Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 7(6):417-424

Influence of Curing Condition on the Mechanical Properties and Durability of High Strength Concrete

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Abstract: The influence of initial curing conditions on the mechanical properties and durability of high strength concrete was investigated. In this work, two different curing conditions (steam curing and standard curing) were applied to the specimens with identical mix designs. Some of the specimens were kept in standard curing condition; the rest were stored in standard curing condition after 10 hours of steam curing. Compressive strength, splitting tensile strength, elastic modulus, shrinkage, freeze-thaw resistance, carbonation, and sulfate resistance of concrete were determined. X-ray diffractometer (XRD), mercury intrusion porosimetry (MIP), and scanning electron microscopy (SEM) image analysis were adopted to measure microstructure evaluation under different curing conditions. Results indicate that, compared with standard curing, steam curing increases the degree of cement hydration, the average diameter of pores, and the amount of hydration products. Steam-curing concrete exhibits higher strength at early age and lower shrinkage, while the standard-curing concrete has higher strength, elastic modulus, freeze-thaw resistance, carbonation and sulfate resistance than those of steam-curing concrete at later age.

DOI: 10.6135/ijprt.org.tw/2014.7(6).417
***Key words**: Curing condition; Durability; High strength concrete; Mechanical properties.*

Introduction

Because of its excellent mechanical performance and durability, high strength concrete with low water-binder ratio and mineral admixture replacement plays a fundamental role in infrastructure, such as high-rise buildings, bridges, and tunnels, etc. As shown in existing research of cement-based materials, mechanical performance and durability of mortar and concrete are significantly influenced by curing conditions, the type and amount of binding materials, and the water-binder ratio [1].

The purpose of curing is to ensure the proper progress of cement hydration reaction under adequate relative humidity and temperature. Curing of concrete is essential to its mechanical performance and durability. It is well known that mechanical performance and durability of concrete depend on the rate and degree of cement hydration, both of which are controlled by the quality and quantities of the binding materials (quantity doesn't affect rate or degree of hydration, unless temperature effect is considered) present in the mix, as well as the curing condition including temperature and the availability of moisture [2]. After placement, curing condition is the most critical factor that influences cement hydration. Proper curing can provide adequate moisture content and temperature for cement hydration so that the desired properties of concrete can be developed [3-5]. Curing becomes more important if concrete contains mineral admixtures or is subjected to dry and hot environments, especially at an early age [6].

Under standard curing conditions, the curing period for ordinary Portland cement concrete usually lasts for several days, due to the slow rate of cement hydration and the hardening process. Researchers have reported that concrete with mineral admixtures requires a longer curing period because of its retarded strength gain especially at lower temperatures [7, 8]. The use of mineral admixtures to partially replace Portland cement is an effective way to reduce costs, conserve energy, and improve the mechanical performances and durability of concrete [9, 10]. It is necessary to prepare high performance concrete which has been implemented in bridges and tunnels. It has generally been accepted that curing is more important for concrete with mineral admixtures, compared to normal concrete without mineral admixtures [11].

It is well known that steam curing is widely used to provide a desired strength level for concrete with mineral admixtures in a short time by accelerating its hardening process [12]. Currently, heat treatment methods such as initial steam curing at atmosphere pressure is increasingly used in precast concrete elements—for example, precast beams and tunnel segments—in order to enhance the early performance of concrete and production efficiency. Research by Paya et al. [13] on the strength development of mortars with fly ash cured at 20^{o}C and 40^{o}C showed that there was a significant increase of compressive strength for fly ash mortars at early age, with the increase of curing temperatures. Maltais et al. [14] determined that the properties of high performance concrete with mineral admixtures could be improved by steam curing at low pressure, compared to standard curing. Numerous workers [15-18] have reported that initial steam curing could accelerate hydration of cement and mineral admixtures, and be beneficial to the early-age strength development. But the data from Kjellsen [19] and Barbara [20] indicated that higher curing temperature during placing and setting adversely affected the porosity and the strength at later ages. The durability of concrete is vital to the safety and the stability of

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Note: Submitted March 12, 2014; Revised July 26, 2014; Accepted August 22, 2014.

Table 1. Chemical Composition and Physical Properties of Cement and Mineral Admixture.

