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Properties of concrete incorporating fly ash and ground granulated blast-furnace slag

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Abstract

This paper presents a laboratory study on the influence of combination of fly ash (FA) and ground granulated blast-furnace slag (GGBS) on the properties of high-strength concrete. A contrast study was carried out for the concrete (GGFAC) incorporating FA and GGBS, control Portland cement concrete and high-volume FA high-strength concrete (HFAC). Assessments of the concrete mixes were based on short- and long-term performance of concrete. These included compressive strength and resistance to H_2SO_4 attack. The microstructure of the concretes at the age of 7 days and 360 days was also studied by using scanning electron microscope. The results show that the combination of FA and GGBS can improve both short- and long-term properties of concrete, while HFAC requires a relatively longer time to get its beneficial effect.

Keywords: Ground granulated blast-furnace slag; Fly ash high-strength concrete; Sulfate attack; Strength; Scanning electron microscope

1. Introduction

High-strength concrete has been widely used. Achieving adequate levels of durability in order to improve the performance and reduce the life cycle costs of concrete structures continues to be a serious problem for engineers. Benefits, in terms of high-strength concrete durability, of using additional binder materials are well established and the use of fly ash (FA) is now considered commonplace [1–4]. FA, a by-product of thermal power stations, is a most available supplementary cementing material worldwide. There are approximately 600 million tonnes of fly ash available nowadays [5], which indicates that there is a potential for the use of much larger amounts of FA in concrete. Unfortunately, due to the slow rate of hydration of FA, the concrete with high-volume FA has lower strength and lower durability performance than control Portland cement concrete (PCC) at early ages [6–8]. This limits the wide use of high-volume FA concrete by engineers. Some attempts were made to increase the early-age properties of the high-volume FA concrete by incorporating some activators and early-strength agents or small percentage (3% and 8.5%) of silica fume in the system [9–12]. However, activators and early-strength agents are generally alkaline substances, which may lead to alkali-silica reaction [9]. At the same time, studies have shown that the use of silica fume did not significantly affect the early-age properties of the high-volume FA high-strength concrete (HFAC) [10,11]. In this paper, an effort is made to investigate the influence of combination of FA and ground granulated blast-furnace slag (GGBS) on the strength development of concrete.

Environmental conditions may greatly affect the durability of concrete. One of the most aggressive environmental agents is sulfate (soil, groundwater and seawater). Presently, the sulfate attack on the concretes up to the age of 1 year was also studied by immersing them into 2% H_2SO_4 solution at room temperature, and the mechanical parameters (i.e. the weight change and the change in compressive strength) were evaluated.

2. Experimental program

2.1. Materials

The cementitious materials used in this test were Portland cement, Fly ash and GGBS. Their chemical

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Table 1
Chemical and physical properties of cement, FA and GGBS (%)

	Cement	FA	GGBS
Specific gravity	3.05	2.43	2.79
Compressive strength, 28 day, MPa	56.7	–	–
Pozzolanci activity index, 28 day, %	–	85.4	106.3
Specific surface, Blaine, m^2/kg	392	565	599
SiO_2	20.6	63.5	34.4
Al_2O_3	4.0	11.1	9.0
Fe_2O_3	3.1	5.2	2.58
CaO	62.8	14.7	44.8
MgO	2.6	1.98	4.43
SO_3	3.1	0.35	2.26
Na_2O	–	0.48	0.62
K_2O	–	0.4	0.5
LOI	1.8	2.1	1.32

compositions and physical properties are given in Table 1. Coarse aggregate was crushed wacke-rock with a maximum size of 20 mm and a specific gravity of 2.70. The fine aggregate was natural sand with a fineness modulus of 2.35 and a specific gravity of 2.50. Details of the mix proportions for concretes are given in Table 2. The control mix was cast using Portland cement, while the other mixes were prepared by replacing part of the cement with different mineral admixtures on mass-for-mass basis. The same water/binder ratio of 0.28 was used for the concrete mixes with different amount of superplasticiser so that the fluidity of concretes did not change due to the effect of the different mineral admixtures.

