

Research Article

Influence of Steam Curing Method on the Performance of Concrete Containing a Large Portion of Mineral Admixtures

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A comparison was made between the impact of raising the thermostatic temperature and the impact of prolonging the thermostatic time on the performance of steam-cured concrete containing a large portion of fly ash (FA) or ground granulated blast furnace slag (GGBS) by analysing the form removal strength, chemically combined water content, reaction degree, strength development, chloride permeability, and volume stability. For the materials and test conditions reported in this study, raising the thermostatic temperature is more favourable for concrete containing FA, as indicated by the significantly higher form removal strength and the higher growth of reaction degree of FA compared with prolonging the thermostatic time. With an increase in the thermostatic temperature, the hydration degree of a binder containing FA or GGBS initially increases and subsequently decreases. Although concrete containing FA can obtain satisfactory form removal strength with steam curing at 80°C, the late strength development of concrete containing FA is slow for the same curing conditions. The effect of the late performance of resistance to chloride ion permeability improved by FA is better than the effect improved by GGBS. The risk of destroying the structure of concrete containing a large portion of FA or GGBS due to delayed ettringite formation (DEF) is minimal when specimens were steam-cured at 80°C.

1. Introduction

Concrete is one of the most common construction materials. Cast-in-situ concrete and precast concrete are two techniques that housing developers and construction workers often adopt. However, precast concrete members have been increasingly utilized in civil engineering construction in recent years due to their advantages: reliable quality assurance, simple production process, faster construction speed, and environmentally friendly building operations [1–3].

Currently available information indicates that the technique of steam curing is the most frequently employed technique among various production processes of prefabricated members [4, 5]. The benefits of steam curing are as follows: simple process, convenient operation, production with high early strength, short production cycle, and superior economic benefits [5–7]. The steam curing process includes the following four stages: the precuring stage, the heating stage, the thermostatic stage, and the cooling stage [8, 9]. The thermostatic temperature is generally less than 60°C during steam curing because of two reasons. Firstly, the

growth of the late performance of concrete will be small if the thermostatic temperature is excessive during steam curing [10–12]. Secondly, the formation of ettringite produced by cement hydration in the case of a minimum curing temperature of 70°C is decomposed during steam curing and reformed during the service life. This process is called delayed ettringite formation (DEF), and it can substantially weaken the late performance of concrete [13–15].

Mineral admixtures are extensively applied in blended cement and concrete; this process is a substantial contribution to the field of civil engineering. The technology of steam curing has been primarily employed for pure cement concrete rather than concrete with a large portion of mineral admixtures as many researchers and housing developers have expressed their concern that the early compressive strength of concrete with a large portion of mineral admixtures is low [16–18], which make it difficult to satisfy the requirements of form removal strength of steam-cured concrete at the end of steam curing. This is an obstacle to the use of steam curing for concrete that incorporates a large portion of mineral admixtures.

TABLE 1: Chemical compositions and specific surface areas of OPC, GGBS, and FA.

	OPC	GGBS	FA
SiO ₂ (%)	21.10	31.76	53.33
Al ₂ O ₃ (%)	6.33	14.84	27.65
Fe ₂ O ₃ (%)	4.22	0.60	6.04
CaO (%)	54.86	36.44	2.86
MgO (%)	2.60	9.08	1.35
SO ₃ (%)	2.66	1.94	0.45
Na ₂ O _{eq} (%)	0.53	0.56	0.64
Loss on ignition (%)	2.42	0.86	4.71
Specific surface area (m ² /kg)	376	430	358

$$\text{Na}_2\text{O}_{\text{eq}} = \text{Na}_2\text{O} + 0.658\text{K}_2\text{O}.$$

Although the early strength of concrete with a large portion of mineral admixtures is low at room temperature, high temperatures can promote the early hydration of a binder. By adjusting the thermostatic time and the thermostatic temperature under steam curing conditions, concrete with a large portion of mineral admixtures may achieve the required form removal strength. To address the problem of form removal strength and promote the high performance of steam-cured concrete that incorporates mineral admixtures, this paper addresses the influence of prolonging the thermostatic time and improving the thermostatic temperature on the form removal strength of concrete that incorporates a large portion of mineral admixtures. Our study also focused on a comparison between the impact of prolonging the thermostatic time and the impact of raising the thermostatic temperature on the hydration degree of a binder, the strength development and the resistance to the chloride ion permeability of concrete, and the volume stability of steam-cured concrete with a large portion of mineral admixtures.

2. Raw Materials and Test Methods

2.1. Raw Materials. P.O 42.5 ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBS), and fly ash (FA) were employed in this study. The chemical compositions and specific surface areas of these powder materials are shown in Table 1. The fine aggregates consisted of natural river sands with particle sizes that ranged from 0.08 to 5 mm. The coarse aggregates consisted of crushed limestone smaller than 25 mm.

2.2. Test Methods. Table 2 exhibits the mix proportions of pastes that were used to measure the hydration property of a composite binder. Table 3 exhibits the mix proportions of concrete. Pastes in the plastic tube were prepared. Concrete samples with the dimensions of $10 \times 10 \times 10 \text{ cm}^3$ were prepared for an experiment on compressive strength and the chloride ion permeability of concrete. Concrete samples with the dimensions of $10 \times 10 \times 300 \text{ cm}^3$ were prepared for an experiment on volume stability of concrete.

The pre-curing time for steam curing was three hours (20°C). The heating and cooling rate was $15 \pm 1^\circ\text{C}/\text{h}$. Eight

TABLE 2: Compositions of the pastes (%).

