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Effects of curing procedures on the strength and permeability of cementitious composites incorporating GGBFS

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In this study, the effects of curing procedures on properties of samples incorporating ground granulated blastfurnace slag (GGBFS) were examined. The replacement levels by GGBFS were 0, 35, 50 and 65% by mass of cement. Three different curing methods were used: water, air and steam curing. Permeability as well as compressive and flexural strength was measured to determine performances of the samples.

Test results indicated that steam curing greatly helped the development of both compressive and flexural strength for the samples incorporating GGBFS in the early ages. However, a reverse trend was observed at later ages. It was also found that the beneficial effect of steam curing became more significant in terms of permeability as the GGBFS content increased. Additionally, air curing has potentially a negative effect on the mechanical properties of both control and GGBFS blended samples due to a lack of the moisture availability for hydration.

Based on the test results, thus, it can be concluded that the use of GGBFS holds promise in the production of precast concrete elements taking into consideration economical and mechanical factors.

Key words: Curing procedures, Ground granulated blastfurnace slag, Strength, Permeability.

Introduction

There has been an increasing interest for the use of supplementary cementitious materials such as fly ash, silica fume, metakaolin and slag, whether natural or by-products, in the production of cementitious composites because of ecological, economical, and diversified product quality reasons. In particular, ground granulated blast-furnace slag (GGBFS), a by-product of the transformation of ion ore into pig-iron in a blast furnace, is one of these materials whose use in cementitious materials manufacture goes to as far back as 1880 [1]. Recently, GGBFS-based blended cements are now marketable worldwide due to their benefits in terms of strength and durability [2, 3]. It was also reported that the mechanical properties and microstructure of GGBFS-based composites are very sensitive to high-temperature conditions [4-6].

It has been generally accepted that the performance of hardened cementititous composites is greatly dependent on the curing temperature and duration as well as environmental conditions. In particular, steam curing with heat treatment at high temperature is commonly used in the production of precast concrete elements to increase the rate of hydration and accelerate early-age strength development [7].

There is useful information in the literature related to the effects of curing procedures on Portland cement concrete properties [8]. However, studies on the effects of curing conditions on the performance of cementitious composites incorporating GGBFS have been rarely reported.

The purpose of this study is to assess periodical performance of samples incorporating GGBFS cured in three different environments by measuring compressive and flexural strength, as well as measuring the permeability by using the rapid chloride ion penetration test (RCPT) according to ASTM C 1202.

Experimental

The cement used in this study is ordinary Portland cement and complies with ASTM C 150 Type I. The ground granulated blast-furnace slag (GGBFS) used in this investigation was a Grade 100 with a specific surface area of 430 m^2/kg. The chemical composition and mineralogical compound of the cement and GGBFS are given in Table 1. The aggregate used was a natural river sand with a maximum size of 5 mm, fineness modulus of 2.75, dry specific gravity of 2.6, and moisture content of 3.5%. The sand: cementitious materials (cement + GGBFS) ratio used was 2 : 1 by mass. The water/cementitious materials ratio (w/cm) of mixture was 0.45.

In this study, three methods of curing were used: (1) water curing, (2) air curing, and (3) steam curing. For water curing, the samples were wrapped in a plastic envelope to prevent evaporation of free water for 12 h after casting. They were then continuously cured in water at 20 ± 3 °C after demolding. For the second curing method, the samples were air-cured in laboratory conditions (T = 20 °C, RH = 50%).

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Table 1. Chemical composition and mineralogical compound of cement and GGBFS

	Chemical composition, %									Mineralogical compound, %			
	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	I.O.L	C_2S	C_3S	C_3A	C_4AF
Cement	64.4	21.9	5.0	2.9	1.9	2.0	0.5	0.2	0.7	24.7	51.3	8.3	8.9
GGBFS	42.8	36.2	9.3	1.2	-	6.8	0.4	0.3	0.4	-	-	-	-

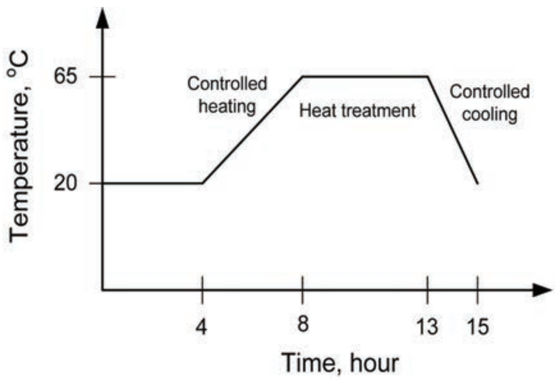

Fig. 1. Heat treatment procedure for steam curing.