2.2. Test procedure

All concrete mixtures were mixed in a pan mixer, following the procedures recommended by Chinese Standard JGJ 55-81. After mixing a vibrating table was used to ensure good compaction. The surface of the concrete was then smoothed, and wet cloth was used to cover the concrete until the specimens were demolded 1 day after casting.

Compressive strength tests were carried out on 150 mm cube specimens, according to Chinese Standard GB-8185. In the experiment, moist curing was applied to the specimens. The specimens were dried 24 h prior to testing for every mix at the required age, and the average strength of three specimens was used as an index.

The resistance to acid attack was carried out according to Chinese Standard GBJ82-85. The specimens with a size of 100 × 100 × 300 mm were immersed in 2% H_2SO_4 solution at room temperature after 3 days of moist curing. The solution was stirred every day and changed at intervals of 30 days. The surface of concrete was brushed at intervals of 7 days using a steel brush, and then the weight of the specimen was determined. The weight change (i.e. the ratio between the weight loss and the original weight) was used as an index. Compressive strength of the concretes was measured after 1, 4, 8, 16, and 50 weeks immersion in H_2SO_4 solution. At each test age, three specimens stored in water and three stored in H_2SO_4 solution were tested. The relative strength was calculated as the ratio between the concrete strength in H_2SO_4 solution and the concrete strength in water.

In order to give an explanation for the properties of the concrete incorporating FA and GGBS from a microscale view, a tentative study was made using scanning electron microscope (SEM). Six samples with a size of $1 \times 1 \times 1$ cm^3 from each mix were prepared for the analysis. Three of them were taken at 7 days, and the other three at 360 days. All samples were put into pure alcohol before test. The samples were gold-coated and then observed under the H-1030 SEM.

3. Experimental results

3.1. Development of compressive strength

Fig. 1 shows the strength development of PCC, HFAC (containing 40% of FA) and the concrete (GGFAC) incorporating a combination of 25% FA and 15% GGBS. From this figure, we can see the general trend of increasing strength with age up to 1 year for all concretes. As expected, the behavior of HFAC at early ages is different from that of PCC and GGFAC. Though it has the highest strength at the end test age, its strength is the lowest before 56 days. The strength development of GGFAC is similar to that of PCC, only with slightly lower values before 28 days. This indicates that GGFAC can achieve adequate early compressive strength, while maintaining a high long-term strength.

Table 2
Mix proportions of concretes kg/m^3

Binder combination	Binder				Water	Aggregate		W/Binder[a]	Super plasticizer dosage[b]
	PC	FA	GGBS	Total		Fine	Coarse		
PCC	500	–	–	500	140	659	1162	0.28	1.7
HFAC	300	200	–	500	140	644	1135	0.28	1.5
GGFAC	300	125	75	500	140	647	1140	0.28	2.0

[a] Water/Binder (i.e. PC plus additional materials) ratio.

[b] Dosages given as percent of total binder content by mass.

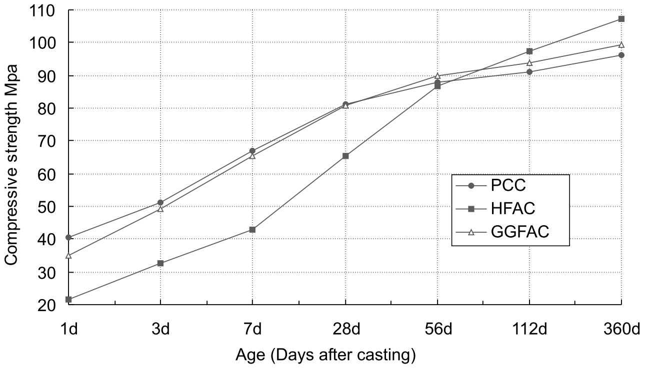


Fig. 1. Development of the compresive strength versus time.

Table 3 shows the strength gain of the concretes between 28 days and 1 year. PCC obtains a strength increase of 18.7% during this period. The compressive strength of GGFAC increases 23.3%, higher than that of PCC, but lower than that of HFAC.