Sample	Binder			Water/binder ratio
	OPC	GGBS	FA	
CC	100	0	0	0.4
FF	60	0	40	0.4
BB	60	40	0	0.4



FIGURE 1: The measurement of volume stability of concrete.

thermostatic times were adopted: 8 h, 9 h, 10 h, 11 h, 12 h, 13 h, 14 h, and 16 h. Four thermostatic temperatures were adopted: 60°C, 70°C, 80°C, and 90°C. Concrete that was used to measure the compressive strength and chloride ion permeability were cured at 20°C and a relative humidity greater than 95% after steam curing.

The chemically combined water (w_c) content of hydration products was tested by the difference of weight between a sample dried at 80°C and a sample heated at 1060°C, which were standardized by the weight after drying at 80°C, and by subtracting the loss of ignition of the raw materials. The permeability of chloride ion of the concrete was obtained in accordance with ASTM C1202 "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration." In order to control the quality of steam-cured concrete, the deviation of strength was restricted to be less than 10%. The determination of the degree of reaction of fly ash was based on a selective dissolution procedure using concentrated hydrochloric acid and water [19, 20]. The determination of the degree of reaction of GGBS was based on a selective dissolution procedure using salicylic acid-methanol-acetone solution [21].

This study involves an experiment on the volume stability of concrete. Concrete that was used to measure volume stability was cured in a saturated $\text{Ca}(\text{OH})_2$ solution at 20°C after steam curing. As water is a necessity to DEF, the specimens after steam curing were placed in a saturated $\text{Ca}(\text{OH})_2$ solution to keep concrete completely wet during curing. This type of practice can prevent $\text{Ca}(\text{OH})_2$ dissolution and drying shrinkage. The consequence of the volume stability analysis was confirmed by measuring the lengths of the concrete specimens using a comparator at scheduled ages. Test probes were installed in advance on both ends of the concrete specimens. Concrete that was used to measure volume stability and the process of measuring volume stability are shown in Figure 1.

3. Results and Discussion

3.1. Form Removal Strength of Concrete. The influence of thermostatic time and thermostatic temperature on the form removal strength of steam-cured concrete is presented in

TABLE 3: Mix proportions of the concrete (kg/m³).

Sample	OPC	GGBS	FA	Fine aggregates	Coarse aggregates	Water
C	350	0	0	812	1077	161
F30	245	0	105	812	1077	161
F40	210	0	140	812	1077	161
F50	175	0	175	812	1077	161
B30	245	105	0	812	1077	161
B40	210	140	0	812	1077	161
B50	175	175	0	812	1077	161
B60	140	210	0	812	1077	161

TABLE 4: Removal strengths under different curing conditions.

Samples	Thermostatic temperature/°C	Thermostatic time/h	Removal strength/MPa
C	60	9	28.7
F30	60	11	23.7
	80	9	35.7
F40	60	11	17.7
	80	9	29.7
F50	60	13	10.4
	80	11	26.8
B30	60	11	27.8
	80	9	31.0
B40	60	11	32.7
	80	9	27.2
B50	60	11	20.0
	80	9	22.6
B60	60	11	19.4
	80	10	27.8

Table 4. The form removal strength of pure cement concrete that is cured at 60°C for 9 h in steam curing is established as the control group. When a thermostatic temperature of 60°C is maintained, the form removal strength of concrete F30 (thermostatic time: 11 h), F40 (thermostatic time: 11 h), and F50 (thermostatic time: 13 h) is lower than the form removal strength of the control group. When a thermostatic temperature of 80°C is maintained, the form removal strength of concrete F30 and F40 (thermostatic time: 9 h) is higher than the form removal strength of the control group. When the thermostatic temperature is increased to 80°C and the thermostatic time is simultaneously prolonged to 11 h, the form removal strength of concrete F50 is also similar to the form removal strength of the control group. It is an indication that the degree of influence of raising the thermostatic temperature on the form removal strength of concrete containing FA is superior to the degree of influence of prolonging the thermostatic time on the form removal strength of concrete containing FA. Raising the thermostatic temperature to 80°C can attain satisfactory form removal strength.

By utilizing the form removal strength of pure cement concrete under steam curing at 60°C for 9 h as the reference, the form removal strength of concrete B30 and B40 cured at 80°C for 9 h is similar to the form removal strength of the control group. The form removal strength of concrete B50

that was cured at 80°C for 9 h is obviously lower than the form removal strength of the control group. However, by prolonging the thermostatic time to 10 h, the form removal strength of concrete B60 that was cured at 80°C is similar to the form removal strength of the control group. By prolonging the thermostatic time to 11 h and controlling the thermostatic temperature (60°C) as a constant, the form removal strengths of concrete B30 and B40 are similar to the form removal strength of the control group and the form removal strengths of concrete B50 and B60 are lower than the form removal strength of the control group. Both raising the thermostatic temperature and prolonging the thermostatic time enhance the form removal strength of concrete that incorporates a large portion of GGBS. When the content of GGBS in cementing materials exceeds 50%, methods of prolonging the thermostatic time and raising the thermostatic temperature need to be simultaneously employed to obtain the satisfactory form removal strength as the influence of prolonging the thermostatic time on enhancing the form removal strength is limited.

