study used water-reducing and -retarding chemical admixtures of Type D following ASTM C494 [17]. The chemical admixture used in the experiment was a hydroxylated organic base. The specific gravity of the admixture was 1.15. The type D admixture was used to delay the setting time of concrete for concreting in hot weather and for extending the delivery time of ready-mixed industrial concrete in Thailand. The dosage of the chemical admixture used in this study is 4 cc/1 kg cement.

3. Experimental Methodology and Concrete Mix Proportions

3.1. Fresh Concrete Properties

To ensure that concrete containing glass powder can be used in the ready-mixed concrete production process, the fresh concrete properties (setting time and slump) were tested before casting to compare the workability of the mix designs. The mix proportions of the fresh concrete used in the property testing are shown in Table 3.

The setting time test followed ASTM C403 [18], and the slump test followed the ASTM C143 standard test method [19].

In Thailand, the standard delivery time for ready-mixed concrete is 30–60 min. Thus, in this study the slump test was conducted in the initial stage, at 30 min and 60 min.

Table 3. Proportions of concrete mixtures used in tests of setting time, slump, and compressive strength (kg/m^3).

W/B	Mix	OPC (kg)	GP (kg)	FA (kg)	SF (kg)	Water (kg)	Sand (kg)	Rock (kg)	Type D (cc)
0.67	OPC	300	0	0	0	200	820	1080	1200
	FA10	270	0	30	0	200	800	1080	1080
	FA20	240	0	60	0	200	800	1080	960
	GP10	270	30	0	0	200	810	1080	1080
	GP20	240	60	0	0	200	800	1080	960
	SF10	270	0	0	30	200	820	1080	1080
0.50	OPC	400	0	0	0	200	760	1050	1600
	FA10	360	0	40	0	200	750	1050	1440
	FA20	320	0	80	0	200	750	1050	1280
	GP10	360	40	0	0	200	750	1050	1440
	GP20	320	80	0	0	200	750	1050	1280
	SF10	360	0	0	40	200	250	1050	1440
0.40	OPC	500	0	0	0	200	700	1020	2000
	FA10	450	0	50	0	200	690	1020	1800
	FA20	400	0	100	0	200	690	1020	1600
	GP10	450	50	0	0	200	700	1020	1800
	GP20	400	100	0	0	200	690	1020	1600
	SF10	450	0	0	50	200	690	1020	1800

3.2. Hardened Concrete Properties

3.2.1. Compressive Strength

For the compressive strength test, cubic concrete specimens 10 × 10 × 10 cm^3 in size, in accordance with BS-EN 12390-2:2000 [20], were prepared and tested at 1, 3, 7, 14, and 28 days. The mixture proportions contained 10% or 20% glass powder, 10% or 20% fly ash, or 10% silica fume. The water-to-binder ratio (W/B) was 0.40, 0.50, or 0.67. Before compressive strength testing, the specimens were placed in water at 20°C for curing. The concrete mix proportions used for this test are shown in Table 3.

3.2.2. Ability to Resist Chloride Penetration

To compare the ability to resist chloride penetration, quick tests were conducted in accordance with ASTM C1202 [21]. Before the experiment, each specimen was submerged in water for 14 and 28 days. The concrete mix proportions used in this test are shown in Table 4.

3.2.3. Drying Shrinkage

Drying shrinkage testing was conducted on a prism size of 7.5 × 7.5 × 28 cm^3 in accordance with AS 1012.13-1992 [22]. Each specimen was cured in a lime-saturated solution for 7 days and then stored in a control chamber at 23±1°C and a humidity of 45%–55%. The specimen length was measured until the specimens were 75 days old. The concrete mix proportions used in this test are shown in Table 4.

Table 4. Proportions of concrete mixtures used in durability tests (kg/m^3).