Label	W (%)								Density (g/cm^3)	Specific surface area (m^2/kg)	Water Demand Ratio (%)
	SiO_2	Al_2O_3	Fe_2O_3	TiO	CaO	MgO	SO_3	Loss			
Cement	20.47	5.90	4.80	—	59.64	3.74	2.08	2.44	3.15	350	—
GGBFS	34.76	15.39	1.20	—	35.86	9.07	3.84	—	2.80	440	99

Table 2. The Grading of Fine Aggregate.

Sieve Size (mm)	5	2.5	1.25	0.63	0.315	0.16	< 0.16
Cumulative Percentage Retained，by Mass (%)	3.5	12.5	21.0	49.6	86.9	96.9	100

Table 3. The Grading of Coarse Aggregate.

Sieve Size /mm	25	20	16	10	5
Cumulative Percentage Retained，by Mass (%)	0	21.3	42.2	77.1	97.3

critical infrastructure such as bridges and tunnels. Therefore, it is necessary to investigate the influence of curing condition on the high strength concrete, which is widely used in critical infrastructures.

The objective of this study is to investigate the influence of initial curing condition on high strength concrete with mineral materials, including its mechanical properties (compressive strength, splitting tensile strength and elastic modulus) and durability (frost resistance, shrinkage, carbonization and sulfate resistance). Specimens prepared with binders including Portland cement and slag were kept at two different curing conditions, steam curing at atmosphere pressure and standard curing. The changes in microstructure with age were determined by MIP, scanning electron microscopy (SEM), and x-ray diffractometer (XRD) techniques.

Experimental Program

Materials

42.5R Portland cement, which complies with the requirements of Chinese National Standard GB175-2007, was used. The ground granulated blast furnace slag (GGBFS) was obtained from the Wuhan steel plant. The chemical and physical properties of cement and GGBFS are given in Table 1.

Fine aggregate used was natural sand with a fineness modulus of 2.6, plotted in Zone II according to Chinese national standard JGJ 52-2006, and its grading is shown in Table 2. The coarse aggregate used was broken gravel with continuous grading, as listed in Table 3. The maximum particle size of coarse aggregate was 25 mm, and its crushed index was 8.3%. Naphthalene superplasticizer (SP) with a water reducing ratio of 28% was used in the mix.

Curing Condition and Mix Proportions

Two different curing conditions were used, the standard curing (RH ⩾95% at 20±2^{o}C) and steam curing. Based on the results of orthogonal test, the mix proportion and steam curing regime of high strength concrete were selected. Mix proportions of high strength concrete are presented in Table 4. A detailed description of steam curing regime is given in Fig. 1. The procuring temperature was 30^{o}C, the duration of procuring was 3h, the heating rate was 15^{o}C/h, the duration of steam curing at 50^{o}C was 3h, the rate and duration of cooling was 15^{o}C/h and 2 h respectively, and the relative humidity of the steam-curing condition was not less than 90%.

Table 4. Mix Proportions of High Strength Concrete (kg/m^3).

Cement	GGBFS	Fine Aggregate	Coarse Aggregate	Water	SP
360	100	698	1140	152	5.4

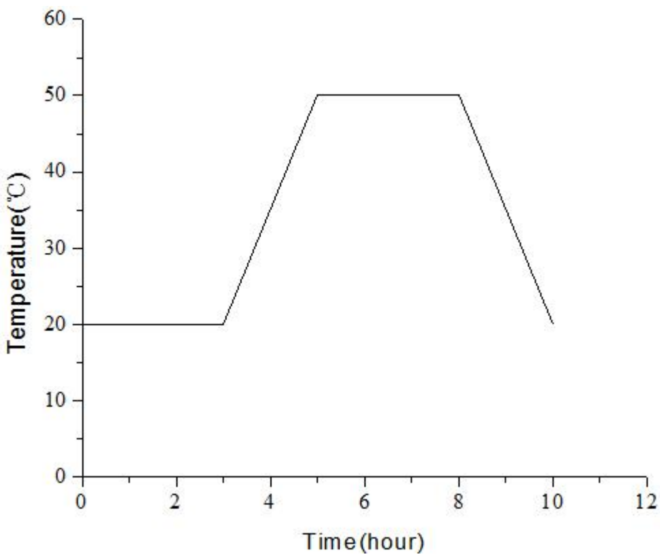


Fig. 1. Steam Curing Regime.