3.2. *Chemically Combined Water Content.* w_c content of hydration products reveals the hydration degree of the same binder. The influences of the thermostatic time on w_c content of cement paste, the paste containing a large portion of GGBS,

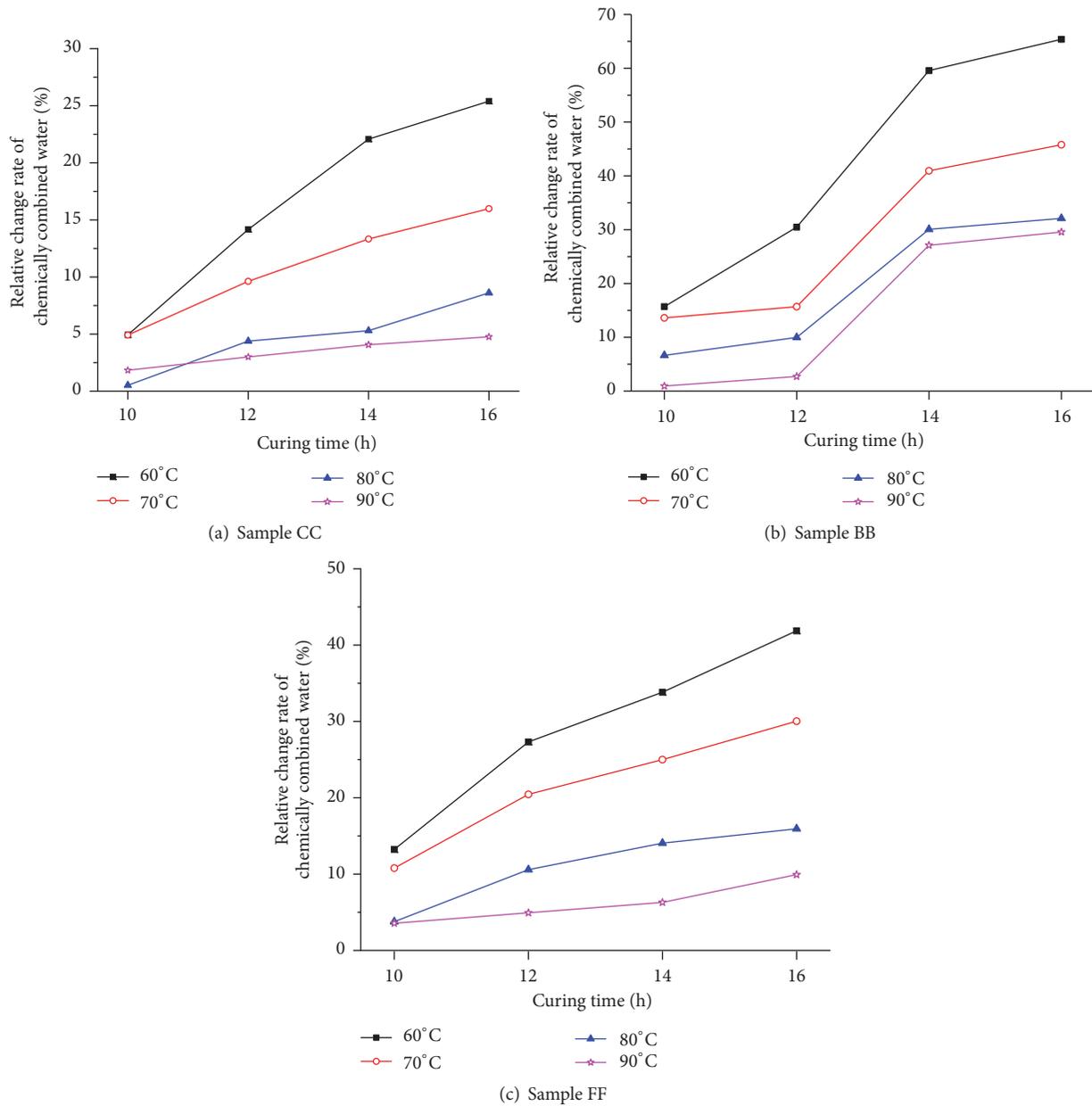


FIGURE 2: The influence of thermostatic time on w_c content.

and the paste containing a large portion of FA are illustrated in Figures 2(a), 2(b), and 2(c), respectively, at the end of the steam curing process. The ordinates in Figure 2 denote the relative change rate of w_c content of pastes that were cured for 10 h, 12 h, 14 h, and 16 h relative to the paste cured for 8 h.

Figure 2(a) indicates that w_c content of pure cement paste increases with an increase in thermostatic time; however, if the curing temperature in the thermostatic period is low, the growth rate of w_c content is high with the extension of thermostatic time. This finding may be attributable to this reason: 8 h of curing in the thermostatic period is sufficient for the hydration degree of cement achieving a high level when the temperature in the thermostatic period is sufficiently high. Few contributions to improving the

hydration degree of cement have been achieved by prolonging the thermostatic time under this circumstance.