W/B	Mix	OPC (kg)	GP (kg)	FA (kg)	SF (kg)	Water (kg)	Sand (kg)	Rock (kg)	Type D (cc)
0.67	OPC	300	0	0	0	200	820	1080	1200
	FA10	270	0	30	0	200	800	1080	1080
	FA20	240	0	60	0	200	800	1080	960
	GP10	270	30	0	0	200	810	1080	1080
	GP20	240	60	0	0	200	800	1080	960
	SF10	270	0	0	30	200	800	1080	1080
0.44	OPC	450	0	0	0	200	740	1030	1800
	FA10	405	0	45	0	200	720	1030	1620
	FA20	360	0	90	0	200	720	1030	1440
	GP10	405	45	0	0	200	730	1030	1620
	GP20	360	90	0	0	200	720	1030	1440
	SF10	405	0	0	45	200	720	1030	1620

4. Experimental Results

4.1. Fresh Concrete Properties

4.1.1. Setting Time

The measured stiffening and initial setting times of each mixture are shown in Figs. 2–4. When the cement in concrete was replaced with glass powder, fly ash, or silica fume, the initial setting time was found to be reduced significantly compared to that of OPC concrete. Concrete with silica fume had the fastest setting time, whereas concrete containing glass powder had roughly the same setting time as concrete containing fly ash at the same replacement level. Thus, in concrete production, if the same setting time is needed, the dosage of the admixture and the water amount should be adjusted.

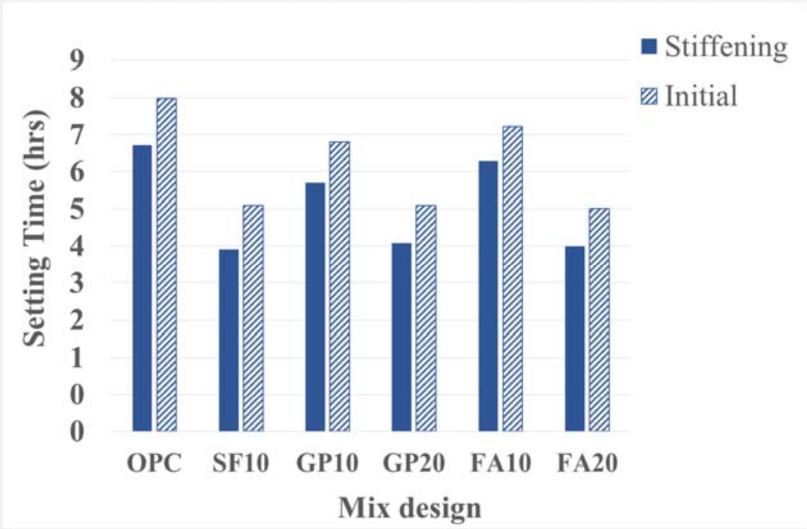

Fig. 2. Stiffening and initial setting time of mix design W/B 0.67.

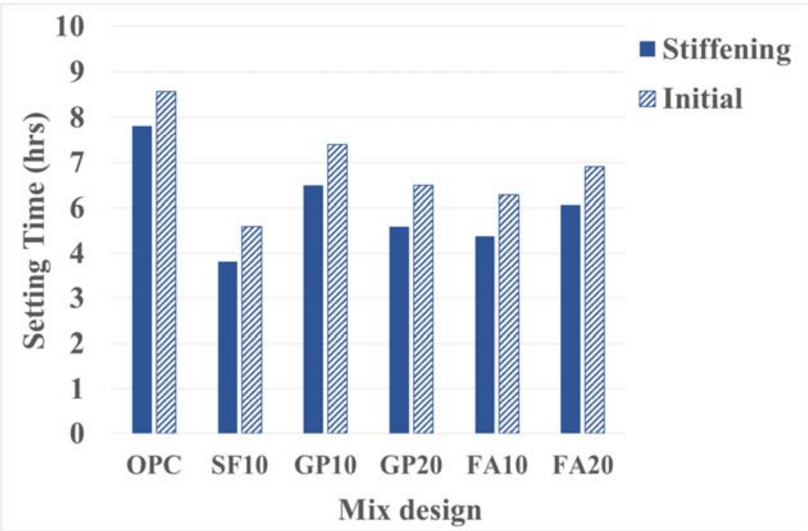

Fig. 3. Stiffening and initial setting time of mix design W/B 0.50.