Testing Procedure

Mixing and specimen preparation were performed at room temperature. The specimens were divided into two groups. The first group was left in a casting room for 24 h. Then the specimens were stored in a standard curing room, followed by measurement on 7-day and 28-day compressive strength, 28-day splitting tensile strength, and elastic modulus. The other group was removed from the mold after steam curing; some of them were used to measure the compressive strength (named as demoulding strength at the time interval of 10 h after adding water) at once, others were put in the standard curing room. Their strength and elastic modulus were measured and compared with those under standard curing condition at the same age. The results of compressive strength, splitting tensile strength and elastic modulus were recorded with the average value of three test specimens respectively.

The freeze–thaw resistance of concrete aged 28 days under different curing conditions was determined according to Chinese national standard GB 50082-2009, which was similar to ASTM C666. Three specimens were tested for each concrete. The changes in the relative dynamic modulus and weight were calculated every 25 freeze–thaw cycles, and the average value was reported. According to GB 50082-2009, the damage criteria was that weight loss exceeds 5.0%, or their relative dynamic modulus was lower than 60%. In this case, the maximum number of freeze–thaw cycles was taken as the frost resistance grade of concrete.

Shrinkage of concrete under different curing conditions was measured using a group of three prism specimens with the dimensions of 100mm×100mm×400mm following the procedure described in GB 50082-2009. When the concrete was casted, a strain gauge was embedded in the specimen to measure the shrinkage. The none group of specimens were demolded after 24h stored in the room and removed to standard curing room, and the other group of specimens were removed from the mold after 10 hours steam curing, as shown in Fig. 1, then they were put into the standard curing room. At the age of 3 days, all the specimens were moved to a drying room with a temperature of 20 ± 2^{o}C and relative humidity of 50 ± 5%.The length of the specimen was determined by a comparator with the precision of 0.001 mm. The initial comparator reading was taken immediately when the specimens were in the drying room. Readings were taken on 1, 3, 7, 14, 21, 28, 45, 60, 90, and 180 days after the end of moist curing. Before each measurement, the comparator dial was calibrated. The shrinkage strain was calculated by the comparator readings, which was similar to that described in [21]. Mean values of shrinkage strain at different ages were calculated from tests of the three specimens.

The carbonation of high strength concrete was conducted with a carbonation acceleration chamber according to GB 50082-2009. For the carbonation test, prism specimens (100 mm×100 mm×400 mm, two for each curing condition) were demolded after initial curing under standard curing condition until 28-day age, then dried at a constant temperature of 60^{o}C for 48h. The specimens were sealed by ceresin wax at the cast, bottom, and side faces; the surface where the carbonation depth would be measured was left unsealed. The specimens were put in a carbonation acceleration chamber at 20 ±5^{o}C with a relative humidity of 70 ± 5%, and a CO_2 concentration of 20 ± 3%, which is much higher than that of the atmosphere. The carbonation depth was measured by cutting 60 mm thickness from the unsealed surface, spraying the exposed cross-section with a 1.0% phenolphthalein solution, and evaluating the carbonation depth from the resulting change in color after reaching specified ages.

To evaluate the influence of curing condition on the resistance of the high strength concrete to sulfate attack, cube specimens (100mm×100mm×100mm) were utilized to measure the compressive strength before and after immersion in the sodium sulfate solution. All specimens were demolded after initial curing and stored in standard curing condition until the age of 28 days. After curing, the compressive strength of the specimens was determined before they were immersed in a 5% sodium sulfate solution in a fresh water tank (reference medium) for 90 and 180 days. After this treatment, the compressive strength was measured. The sulfate resistance was determined by the compressive strength variation of specimens immersed in the sulfate solution or water at the same age. The temperature of the solution was maintained at 20 ± 2^{o}C, and the pH of the sulfate solution should be controlled within a range of 6.0–8.0 by titration with diluted sulfuric acid solutions which must be renewed at regular time intervals (2 months).

Scanning Electron Microscopy (SEM)

A scanning electron microscopy was used to obtain the microscopic morphology of samples under different curing conditions. Resolution of the apparatus was 3.5 nm and the accelerating voltage was 20 kV. Before analysis, the samples were coated with a thin film of gold conducting film by evaporation.