3.2. Chemical corrosion in H_2SO_4 solution

3.2.1. Compressive strength

Test results of the compressive strength are reported in Table 4. The strengths of both GGFAC and HFAC increase with increasing immersion period in H_2SO_4 solution. However, GGFAC demonstrates a higher early-strength than HFAC. The strength of PCC increases before 8 weeks, but decreases with continued exposure to H_2SO_4 environment. For both the short- and long-term strengths, GGFAC is the highest.

Fig. 2 shows the change of the relative strength (the ratio between strength in H_2SO_4 solution and the strength in water). It is shown that the relative strengths for all concretes decrease with increasing exposure to H_2SO_4 solution, but their amplitudes of decrease are different. For PCC, the relative strength decreases rapidly and reaches a minimum of 80.1% at the test end. The relative strength of HFAC shows a gradual drop and reaches a value as low as 86.7% at 50 weeks, which is significantly smaller than that of GGFAC.

Table 4
Compressive strength of concretes in H_2SO_4 solution

	1 week	4 weeks	8 weeks	16 weeks	50 weeks
PCC	48.6	78.5	83.2	82.7	78.1
HFAC	36.4	67.2	85.8	88.9	96.8
GGFAC	49.8	80.1	87.2	90.3	97.2

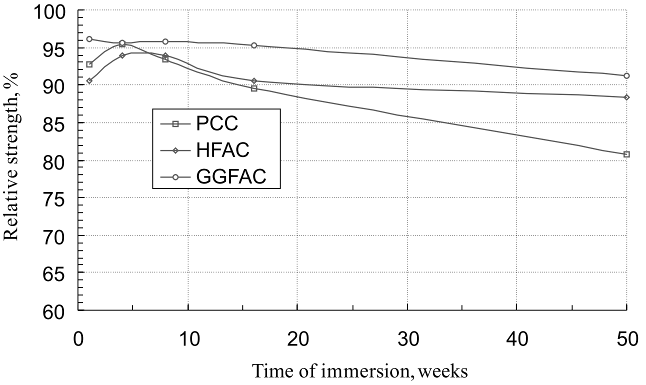


Fig. 2. The realtive strength of concretes at selected ages.

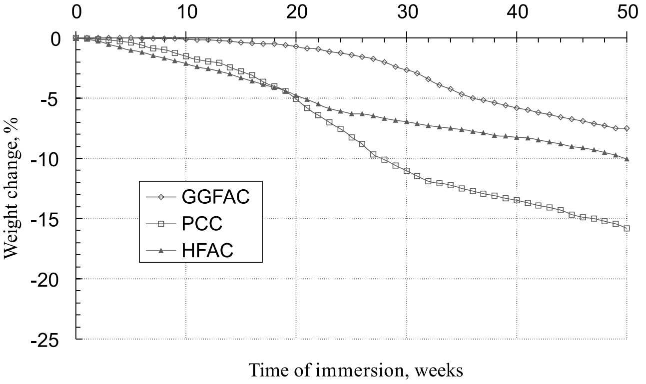


Fig. 3. Weight change of concentrates in 2% H_2SO_4 solution.

3.2.2. Weight change

Fig. 3 depicts the test results of weight change versus time for the concretes. There is a relatively large amount of weight change associated with PCC, which increases at a rapid rate initially (~32 weeks) and is followed by a relatively slow rate. The total change of PCC after 50 weeks exposure to H_2SO_4 solution is about 16%. For HFAC, the weight change is comparable to that of PCC before 20 weeks. Then, it increases gradually and reaches the value of 10% by the end of 50 weeks. The weight change of GGFAC shows a slow process and is

Table 3
Compressive strength gain of concretes

Binder combination	Cube compressive strength (MPa)							Strength gain from 28 day to 1 year (%)
	1 day	3 day	7 day	28 day	56 day	112 day	360 day	
PCC	40.5	51.2	66.8	81.1	87.9	91.2	96.3	18.7
HFAC	21.7	32.6	43	65.2	86.7	97.5	107.1	64.3
GGFAC	35.1	49.3	65.4	80.6	89.8	93.7	99.4	23.3

the lowest over the entire immersion period, still remaining below 8% after 50 weeks exposure to H_2SO_4 solution.