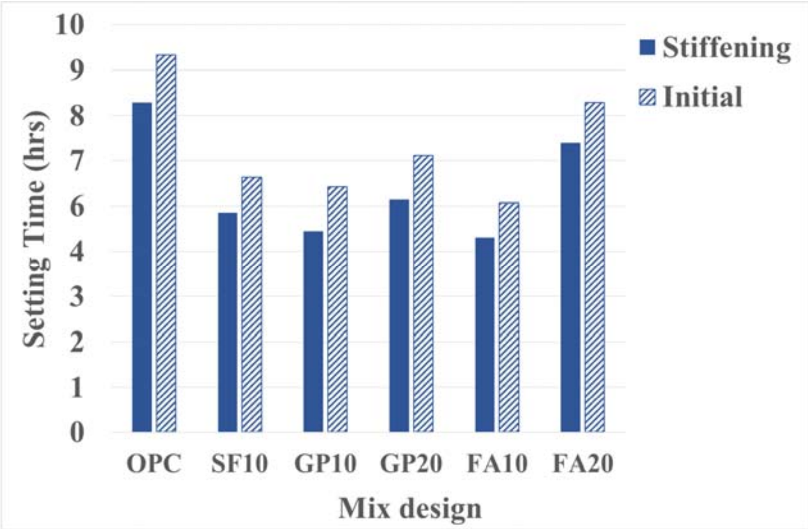

Fig. 4. Stiffening and initial setting time of mix design W/B 0.40.

4.1.2. Slump and Slump Retention

Figs. 5–7 show the slump values of each concrete mixture in the initial stage and after mixing for 30 min and 60 min. The results show that concrete that contains fly ash as an additive has a higher initial slump than normal concrete. When concrete has the same amount of water and same chemical admixture dosage, fly ash can increase the initial workability after mixing. However, the slump value after 30 min remains the same as that of normal concrete. A previous review reported that fly ash can reduce the friction between cement and aggregates, resulting in greater workability of fresh concrete [4] in the initial stage.

For concrete containing glass powder and silica fume, the slump values decreased, especially at 30 min and 60 min. The slump values were lower when a higher proportion of glass powder was used. This is because the sharp, irregular geometric forms of the glass particles may increase the frictional force between the particles, decreasing the fluidity [11].

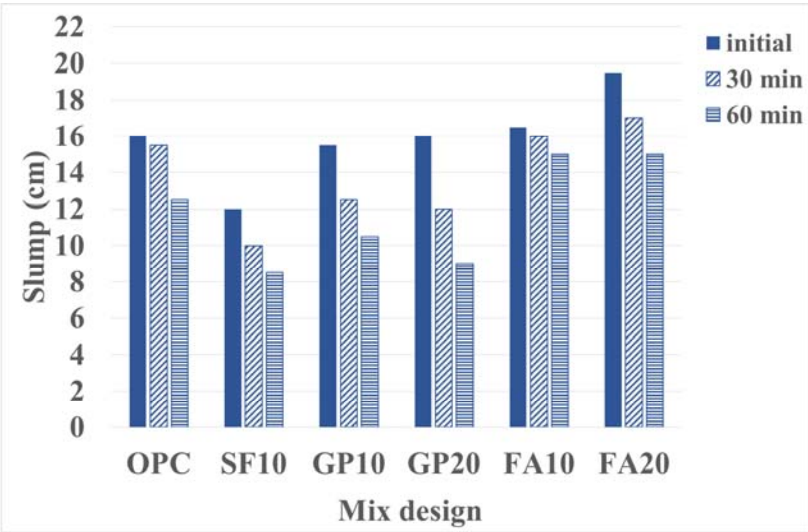

Fig. 5. Slump of mix design W/B 0.67.