X-ray Diffractometer (XRD)

For better understanding of the difference, the samples under different curing conditions were examined by X-ray Diffraction (XRD) analysis on an X-ray diffractometer using Fe Ka radiation at 40 kV and 30 mA. The scan range was 10°- 90° and a speed of 4°/min. The samples taken from concrete after compressive strength test were ground finely and stored in airtight plastic containers.

Mercury Intrusion Porosimetry (MIP)

A mercury porosimetry analyzer, PM-3, made by Quantachrome. Ltd. in America, was used to determine the pore size distribution of samples under different curing conditions. The MIP measurement could evaluate pores ranging from 4 nm to 7000 nm. Before testing, the samples were all fully dried in an oven at 105℃ until mass stabilization and each MIP value was the average of two samples. The samples for pore measurements were drilled out from cubic specimens with no coarse aggregates.

Experimental Results and Discussion

Mechanical Properties

Table 5 presents the difference of compressive strength, splitting tensile strength and elastic modulus of concrete cured at different conditions. The experimental results indicate that initial curing condition does have a remarkable influence on the mechanical performance of high strength concrete. It can be seen that the 10-hour compressive strength of steam curing concrete is 17.4 MPa, right after the final setting. Though the specimens exposed to steam curing exhibit high strength value, the variation of the 7-day compressive strength of concrete kept under two different curing conditions becomes minor. And the standard curing concrete indicates a greater increase in compressive strength after 7-day age and has better performance than steam-curing concrete in terms of compressive strength, splitting tensile strength, and elastic modulus at 28 days.

It is accepted that high temperature can accelerate the cement hydration and pozzolanic reaction. Under steam curing condition, the hydration rate of cement and the generation speed of hydration

Table 5. Strength and Elastic Modulus of Concrete.

Curing	Compressive Strength (MPa)			Splitting Tensile Strength (MPa)	Elastic Modulus (GPa)
	Demolding (10h)	7-day	28-day	28-day	28-day
Standard（P0）	—	48.1	69.8	5.75	42.4
Steam（P1）	17.4	51.1	65.6	5.43	37.8

product increase quickly at early age resulting in the hydration products surrounding the un-hydrated cement particles. The rate of cement hydration is faster than that of the hydration products' diffusion and dissolution. The hydration products become coarse and thick, which retard cement hydration and pozzolanic reaction by obstructing water penetration. Therefore, after initial steam curing, concrete exhibits higher strength at an early age while exhibiting a lesser increase in strength later. Under standard curing condition, the production of cement hydration products can keep pace with their diffusion and dissolution, the hydration products become fitness, fineness and uniform, the hydration degree of GGBFS is increased by the cement hydration as time goes by. Because of this, standard-curing samples exhibit higher mechanical performance than those of steam-curing concrete at 28 days.

Freeze-thaw Resistance

The variation of the mass and relative dynamic elastic modulus of high strength concrete cured under different conditions and subjected to 300 freeze-thaw cycles is shown in Fig. 2. It can be seen that the loss of mass and relative dynamic elastic modulus of all specimens increase with freeze–thaw cycles. However, the loss of mass and relative dynamic elastic modulus for both concrete groups after 300 freeze–thaw cycles are no more than 5.0% and 40% respectively, which implies the freeze–thaw resistance for both groups of concrete is fine, according to GB 50082-2009.

It is noted that the reduction of mass and relative dynamic elastic modulus for steam-curing concrete is larger than those for standard-curing concrete at the freeze–thaw cycles. The mass and relative dynamic elastic modulus loss contents for standard-curing concrete are 0.49% and 4.7% at 300 freeze–thaw cycles, respectively, while those for steam-curing concrete are 0.74% and 7.9% at the same cycles.