3.3. Microstructure studies

The SEM observation is made with specimens at the age of 7 and 360 days, respectively. The image characteristics of concretes at 7 days are shown in Figs. 4(a)–6(a). As can be seen from Fig. 4(a), there are great deals of needle-shaped ettringite and plated-shaped calcium hydroxide in PCC, and large pores can also be observed. Fig. 6(a) shows that there are numerous un-hydrated FA particles in HFAC. However, The SEM observation of GGFAC (Fig. 5(a)) shows that this microstructure changes greatly with the incorporation of GGBS, and no FA particles can be observed. The main hydration products are cotton-shaped C–S–H gel and a certain amount of needle-shaped ettringite.

The characteristics of concretes at 360 days are shown in Figs. 4(b)–6(b). It is seen from Fig. 4(b) that though the microstructure of PCC is very compact, there are great deals of plated-shaped calcium hydroxide in it. The microstructures of HFAC and GGFAC are also very compact, and no needle-shaped ettringite or plated-shaped calcium hydroxide can be observed.

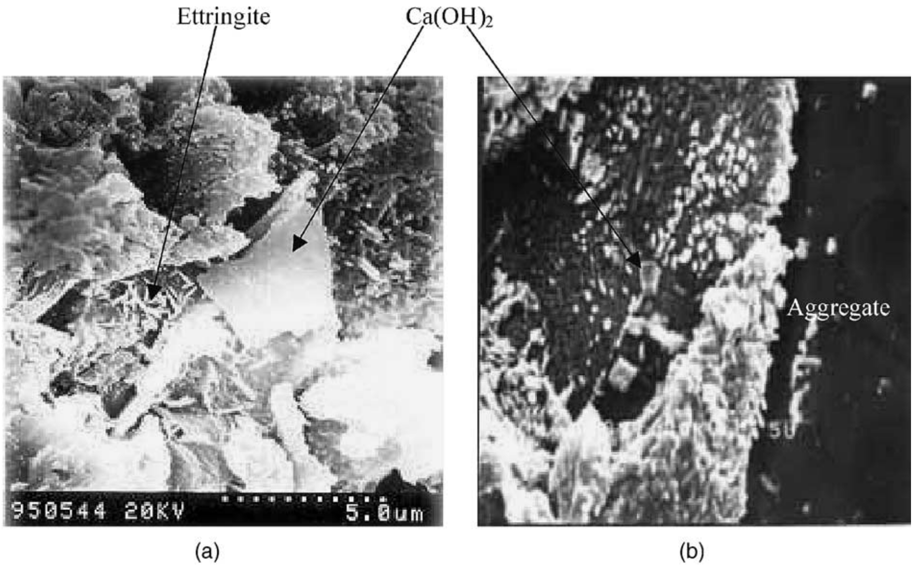


Fig. 4. SEM micrograph of PCC; (a) at the age of 7 days, (b) at the age of 360 days.