Lastly, the samples for steam curing were moved into a steam-curing box (RH = 95%) after casting. The temperature of heat treatment during steam curing was determined as 65 °C. After steam curing, the samples were moved from their molds, and placed in water (20 ± 3 °C) until the ages for testing. The detailed heat treatment procedure for steam curing is shown in Fig. 1.

Compressive and flexural strength measurements were performed on the samples at predetermined ages. For both compressive and flexural strength, three samples were tested and then their values averaged. A rapid chloride ion penetration test (RCPT) was used to evaluate the permeability of samples. This test was based on the standard test method of ASTM C 1202. The total charge passed through the cell was calculated to determine the permeability of samples.

Results and Discussion

Compressive strength

The compressive strength development of the samples incorporating GGBFS under water, air and steam curing is shown in Fig. 2. At 1-day of water curing, the highest compressive strength of 14.2 MPa was observed in control samples (without GGBFS), and the lowest value of 7.3 MPa was for the sample with 65% GGBFS. The compressive strength of the samples decreased with increasing GGBFS content at earlier stages up to 7 days. At 91 days of water curing, however, the 50% GGBFS samples exceeded the control samples in terms of compressive strength.

A negative effect of air curing on the compressive strength development of samples was observed (Fig. 2(b)). This curing regime was selected to simulate the current ongoing practice in the construction industry. It was observed that the general trend of compressive strength of air-cured samples was very similar to that of water-cured samples. However, the air-cured samples exhibited somewhat lower values in compressive strength as compared to the samples cured in water, regardless of the replacement level of GGBFS at every curing age. This may be attributed to the lack of moisture availability for the hydration of cementitious composite, which eventually caused a porous structure introduced by drying shrinkage [9].

Steam curing is the most widely used method to produce precast concrete elements. The results presented in Fig. 2(c), indicated that the application of steam curing improved the compressive strength of the samples compared to water- and air-cured samples, especially in the early stages. For example, the 1-day compressive strength values of all samples exceeded 10 MPa. Under steam curing, however, the rate of strength gain was somewhat lower compared to that for both water and air curing. This is presumably due to a less uniform distribution of hydration products in the cementitious composite because of the rapid initial hydration, resulting in changes in the large capillary

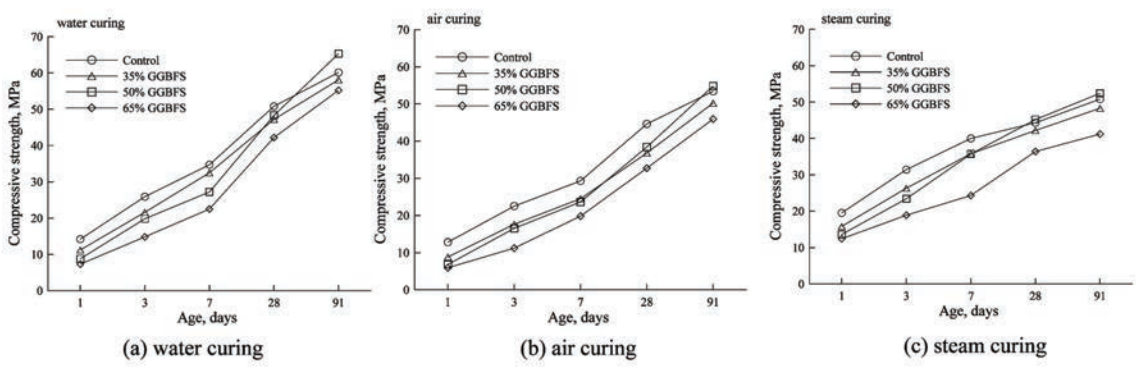

Fig. 2. Compressive strength development of samples incorporating GGBFS.