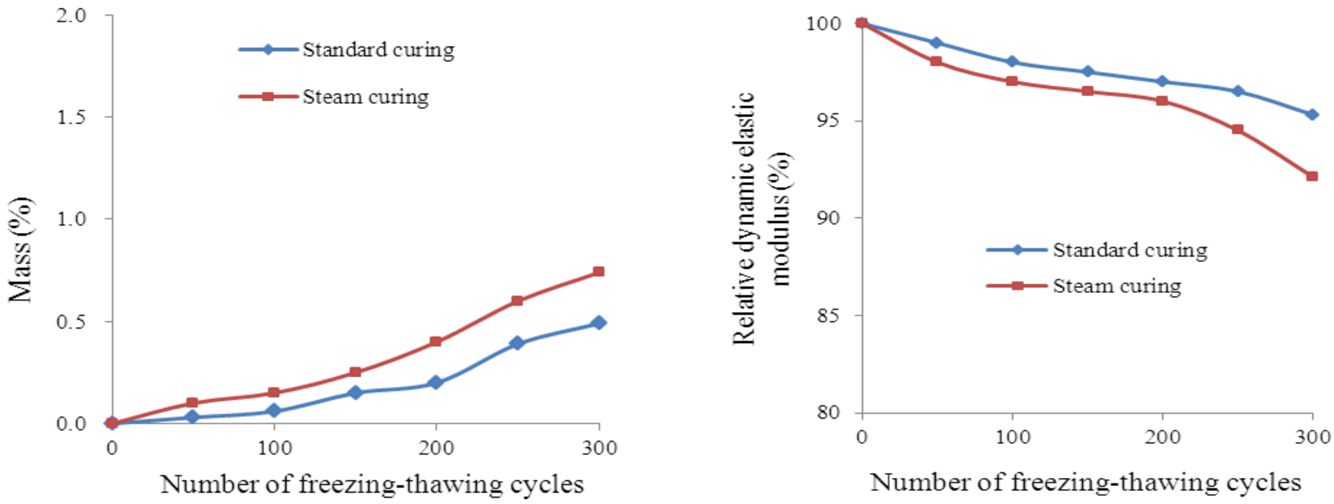
Shrinkage

Fig.3 shows the shrinkage development for the two groups of concrete cured under different conditions within 180 days. The results show that higher shrinkage rates are observed from day 1 to day 45 for both kinds of concrete and the shrinkage rate increases steadily from day 45 to day 90 before gradually reducing from day 90 to day 180. With reference to Fig. 3, it can also be observed that the shrinkage of standard-curing concrete is higher than that of steam-curing concrete during the test period; the shrinkage of standard-curing concrete is 3.07×10^{-4} at day 90 and 3.25×10^{-4} at day 180, while, for steam-curing concrete, those are 2.35×10^{-4} and 2.40×10^{-4} respectively.

What needs to be explained is that the shrinkage tested in this study includes chemical shrinkage, autogenous shrinkage, and drying shrinkage. It was reported that the chemical shrinkage and autogenous shrinkage were attributed to cement hydration and the autogenous shrinkage became more significant for high strength concrete [22, 23]. In this study, the initial deformation is measured at 3 days age when the degree of cement hydration is high for concrete after steam curing. Because of this, there is a larger number of data regarding chemical and autogenous shrinkage unaccounted for in steam-curing concrete than in standard-curing concrete.

Carbonization

The carbonization results of high strength concrete cured under



(a) variation of mass (b) variation of relative dynamic elastic modulus

Fig. 2. Influence of Curing on Freeze–thaw Resistance of High Strength Concrete.

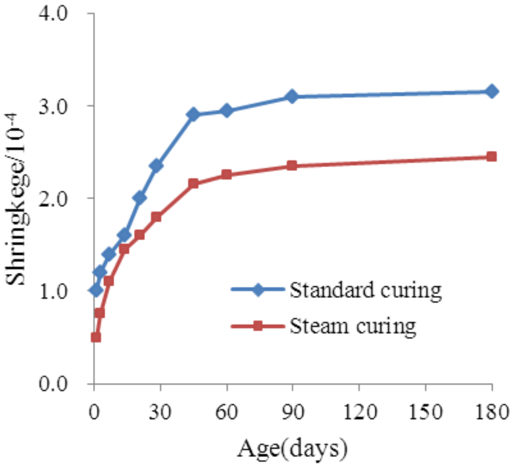


Fig. 3. Influence of Curing Condition on Shrinkage of High Strength Concrete.