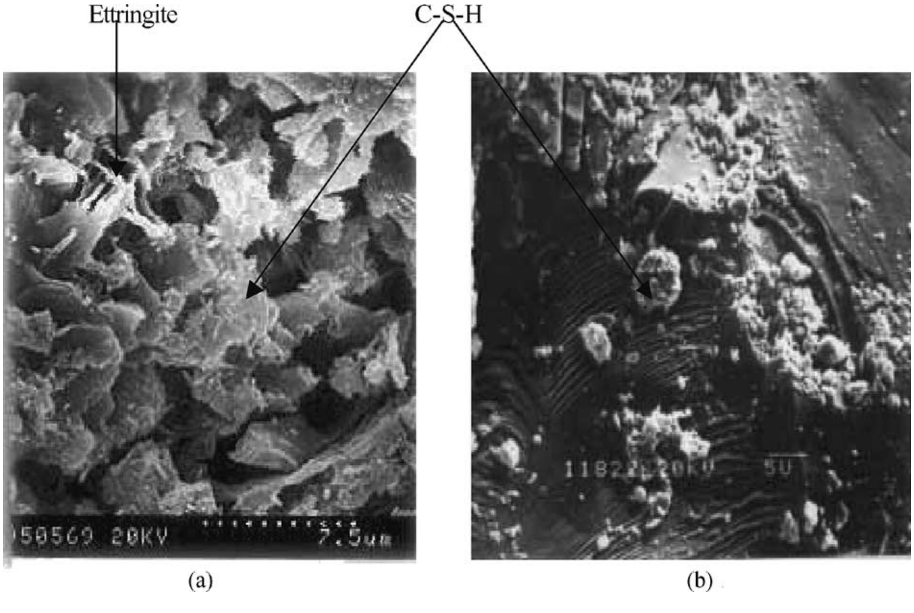


Fig. 5. SEM micrograph of GGFAC; (a) at the age of 7 days, (b) at the age of 360 days.

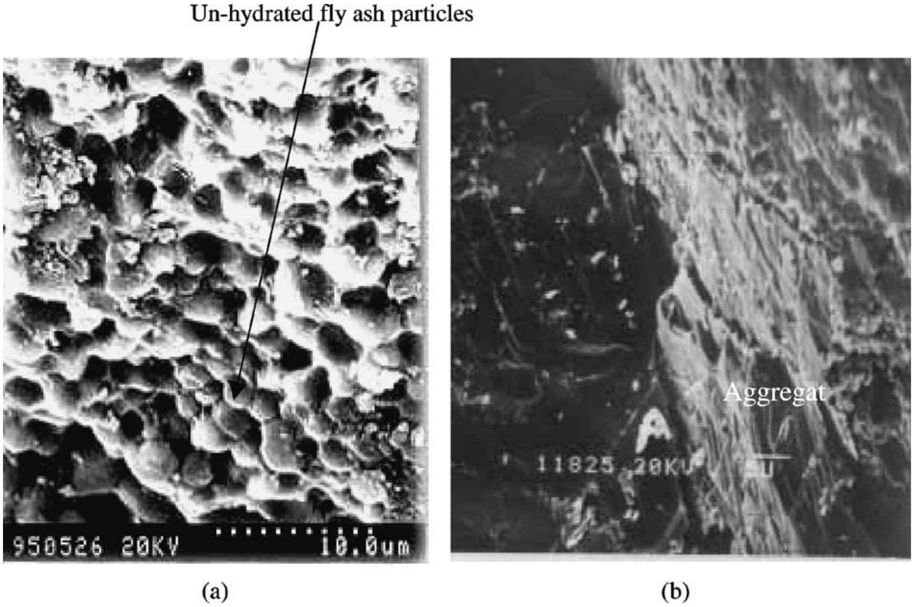
4. Discussion

Results show that GGFAC presents an excellent behavior in both short- and long-term compressive strengths and in resistance to H_2SO_4 attack. Though HFAC has a high long-term strength, its early-age strength is low. PCC has the lowest long-term compressive strength and is poor against H_2SO_4 attack.

The high early-age compressive strength of GGFAC is determined to a large extent by the properties of FA and GGBS. It is well known that for a given replacement level with mineral admixtures, the early-age properties of high-strength concrete are influenced by the reactivity of the mineral admixtures. The more reactive the mineral admixtures are, the higher the early-age strength of the concrete will be. One measure of the reactivity is chemical modulus (i.e. $[CaO + MgO]/SiO_2$). The higher the modulus, the more reactive the mineral admixtures are [13]. From Table 1, we can see that the combination of FA and GGBS has a modulus higher than FA alone. Therefore, the hydration rate of cementitious materials in GGFAC is faster than that in HFAC, which will produce a higher early-age strength. It can also be seen from the SEM images that there are numerous un-hydrated FA particles in HFAC (Fig. 6(a)) at the age of 7 days, but no un-hydrated FA particles or GGBSs are observed in GGFAC (Fig. 5(a)).