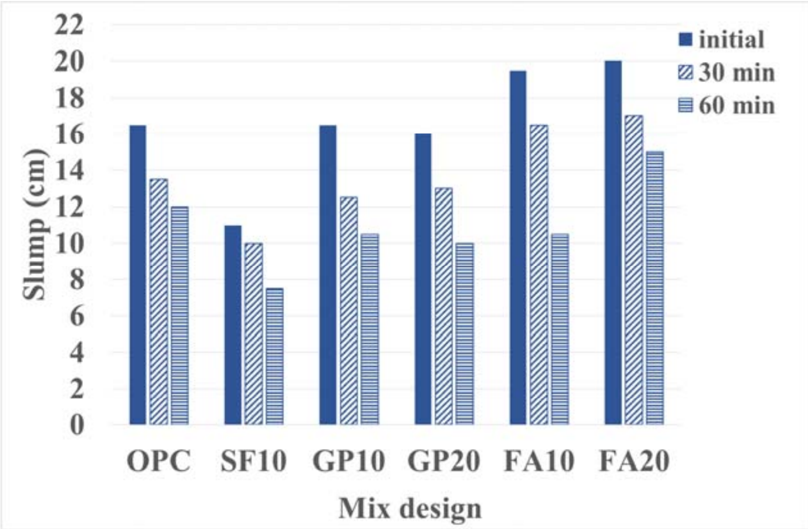

Fig. 6. Slump of mix design W/B 0.50.

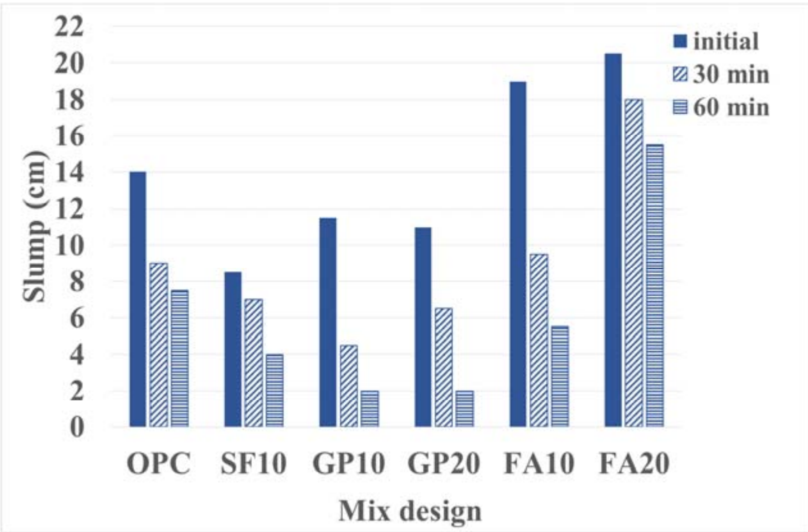

Fig. 7. Slump of mix design W/B 0.40.

4.2. Hardened Concrete Properties

4.2.1. Compressive Strength

Figs. 8–10 show the compressive strength development for all the concrete mixtures. The compressive strength of concrete with 10% finely ground glass powder as the cement replacement seems to be higher than that of pure cement at 1 and 28 days and greater than that of the other mixtures.

The glass powder used in this study had smaller particles than the other cementitious materials; therefore, these small particles can fill the space between the particles in the concrete and improve the compressive strength at 1 day. Furthermore, a previous review reported that glass powder has a smooth surface that does not absorb water inside concrete. Therefore, the negligible water absorption of glass powder can provide more water for cement hydration in the early stage, which might increase the compressive strength [5].

The testing results show that the compressive strength of concrete containing glass powder, fly ash, and silica fume tends to increase after 28 days. However, for the OPC concrete without a pozzolan material, the rate of strength development decreased after 28 days.

The results show that adding 10% glass powder to the concrete improved the compressive strength more than adding fly ash at the same replacement level, and concrete containing 20% glass powder exhibits the same level of strength development as that containing 20% fly ash.

The experimental results also showed that adding 10% or 20% glass powder cannot improve the strength development at 3–28 days as much as adding silica fume. Note that the strength of concrete containing 10% glass powder at an age of 1 day is the same as or slightly higher than that of concrete containing densified silica fume because of the filler effect.