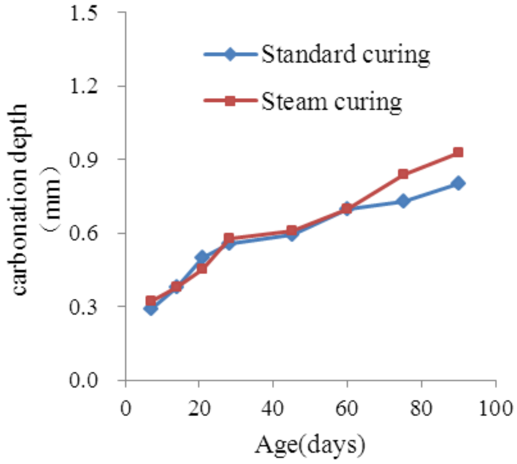


Fig. 4. Influence of Curing Condition on Carbonization of Gigh Strength Concrete.

different conditions with time is given in Fig. 4, which shows that the carbonation depth of both groups of concrete become deep as the age increases, and the carbonation depth of steam-curing concrete is close to that of standard-curing concrete before 60 days age. With reference to Fig. 4, it can also be observed that the carbonation depth of steam-curing concrete is slightly larger than that of standard-curing concrete during the test period; the carbonation depth of steam-curing concrete is 0.84 mm at day 75 and 0.93 at day 90, while, for standard-curing concrete, that are 0.73 mm and 0.8 mm respectively. This can be attributed to the Portland cement in the concrete mixtures partially replaced by GGBFS. That is known to enhance carbonation [24-26] while the effect of curing condition on carbonization of high strength concrete can also be weakened.

Sulfate Resistance

Fig. 5 lists the results of sulfate resistance of high strength concrete under standard curing condition and steam curing condition. With reference to Fig. 5, it can be observed that the compressive strength of high strength concrete decreases after it is immersed in the 5% sulfate solution, and the decreasing rate of compressive strength increases with time. The decreasing rate of compressive strength for standard-curing concrete is 7.2% at day 90 and 11.6% at day 180; for steam-curing concrete, that is 12.9% and 18.2% respectively. It can also be seen that the decreasing rate of compressive strength of steam-curing concrete is higher than that of standard-curing samples at the same age, when they are immersed in the 5% sulfate solution. In general, the influence of the sulfate solution on the standard-curing concrete is lower than that on the steam-curing concrete.

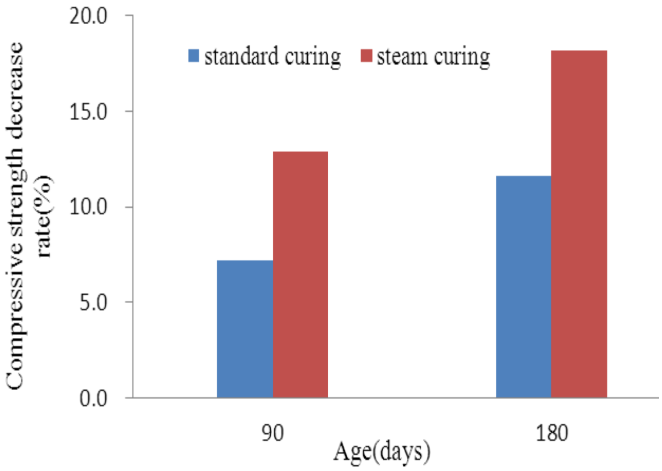


Fig. 5. Influence of Curing Condition on Sulfate Resistance of High Strength Concrete.

Microstructure

XRD analysis of concrete cured under different conditions is shown in Figs. 6 and 7. The diffraction peak intensity in the XRD is used to evaluate the content of hydration products at 1-day age and 28-days age under different curing conditions, as shown in Table 6. With reference to Fig. 6, Fig. 7, and Table 6, it can be observed that the hydration products of the same concrete mix under different curing conditions are basically similar, and the hydration rate and degree of concrete under steam curing condition are higher than those of concrete under standard curing condition, especially at early ages. However, the mechanical performance of concrete under steam curing is no better than that of concrete cured under standard condition at 28 days age. This phenomenon can be explained by the form of hydration. Figs. 8 and 9 are Scanning Electron Microscopy (SEM) photos of standard-curing concrete and steam-curing concrete, respectively. From SEM photos, the standard-curing cement paste is more compact and closed than the one observed in the steam-curing cement paste, and the size of hydration products in standard-curing cement paste is smaller than that of the steam-curing cement paste.

From Figs. 6 and 7, it can also be noted that the diffraction peak intensity of CH in standard-curing concrete is higher than that in steam-curing concrete. This may be due to the higher pozzolanic activity of the GGBFS under steam curing condition as compared to that under standard curing condition. The pozzolanic reaction of GGBFS needs to consume a number of CH in the concrete, which is disadvantageous to the carbonization resistance of concrete.