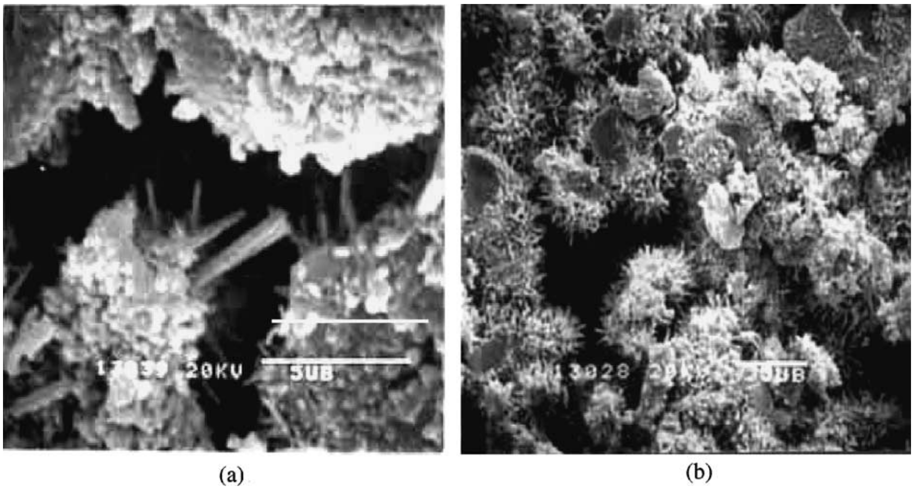
Some studies showed that GGBS is slowly reactive [14], and the addition of GGBS retarded the setting time of concrete [15]. However, we observed that when GGBS was incorporated with FA, the hydration rate of fly ash and GGBS increased at the early-age. The increased hydration rate of the GGBS used have may be due to its large specific surface (599 m^2/kg), compared to the used value of about 400 m^2/kg. This will provide more nucleating sites and OH^- ions as well as alkalis into the pore fluid. Swamy [16] confirmed that the concretes incorporating slag with a fineness of 1200 m^2/kg have the same three-day cube strength as concretes without them. GGBS reacts with the hydrated lime (CH) of Portland cement, forming a secondary calcium silicate compound. At the same time, a lot of homogeneous hydration products like ettingite and CH are also formed, which have larger specific surface than that of Portland cement. The secondary calcium silicate, ettingite and CH act as nucleating sites, precipitates around FA particles and lead to the increase of the hydration rate of FA. On the other hand, when GGBS (with high $CaO + MgO$ content) hydrates, it provides OH^- ions and alkalis into the pore fluid. Further, both the OH^- ions and alkalis react with SiO_2 and break down the glass phase of FA, which, as a result, accelerates the process of hydration. From Fig 7, we can see that the glass phase of FA is broken down, and a lot of secondary calcium silicate, ettingite and CH are produced in the surface of fly ash.

The performance of concretes against H_2SO_4 attack depends primarily on the permeability performance, the C_3A content and the amount of $Ca(OH)_2$ produced. That the GGFAC has superior resistance against H_2SO_4 attack is attributed to: (1) The pore refinement process occurs due to the conversion of dense $Ca(OH)_2$ into secondary C–S–H gel by pozzolanic reaction. (2) The generation of discontinuous pore structure occurs due to



(a) (b)

Fig. 6. SEM micrograph of HFAC; (a) at the age of 7 days, (b) at the age of 360 days.



(a) (b)

Fig. 7. SEM micrograph of GGFAC; (a) at the age of 12 h, (b) at the age of 1 day.

a net reduction in $Ca(OH)_2$ content caused by strong pozzolanic reaction. (3) The amount of free $Ca(OH)_2$ reduces due to the pozzolanic reaction.

The poor resistance of PCC to H_2SO_4 attack is due to the presence of large pores and free $Ca(OH)_2$ in the concrete.