Conclusions can be drawn from Figures 2(b) and 2(c). (1) When the curing temperature in the thermostatic period is low, the growth rates of w_c content of the binder with a large portion of GGBS and the binder with a large portion of FA are high due to the extension of thermostatic time, which is similar to the pure cement paste. (2) The order of the degree of influence of prolonging the thermostatic time on improving w_c content of binders is the binder containing large portion mineral admixtures > the pure cement paste at the same thermostatic temperature. This finding may be attributable to this reason: when considering the binder containing a large portion of GGBS or FA, the thermostatic time may

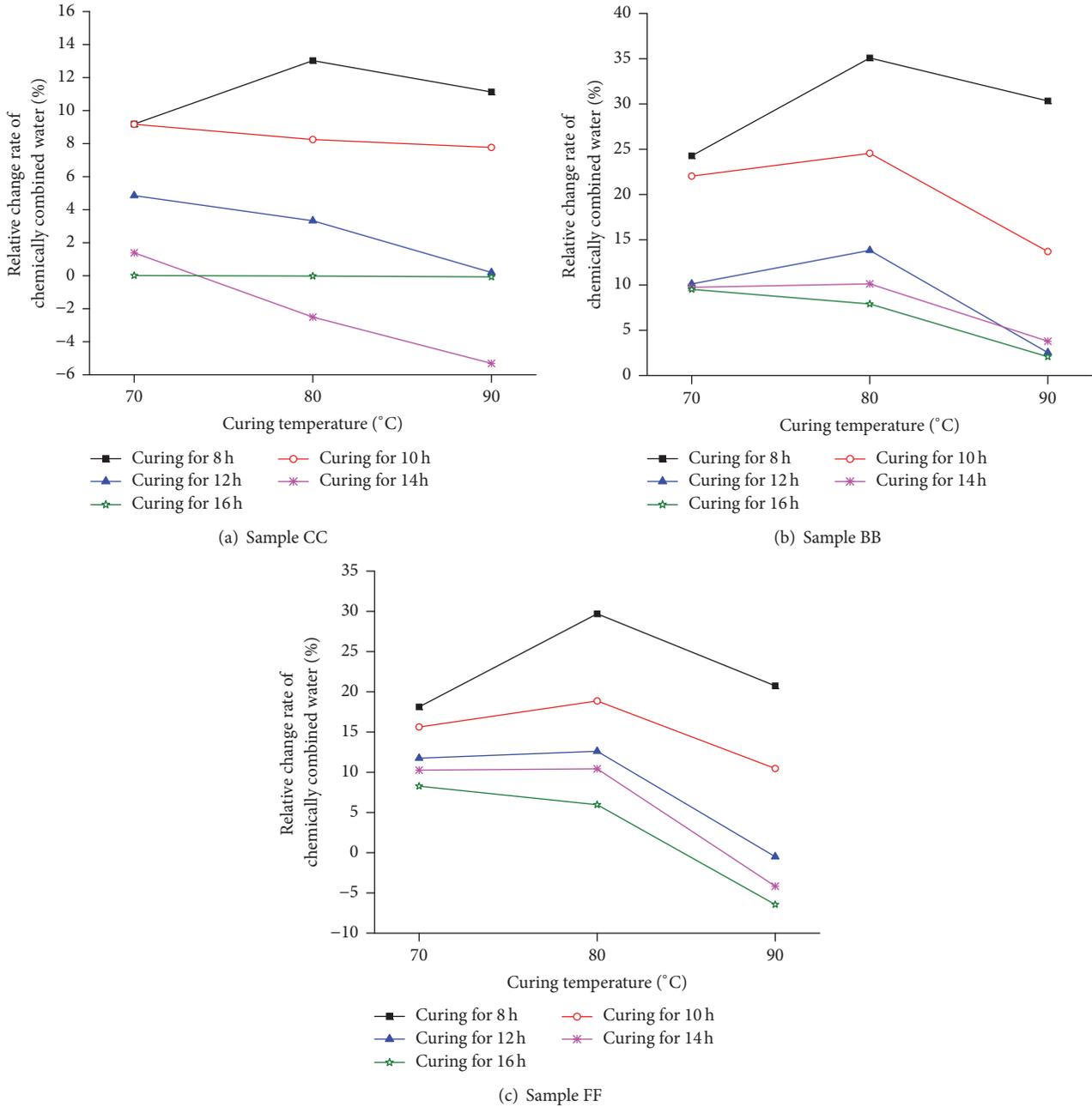


FIGURE 3: The influence of thermostatic temperature on w_c content.

improve not only the hydration reaction of cement but also the reaction of GGBS or FA. (3) The order of the degrees of influence of prolonging the thermostatic time on improving w_c content of binders is the binder containing a large portion of GGBS > the binder containing a large portion of FA. The order of the degree of influence of the thermostatic time on the hydration degree is the binder containing a large portion of GGBS > the binder containing a large portion of FA. This finding is consistent with the trend for the form removal strength that is presented in Table 4.

The influence of the thermostatic temperature on w_c content of cement paste, the paste containing a large portion

of GGBS, and the paste containing a large portion of FA at the end of the steam curing process is illustrated in Figures 3(a), 3(b), and 3(c), respectively. The ordinates in Figure 3 denote the relative change rate of w_c content of pastes cured at 70°C, 80°C, and 90°C relative to the paste cured at 60°C. A positive relative change rate indicates that an increase in the thermostatic temperature from 60°C can further enhance the hydration of binder. A negative relative change rate indicates that an increase in the thermostatic temperature from 60°C would inhibit the hydration of binder.

Figure 3(a) reveals that w_c content of the hydration products of cement has not always increased with an increase

TABLE 5: Reaction degree of fly ash and GGBS/%.

	Thermostatic temperature/ $^{\circ}$ C	Thermostatic time/h		
		8	12	16
Fly ash	60	2.11	4.26	6.39
	80	5.79	7.96	9.73
GGBS	60	7.86	10.15	13.18
	80	9.84	13.15	15.25

in the thermostatic temperature. When the thermostatic time is 8 h, 10 h, 12 h, and 14 h, w_c content initially increases and subsequently decreases with an increase in thermostatic temperature. When the thermostatic time is 16 h, w_c content remains unchanged with an increase in the thermostatic temperature. Therefore, when the thermostatic period is short, an increase in the thermostatic temperature from 60° C to 70° C can enhance the hydration degree of pure cement paste. For a long thermostatic period, an increase in the thermostatic temperature is not needed to enhance the hydration degree of pure cement paste.