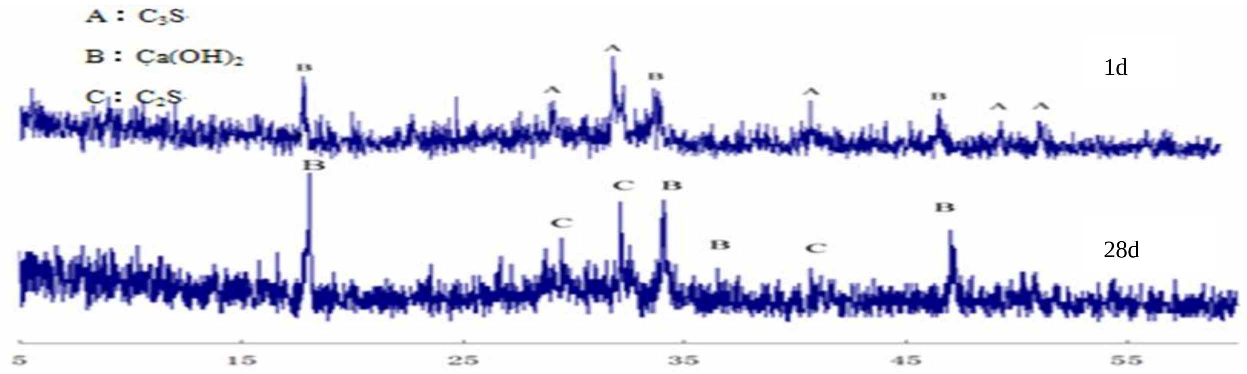


Fig. 6. XRD Analyses of Standard-curing Concrete at 1 Day and 28Days.

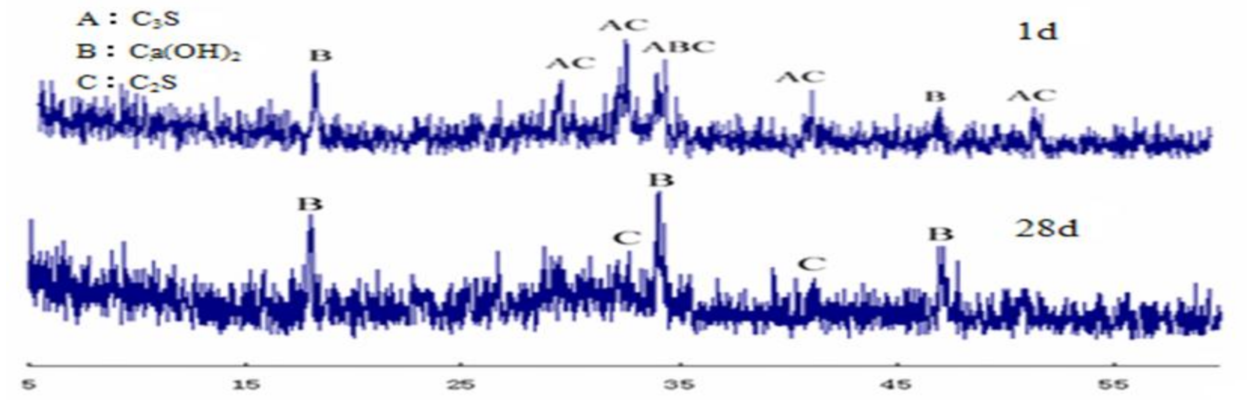


Fig. 7. XRD Analyses of Steam-curing Concrete at 1 Day and 28 Days.

Table 6. The Diffraction Peak Intensity (XRD) for Concrete Under Different Curing Condition (CPS)

Curing Condition	1-day			28-day		
	C_3S	CH	AFt	C_3S	CH	AFt
Standard	101	178	78	80	212	80
Steam	85	156	103	75	196	104

Therefore, compared with standard-curing concrete, the carbonization resistance of steam-curing concrete is poor from this point of view.

Measured by MIP, the porosity, average pore diameter, and pore size distribution of concrete cured for 28 days age under different conditions are presented in Table 7.