HFAC is also poor against H_2SO_4 attack at the early-age. The reason is that there are numerous un-hydrated FA particles in the concrete, and the matrix is significantly porous at the early-age. Furthermore, the amount of C–S–H gel in HFAC formed by cement hydration is less than that in PCC or GGFAC. The reduction in the amount of C–S–H gel and the porosity of the matrix in HFAC are responsible for the poor resistance to H_2SO_4 attack.

5. Conclusions

The following conclusions can be made based on the test results of this study:

1. GGHFC can achieve adequate early-age compressive strength, while maintaining a long-term strength higher than PCC.
2. GGHFC is superior to both HFAC and PCC against H_2SO_4 attack, and its weight change is about 8% after 50 weeks exposure to 2% H_2SO_4 solution.
3. The relative strengths of GGHFC, HFAC and PCC decrease due to the decalcification and the expansive corrosion of hardened cement in H_2SO_4 solution. However, the decreasing rate of GGFAC is the lowest.
4. Initial results from SEM images show that the hydration rate of HFAC is lower than that of GGFAC, and there are a lot of ettringite and calcium hydroxide in PCC.

References

[1] Alasali MM, Malhotra VM. Role of structural concrete incorporating high volumes of fly ash in controlling expansion due to alkali-aggregate reaction. ACI Mater J 1991;88:159–63.
[2] Sivasundaram V, Malhotra VM. Performance of high-volume of fly ash concrete and slag concrete in a sulfate environment. MSL Division Report MSL 93-29(OP&J) Draft, Energy, Mines, and Resources Canada, Ottawa, 1993, p. 25.
[3] Bilodeau A, Sivasundaram V, Painter KE, Malhotra VM. Durability of concrete incorporating high volumes of fly ash from sources in US. ACI Mater J 1994;91:3–12.
[4] Swamy RN, Hung HH. Engineering properties of high volume fly ash concrete. In: ACI SP-178, vol. 1. 1998. pp. 331–359.
[5] Fung N. High performance concrete. Beijing: China Building Industry Press; 1996.
[6] Malhotra VM, Zhang MH, Read PH, Ryell J. Long-term mechanical properties and durability characteristics of high-strength/high-performance concrete incorporating supplementary cementing materials under outdoor exposure conditions. ACI Mater J 2000;97:518–25.
[7] Langley WS, Carette GG, Malhotra VM. Strength development and temperature rise in large concrete blocks containing high volumes of low-calcium (ASTM class F) fly ash. ACI Mater J 1992;89:362–8.
[8] Swamy RN, Ali ARS, Theodorakopoulos DD. Early strength fly ash concrete for structural applications. ACI J 1983:414–23.
[9] Aiqin W, Chengzhi Zh, Mingshu T, Ninsheng Zh. ASR in mortar bars containing silica glass in combination with high alkali and high fly ash contents. Cem Concr Compos 1999;21:375–82.
[10] Giaccia GM, Malhotra VM. Concrete incorporating high volumes of ASTM class F fly ash. ASTM Cem Concr Aggregates 1988;10:88–95.
[11] Sivasundaram V, Bilodeau A, Malhotra VM. Effect of curing conditions on high-volume fly ash concrete made with ASTM Type I and III cement and silica fume. Advances in concrete technology. In: Malhotra VM, editor. Proceedings of Second CANMENT/ACI International Symposium, SP-154. Farmington Hills: American Concrete Institute; 1995. p. 509–30.
[12] Swamy RN, Darwish AA. Engineering properties of concretes with combinations of cementitious materials. In: ACI SP-178, vol. 2. 1998. pp. 661–684.

[13] Wainwright PJ, Rey N. The influence of ground granulated blast furnace slag (GGBS) additions and time delay on the bleeding of concrete. Cem Concr Compos 2000;22:253–7.

[14] Swamy RN, Ammar Bouikni. Some engineering properties of slag concrete as influenced by mix proportioning and curing. ACI Mater J 1990;87.

[15] Hogan FJ, Meusel JW. Evaluation for durability and strength development of a ground granulated blast furnace slag. Cem Concr Aggregates 1981;3:40–52.

[16] Swamy RN. Design for durability and strength through the use of fly ash and slag in concrete. In: ACI SP-178, vol. 171. 1997.