Conclusions can be drawn from Figures 3(b) and 3(c): (1) when the thermostatic temperature increases from 60° C to 70° C, w_c content of every group increases; (2) when the thermostatic temperature increases from 70° C to 80° C, w_c content of the pastes, which have thermostatic times of 8 h, 10 h, and 12 h, increases, and w_c content of the pastes, which have a thermostatic time of 14 h and 16 h, remains unchanged or slightly decreased; (3) when the thermostatic temperature increases from 80° C to 90° C, w_c content of every group decreases. Note that the change rate of w_c content of the paste containing a large portion of FA (thermostatic period: 90° C/14 h or 16 h) relative to the change rate of the paste cured at 60° C is negative.

This result indicates that increasing the thermostatic temperature to 80° C can effectively enhance the hydration degree of paste containing a large portion of FA or GGBS. Compared with Figure 3(a), by increasing the thermostatic temperature, the hydration promoting effect of paste containing a large portion of FA or GGBS is more apparent than the hydration promoting effect of pure cement paste. This finding may be attributable to two reasons: firstly, increasing the thermostatic temperature not only improves the hydration reaction of cement but also stimulates the activity of FA or GGBS; secondly, the reaction degree of fly ash and GGBS is much lower than that of cement at normal temperature.

3.3. The Reaction Degree of Mineral Admixtures. The influence of the thermostatic time on the reaction degree of GGBS and FA is presented in Table 5. Regardless of whether the thermostatic temperature is 60° C or 80° C, the reaction degree of GGBS or FA will increase with an extension of the thermostatic time. This result may be attributed to this reason: the longer is the thermostatic time, the longer is the time required to stimulate the activity of GGBS or FA, which will increase the reaction degree of GGBS or FA.

Table 5 also reveals that the reaction degree of FA (thermostatic period: 60° C/8 h) is only 2.1%, which demonstrates

that FA only serves a role in the microaggregate filling effect in this situation. The reaction degree of FA (thermostatic period: 60° C/16 h) is 6.4%, which is substantially higher than the reaction degree of FA after 8 h of curing during the thermostatic period. However, the reaction degree remains at a low level from the point of absolute value. Therefore, prolonging the thermostatic time at 60° C is not an effective way for the concrete containing a large portion of FA to achieve a satisfactory form removal strength. Conversely, the reaction degree of GGBS at 60° C for 8 h is 7.9%, which even exceeds the reaction degree of FA at 60° C for 16 h. The absolute value of the reaction degree of GGBS is obviously higher than that of the reaction degree of FA in an equivalent steam curing system, which suggests that the chemical effect of GGBS is obviously higher than the chemical effect of FA in the early steam curing process.

The following can also be concluded from Table 5. (1) When the thermostatic temperature increases from 60° C to 80° C, the reaction degree of GGBS and FA is improved. (2) The influence of increasing the thermostatic temperature on the reaction degree of FA is more significant from the point of growth.

From the perspective of the reaction degree of mineral admixtures as well as the hydration degree of the whole binder, it is obvious that the promoting effect of increasing the thermostatic temperature is more significant than the promoting effect of prolonging the thermostatic time on the early hydration of the binder containing a large portion of FA. Increasing the thermostatic temperature and prolonging the thermostatic time have a significant role in promoting the hydration of GGBS. This case also applies to the influence of the thermostatic temperature and thermostatic time on the form removal strength of concrete.

3.4. Strength Development of Concrete. The comparison between the strength development of pure cement concrete after steam curing and the strength development of steam-cured concrete containing a large portion of GGBS and FA is shown in Figure 4. The strength development of pure cement concrete (thermostatic period: 60° C/9 h) is employed as the reference. Figure 4(a) shows the strength development of concrete containing FA after steam curing at 80° C. As shown in Figure 4(a), although the form removal strength of steam-cured concrete containing a large portion of FA is not lower than the form removal strength of the control group, the compressive strength of steam-cured concrete containing a large portion of FA is substantially lower than the form removal strength of the control group at the age of 28 days