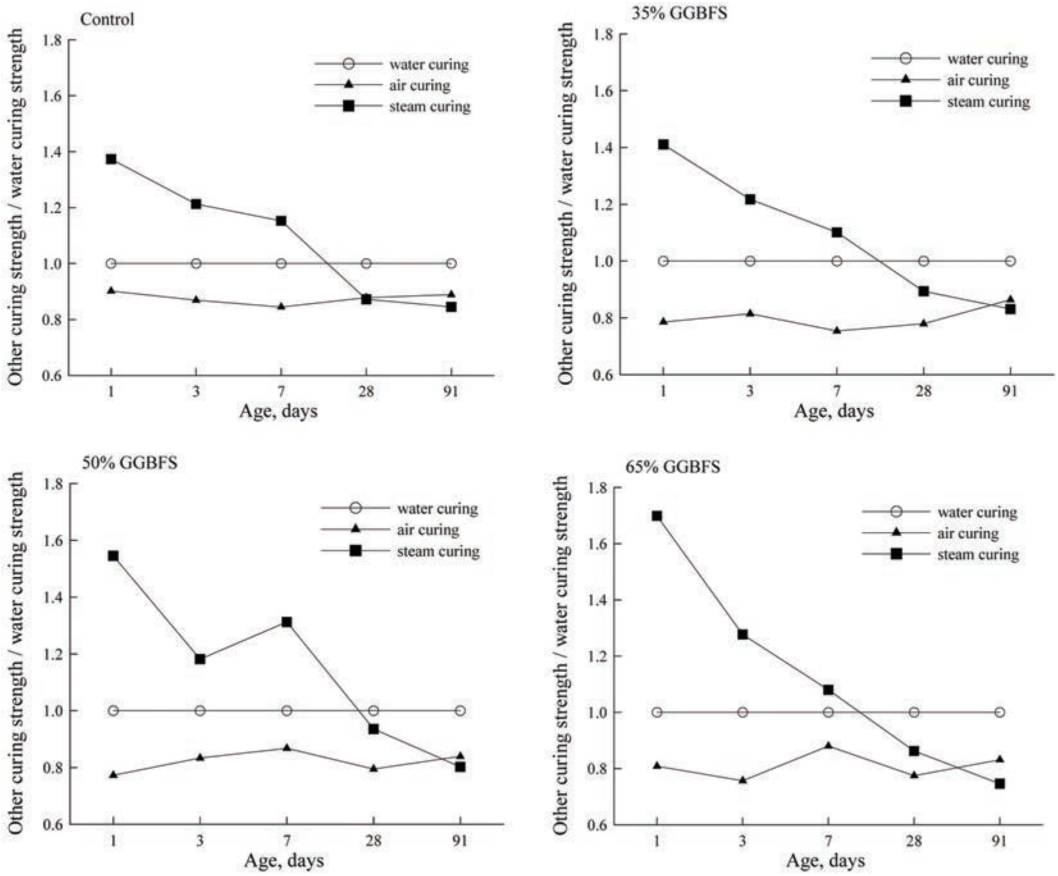

Fig. 3. Effects of different curing procedures on compressive strength ratio of samples incorporating GGBFS.

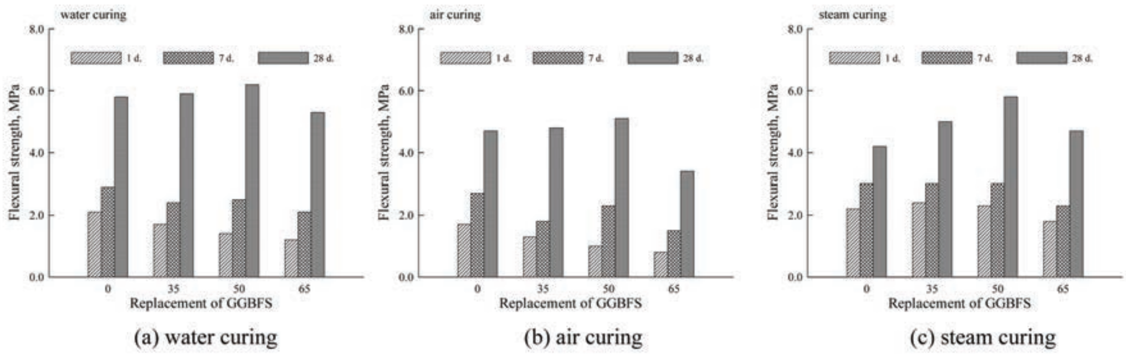

Fig. 4. Flexural strength development of samples incorporating GGBFS.

pore distribution [10].