As shown in Table 7, the initial curing condition affects the total porosity and average pore diameter of concrete greatly. The total porosity of standard-curing concrete is twice that of steam-curing concrete, while its average pore diameter is much smaller than that of steam-curing concrete. It is well known that increase of pore size can decrease the strength of concrete. Though its total porosity is lower, the average pore diameter of steam-curing concrete is lager compared to that of standard-curing concrete. Therefore, the mechanical properties such as compressive strength, splitting tensile strength, and elastic modulus of steam-curing concrete at 28 days age are lower than those of standard-curing concrete. It is generally accepted that mechanical performance and durability of concrete are governed by its pores. Aggressive elements in either liquid or gaseous form can easily transport into concrete through pores existed in the concrete, which can weaken the durability of concrete.

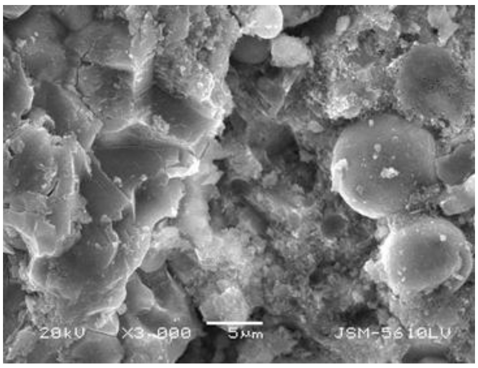


Fig. 8. Scanning Electron Microscopy (SEM) Photos of Standard-curing Concrete.

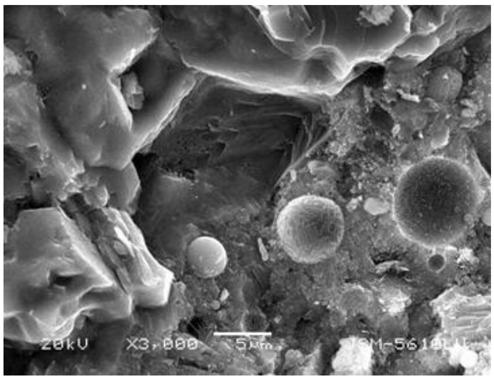


Fig. 9. Scanning Electron Microscopy (SEM) Photos of Steam-curing Concrete.

Table 7. The Pore Structure of Concrete under Different Curing Conditions.

Curing Condition	Total Porosity ($mL \cdot g^{-1}$)	Average Pore Diameter (nm)	Pore Size Distribution (%)			
			＜20 nm	20~50 nm	50~200 nm	＞200 nm
Standard	0.0642	5.47	8.76	68.93	15.87	6.44
Steam	0.0312	32.84	13.25	56.12	17.99	12.72

The transportation of aggressive elements and the transformation of water to ice get easier as the average pore diameter increases. Therefore, the freeze–thaw resistance, carbonization resistance, and sulfate resistance of steam-curing concrete are lower than those of standard-curing concrete.

Conclusions

This experimental study investigated the influence of curing condition on the mechanical performance and durability of high strength concrete with GGBFS. The following conclusions can be drawn from the data determined in this study:

(1) The compressive strength of high strength concrete with GGBFS is eminently enhanced by the steam curing method at 10 hours age, while the 28d compressive strength, splitting tensile strength and elastic modulus of steam-curing concrete are lower than those of standard-curing concrete.

(2) The reduction of mass and relative dynamic elastic modulus of steam-curing concrete are bigger than those of standard-curing concrete at the freeze-thaw cycles, and their values are enhanced with the increase in freeze-thaw cycles.

(3) The shrinkage rate of both kinds of concrete becomes large before 45 days age, and increases steadily after 45 days of age. The shrinkage of standard-curing concrete is higher than that of steam-curing concrete during the test period.

(4) The carbonation depth of both groups of concrete increases with time; The carbonation depth of steam-curing concrete is close to that of standard-curing concrete before 60 days age and slightly deeper after 60 days age.

(5) The compressive strength of both decreases after they are immersed in the 5% sulfate solution, and the decreasing rate of compressive strength increases with the age increased, the decreasing rate of compressive strength of steam-curing concrete is higher than that of standard-curing concrete at the same age.

(6) Compared with standard curing, initial steam curing can accelerate the rate and degree of hydration of concrete with GGBFS, enlarge the size of hydration products, and the average pore diameter.

Acknowledgement

This work was supported by National Natural Science Foundation of China (51208046, 51208047), Fundamental Research Funds for the Central Universities of Ministry of Education of China (Grant No. CHD2011JC091), Research Foundation of Ministry of Transport of China (2013318 J09230), and the National High Technology Research and Development Program of China (2005AA332010).

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