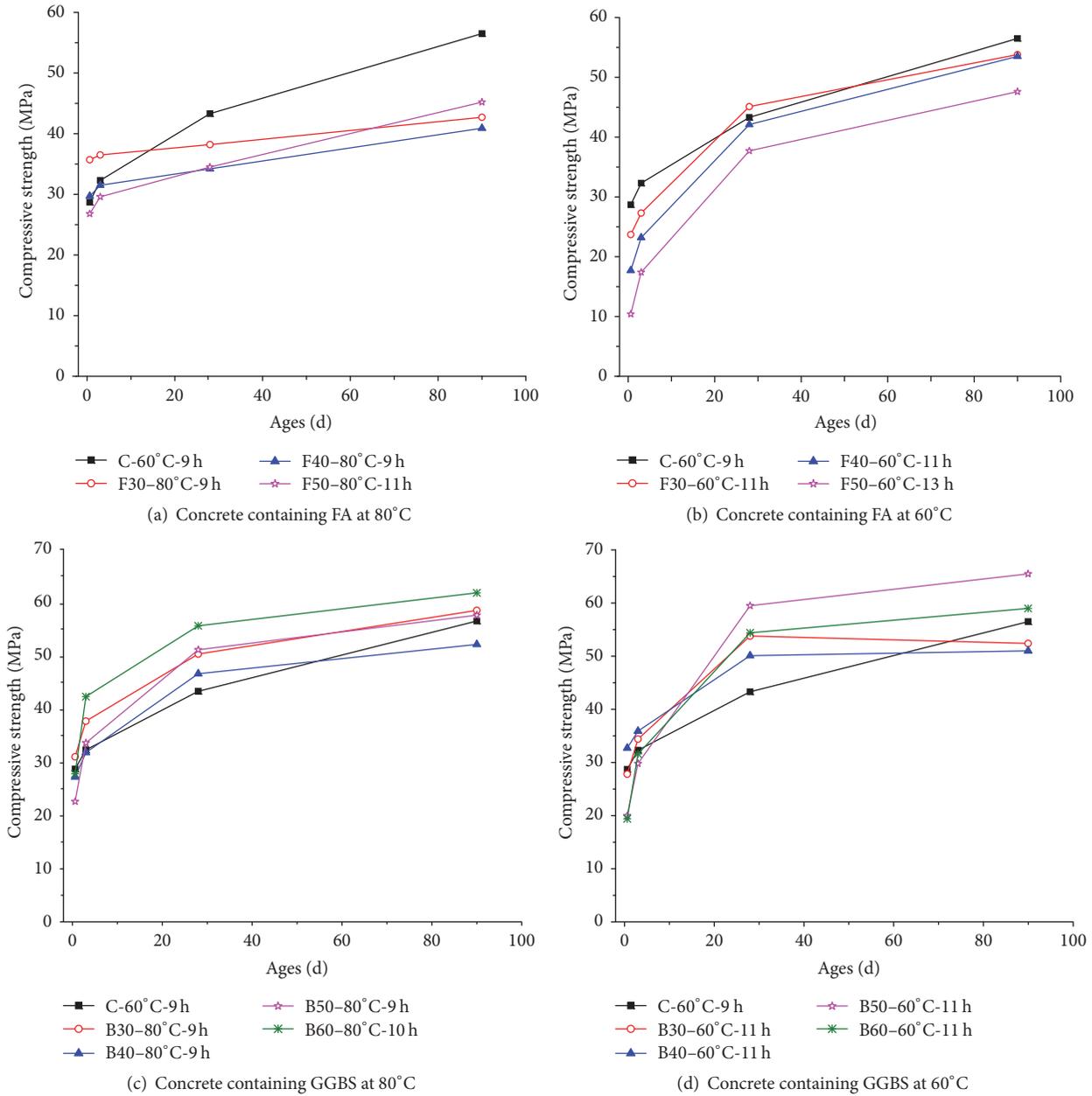


FIGURE 4: Comparison of strength development between pure cement concrete and concrete containing large portion FA or GGBS under steam curing.

and 90 days. After the age of three days, the strength growth of steam-cured concrete containing a large portion of FA is very slow, which differs from the strength growth of ordinary concrete containing FA [22–24]. The greater the content of FA, the greater the contribution of the pozzolanic reaction to the strength at a later age, and the greater the potential for subsequent growth of concrete. High temperatures enhance the form removal strength of concrete containing FA at an early age; however, it hinders the strength development of concrete at a later age. Possible reasons for this phenomenon are as follows. (1) When the thermostatic temperature is 80°C, the early reaction of cement is significant. The gel layer of

C-S-H can be formed in the particles' surfaces of cement and FA, which is disadvantage for further hydration of binder at a later age. (2) The distribution of the hydration product of cement is uneven at elevated temperatures, and a large amount of $\text{Ca}(\text{OH})_2$ crystal exhibits orientation distribution. Thus, the contact area between FA and $\text{Ca}(\text{OH})_2$ is reduced. The pozzolanic reaction of FA at a later age is restricted.

Figure 4(b) shows the strength development of concrete containing FA after steam curing at 60°C. As shown in Figure 4(b), although the growth rate of the late strength of concrete containing FA is similar to the growth rate of the control group, the form removal of concrete containing FA

TABLE 6: Chloride ion permeability of concrete.

Samples	Thermostatic temperature/ $^{\circ}$ C	Thermostatic time/h	28 d		90 d	
			Charge passed/C	Permeability level	Charge passed/C	Permeability level
C	60	9	7111	High	4338	High
F30	60	11	1714	Low	700	Very low
	80	9	644	Very low	503	Very low
F40	60	11	1707	Low	510	Very low
	80	9	682	Very low	278	Very low
F50	60	13	1952	Low	607	Very low
	80	11	518	Very low	200	Very low
B30	60	11	2094	Moderate	1350	Low
	80	9	2628	Moderate	1709	Low
B40	60	11	2424	Moderate	1535	Low
	80	9	2765	Moderate	1650	Low
B50	60	11	1668	Low	1117	Low
	80	9	2075	Moderate	1213	Low
B60	60	11	1515	Low	813	Very low
	80	10	1150	Low	775	Very low

is lower than the growth rate of the control group, especially for the larger content of FA of concrete. At a thermostatic temperature of 60° C, the form removal strength of concrete containing FA is relatively low, which explains why the stimulation degree of 60° C for the early activity of the binder containing a large portion of FA is limited.