Figure 3 gives comparison data on compressive strength of the samples experienced during each curing procedure relative to the compressive strength of water-cured samples. The data confirmed that the compressive strength of samples incorporating GGBFS as well as control samples was significantly dependent on the type of curing procedure. Furthermore, the beneficial effect of steam curing on the strength of the samples was clearly observed at earlier stages up to 7 days. In contrast, with continuous steam curing, the ratio of compressive strength gradually/sharply decreased. Subsequently, the compressive strength of the water-cured samples was higher than that of the steam-cured ones in the later stages (28 and 91 days). Similar results have been reported in the literature [11]. Additionally, it was again confirmed that air curing exhibited a negative effect on the evolution of compressive strength, irrespective of the use of GGBFS, showing relatively lower values in compressive strength ratio between 1 and 91 days of curing age.

Flexural strength

Figure 4 shows the flexural strength of samples measured at 1, 7, and 28 days of curing. As expected, in the earlier stages of water curing, the flexural strength for the samples incorporating GGBFS was a rather low as compared to that for control samples. However, the difference in flexural strength between control and GGBFS samples was almost

Table 2. Results of RCPT

Conditions	Replacement of GGBFS, %	Total passed charge (RCPT), Coulombs	
		7 d.	28d.
Water curing	0	4544	2845
	35	3078	1845
	50	2415	1056
	65	2046	996
Air curing	0	4872	3822
	35	4066	2974
	50	3640	2662
	65	3547	2625
Steam curing	0	4398	2925
	35	2484	1947
	50	1968	1054
	65	1738	844

negligible, while 65% GGBFS samples exhibited somewhat lower values. This trend was apparently observed in the results for flexural strength of air-cured samples (Fig. 4(b)). Although under an air curing environment, flexural strength is more sensitive to microcracks as compared to compressive strength [12], the tendency for flexural strength was in excellent agreement with that for compressive strength, already presented in Fig. 2. More importantly, the beneficial effect of GGBFS on the flexural strength of steam–cured samples was clearly demonstrated (Fig. 4(c)). One point worth emphasizing is the remarkable increases in flexural strength for the samples incorporating GGBFS at 1 day of steam curing. This also strongly suggests a possible application of GGBFS for the production of precast concrete.

Comparatively, at 28 days, the flexural strength of steam-cured control samples was significantly lower than that of water-cured ones. However, the strength reduction of steam-cured samples incorporating GGBFS was not significant. This can be explained by the steam curing procedure including heat treatment, which possibly caused the extended pozzolanic reactions. This finding is also in accordance with previous studies [11, 12].

Permeability

Test results of the effects of curing procedures on the permeability of samples incorporating GGBFS are summarized in Table 2. The permeability decreased with increasing replacement level of GGBFS for all curing procedures at 7 days. However, it should be noted that the beneficial effect of steam curing became more significant as the GGBFS content increased. In addition, results indicated that air curing increases the permeability of both control and GGBFS samples. As mentioned earlier, this result may be attributed to the extensive shrinkage cracking developed in the samples during air curing.

Conclusions

In this study, the test results emphasize the beneficial effect of a steam curing procedure to achieve high strength, especially in the earlier ages of curing. However, after 28 days of steam curing, a strength reduction was observed in all samples. A similar trend was also found in the results of permeability.

Therefore, it appears that the application of GGBFS for precast concrete with a steam curing process may to a certain extent be reliable. However, special care should be taken to prevent delayed ettringite formation (DEF) in cementitious composites when heat treatment in a steam curing procedure is applied [13, 14].

During the curing period, at least within the scope of this study, in comparison with water curing, air curing has potentially a negative effect on the mechanical properties of both control and GGBFS blended samples due to the lack of the moisture availability for hydration.

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