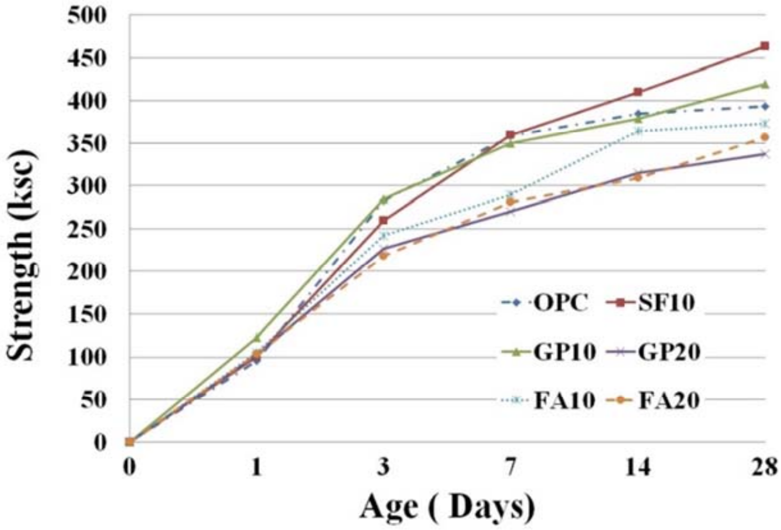

Fig. 8. Compressive strength of concrete W/B 0.67.

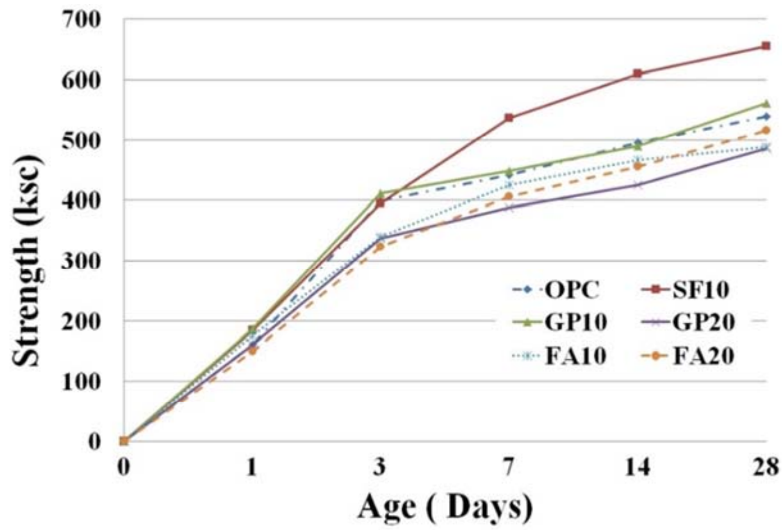

Fig. 9. Compressive strength of concrete W/B 0.50.

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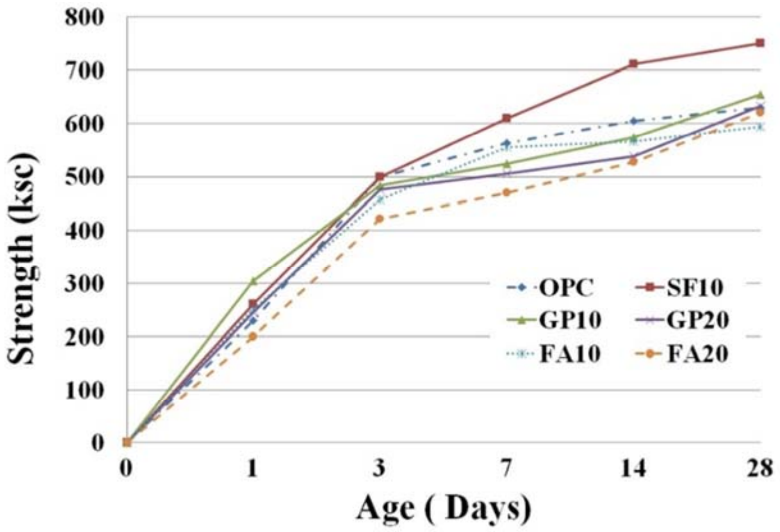

Fig. 10. Compressive strength of concrete W/B 0.40.

4.2.2. Ability to Resist Chloride Penetration

Figs. 11 and 12 show the Coulomb charge passed through the concrete specimens by chloride ions. For the 14-day-old specimens, the testing results show that adding pozzolan can reduce the Coulomb charge passed through the concrete.