Figures 4(c) and 4(d) show the strength development of concrete containing GGBS after steam curing at 60° C and 80° C, respectively. Regardless of whether the thermostatic time is prolonged or the thermostatic temperature is increased, the early strength and the strength growth rate at a later age of concrete that contain a large portion of GGBS are similar to the early strength and the strength growth rate of the control group. Therefore, at high temperatures, the effect of GGBS exceeds the effect of FA in the process of the formation of the concrete strength: first, at 60° C, GGBS exhibits a relatively high activity at an early age and it substantially contributes to the form removal strength and early strength; second, GGBS can display substantial early activity at 80° C; third, even if the concrete containing a large portion of GGBS is cured at 80° C, it can obtain a satisfactory late strength. This finding suggests that GGBS serves an important role in the late strength growth of steam-cured concrete; that is, after steam curing at a high temperature, GGBS can still take a considerable pozzolanic reaction at a high reaction rate at a later age.

3.5. Resistance to Chloride Ion Permeability of Concrete. The comparison between chloride ion permeability of concrete containing a large portion of FA or GGBS and the chloride ion permeability of pure cement concrete after steam curing is illustrated in Table 6. The chloride ion permeability of pure cement concrete (thermostatic period: 60° C/9 h) at the same age is employed as the reference. According to ASTM C1202, which is related to the chloride ion permeability

grade classification, the permeability of the control group at 28 d falls in the “High” level, the permeability of concrete containing FA which is cured at 80° C falls in the “Very Low” level, and the permeability of concrete containing FA which is cured at 60° C falls in the “Low” level. At the age of 90 days, the permeability of the control group falls in the “High” level, and the permeability of concrete containing FA which is cured at 60° C and 80° C falls in the “Very Low” level. This finding suggests that the resistance to chloride ion permeability of steam-cured concrete containing FA is substantially better than the resistance of pure cement concrete, which is one of the advantages to steam-cured concrete containing a large portion of FA. FA can enhance the resistance to chloride ion permeability of concrete at a later age, which has been confirmed by a large number of experiments [25]. The main reason for this improvement is the ability of FA to improve on the pore structure of concrete due to pozzolanic reaction [26]; the secondary hydration products decrease the connected porosity of concrete. Therefore, the higher is the reaction degree of FA, the greater is the contribution to the resistance to the chloride ion permeability of concrete. High temperature curing at an early age can significantly stimulate the activity of FA and enhance the reaction degree of FA. Thus, FA enhances the resistance of steam-cured concrete to chloride ion permeability.

At the age of 28 days, the permeability of steam-cured concrete containing GGBS falls in the “Moderate” or “Low” levels. At the age of 90 days, the permeability of steam-cured concrete containing GGBS falls in the “Low” or “Very Low” levels. The greater is the mixing amount of GGBS, the better is the resistance to the chloride ion permeability of concrete. Compared with pure cement concrete, the concrete containing GGBS can achieve better resistance to chloride ion permeability. In addition, the chloride ion permeability of steam-cured concrete containing GGBS of each group