The reduction in the charge passed by concrete with 10% glass powder was roughly the same as that of concrete containing 10% fly ash, but concrete with 20% glass powder showed a greater reduction in the charge passed than concrete containing fly ash at the same replacement level in both W/B 0.67 and 0.44.

The charge passed is lower at 28 days than at 14 days for all the mixtures. The results show that concrete containing glass powder can exhibit lower Coulomb charge and has a lower value than concrete containing fly ash at the same replacement level in both W/B 0.67 and 0.44. However, the glass powder cannot reduce the value to that of concrete containing silica fume.

The testing results show that the glass powder increased the ability to resist chloride penetration at 28 days to about the same degree as fly ash at the same replacement level.

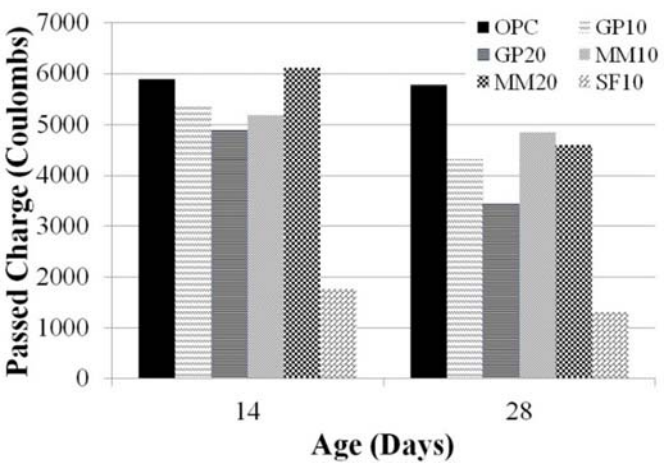

Fig. 11. Coulomb charge passed through concrete W/B 0.67.

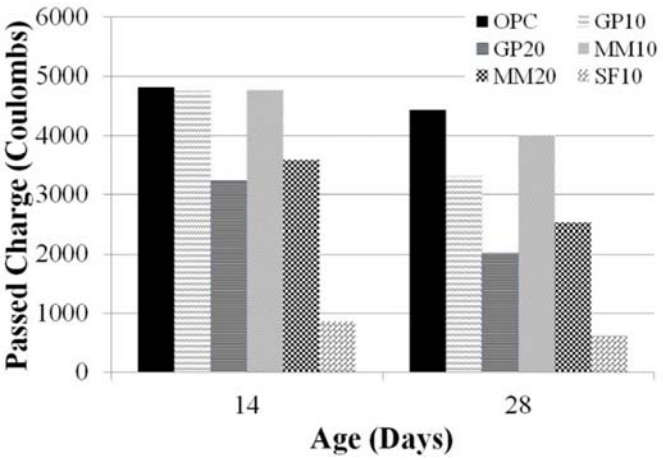

Fig. 12. Coulomb charge passed through concrete W/B 0.44.

4.2.3. Drying Shrinkage

Figs. 13 and 14 show the drying shrinkage values obtained in this study. The results show that concrete containing 10% glass powder had lower shrinkage than all the other mixtures used in this study at 28 days, but at 75 days, the concrete containing silica fume had the lowest value for both W/B 0.67 and 0.44.

For concrete W/B 0.67 at 75 days, the concrete without pozzolan had the highest shrinkage for all the mixture proportions, and the concrete containing glass powder had lower shrinkage than that containing fly ash at the same replacement level. However, the use of glass powder cannot reduce the shrinkage as well as the use of silica fume.

For concrete W/B 0.44 at 75 days, concrete with 10% glass powder had lower shrinkage than concrete containing fly ash at the same replacement level. However, concrete containing 20% glass powder had higher shrinkage than that with 20% fly ash.

As mentioned above, a previous review reported negligible water absorption by glass powder (less than that by fly ash); therefore, glass powder can provide more water for cement hydration [5]. Consequently, the hydrated product in concrete will be increased, and the water in capillary pores will be reduced.

Drying shrinkage in concrete occurs because of the evaporation of water in concrete. Concrete with less water in the pores and a higher hydrated product tends to exhibit lower shrinkage.