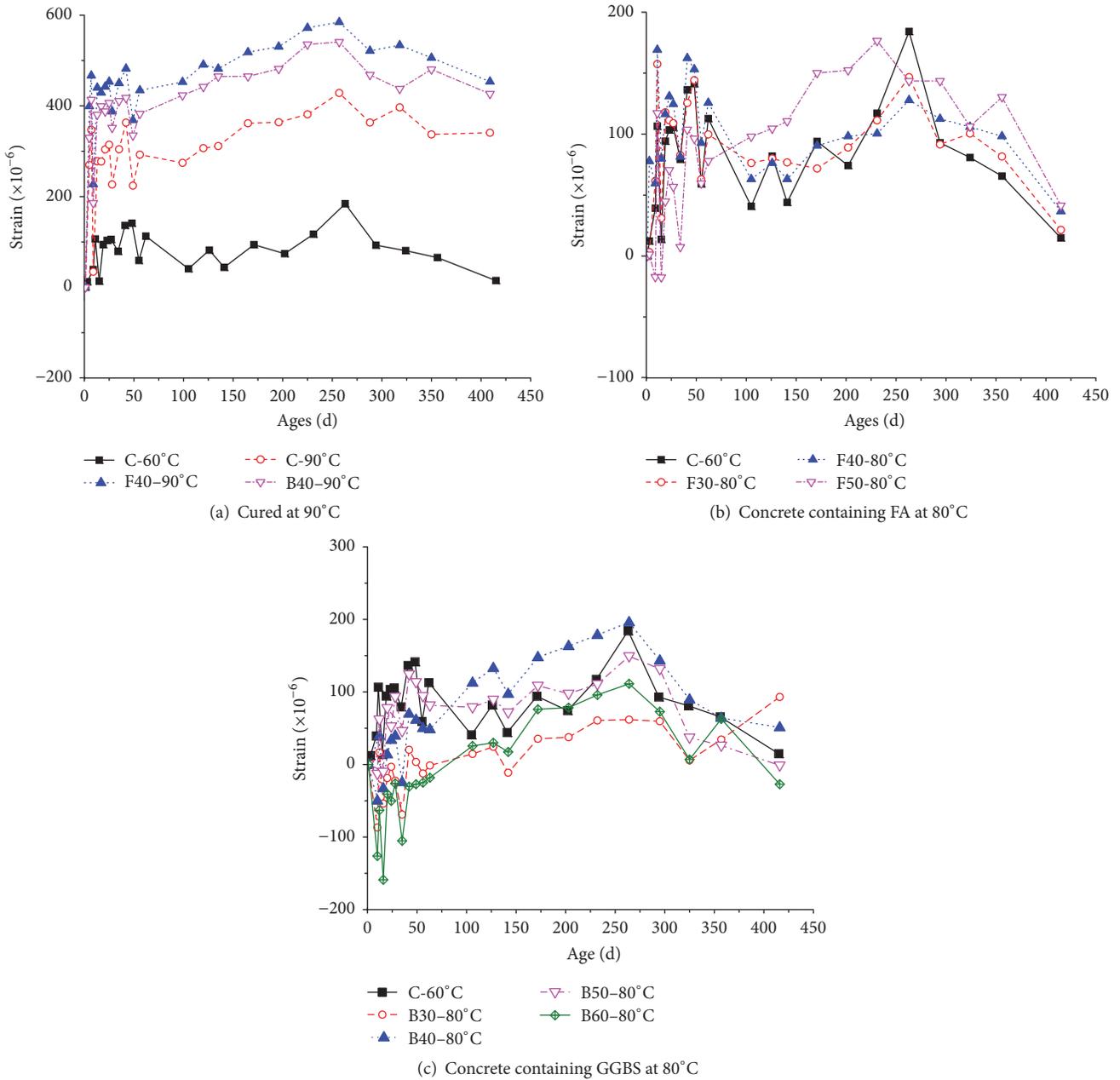


FIGURE 5: Volume deformation of steam-cured concrete.

is not substantially different due to the difference in the curing systems, as both prolonging the thermostatic time and improving the thermostatic temperature can stimulate the reaction activity of GGBS and substantially improve the pore structure of concrete. The effect of the late performance of resistance to chloride ion permeability improved by FA is better than the effect by GGBS. Although the reaction degree of GGBS is higher than the reaction degree of FA after steam curing, the pozzolanic reaction of FA can consume a mass of $\text{Ca}(\text{OH})_2$. The amount of $\text{Ca}(\text{OH})_2$ consumed by GGBS is minimal. Therefore, the reaction of FA plays a significant role in improving the pore structure of concrete.

3.6. Volume Stability Analysis of Concrete. The comparison between the volume deformation of steam-cured concrete containing a large portion of FA or GGBS and the volume deformation of pure cement concrete after steam curing is presented in Figure 5. Figure 5(a) shows the comparison between the volume deformation of concrete containing a large portion of FA or GGBS, the volume deformation of pure cement concrete with steam curing at 90°C, and the volume deformation of pure cement concrete with steam curing at 60°C. The microstrain of pure cement concrete (thermostatic period: 60°C/8 h) is employed as the reference. For steam curing at 90°C, the inflation rates for the cement concrete and

the concrete containing a large portion of FA or GGBS are relatively high, of which the late microstrain varies from 200 to 600. However, the late microstrain of the control group is less than 200. These results indicate that the inflation rates of the cement concrete and the concrete containing a large portion of FA or GGBS are substantially higher than the inflation rates of the control group. A large number of studies have proven that DEF cannot weaken the late performance of concrete at thermostatic temperatures below 60°C. Thus, the inflation rate of the control group can be considered to be a safe value. Conversely, the possibility of the structure of the cement concrete and the concrete containing a large portion of FA or GGBS destroyed by DEF after steam curing at 90°C is significant.

The volume deformation of steam-cured concrete containing a large portion of FA and GGBS with steam curing at 80°C is illustrated in Figures 5(b) and 5(c), respectively. All the concrete types produce normal strain with a certain degree at a later age. The strains of steam-cured concrete containing a large portion of FA or GGBS at 80°C are similar to the strains of the control group. Therefore, the risk of destroying the structure of concrete containing a large portion of FA or GGBS due to DEF when specimens were steam-cured at 80°C is minimal.

4. Conclusions

- (1) Improving the thermostatic temperature is more favourable for concrete containing FA, as indicated by the significantly higher form removal strength and higher growth of reaction degree of FA compared with the method of prolonging the thermostatic time. Both improving the thermostatic temperature and prolonging the thermostatic time contribute to a distinct enhancement of the form removal strength of concrete that incorporates a large portion of GGBS and the reaction degree of GGBS.
- (2) With an increase in the thermostatic temperature from 60°C to 90°C, the hydration degree of binder containing FA or GGBS initially increases and subsequently decreases.
- (3) Concrete containing FA can obtain satisfactory form removal strength with steam curing at 80°C; however, the late strength growth rate of concrete containing FA is low for the same curing conditions.
- (4) The effect of late performance of resistance to chloride ion permeability improved by FA is better than the same effect achieved by GGBS.
- (5) The risk of destroying the structure of concrete containing FA or GGBS due to DEF when specimens were steam-cured at 80°C is minimal.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

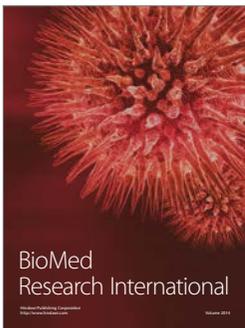
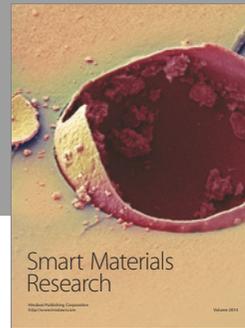
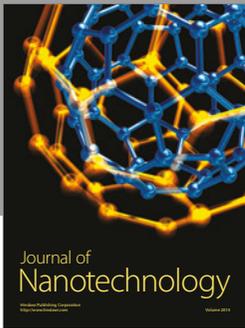
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