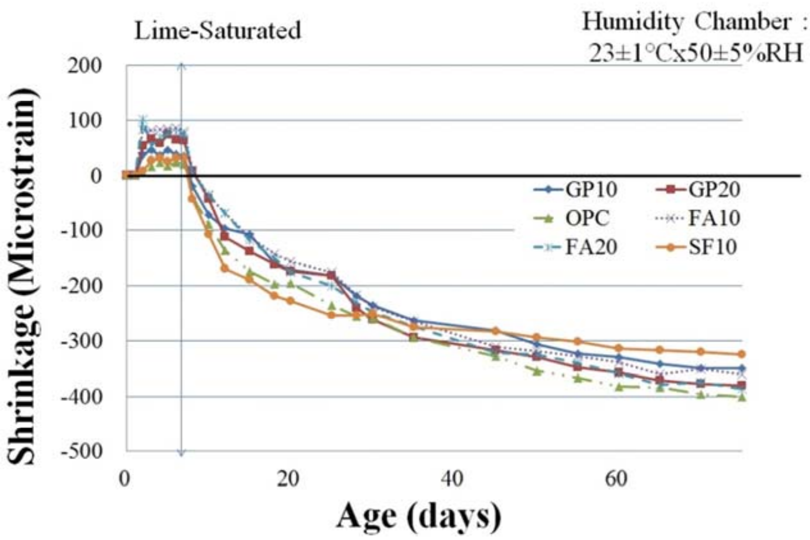

Fig. 13. Drying shrinkage of concrete W/B 0.67.

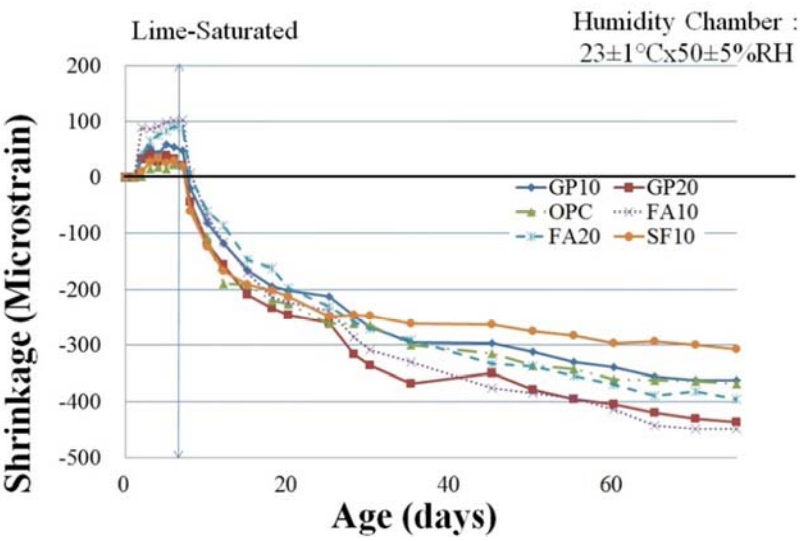

Fig. 14. Drying shrinkage of concrete W/B 0.44.

5. Conclusion

This study showed that concrete containing glass powder has a shorter setting time and lower slump than normal concrete and concrete containing fly ash. Thus, for application at a construction site, the dosage of the chemical admixture should be adjusted to maintain the same level of workability and working time.

Concrete containing 10% finely ground glass powder (approximate mean diameter, 12–15 μm) exhibited greater compressive strength at an age of 1 day. Glass powder can be used as a cementitious additive in concrete and can perform as well as fly ash at the same replacement level in terms of the compressive strength, but glass powder cannot improve the strength level as much as silica fume can. Furthermore, glass powder can improve the ability to resist chloride ions. The testing results show that glass powder can reduce the Coulomb charge passing through the concrete better than fly ash at the same replacement level at ages of 14 and 28 days.

Glass powder (10%) can reduce the amount of drying shrinkage after 75 days compared with that of pure cement concrete and concrete containing fly ash at the same replacement level when the mixture proportion has the same amount of binder and water, but concrete with 10% silica fume can reduce the amount of shrinkage better than concrete with glass powder at the same replacement level.

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