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Influence of steam curing on the compressive strength of concrete containing supplementary cementing materials

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Abstract

Heat treatment is widely used to accelerate the strength-gaining rate of concrete. In general, the ultimate strengths of the heated-treated concrete are lower than those of the standard cured specimens. When ultrafine fly ash (UFA) is included in concrete, the pozzolanic reaction is accelerated through the heat treatment. Sometimes, various chemical activators were used to activate the reactivity of fly ash. In the current study, UFA and slag were used as a replacement for cement, steam curing and chemical activators were used to accelerate hydration of cement and fly ash, and then compared with moist curing. This paper presents the influence of steam curing on the compressive strength of concrete containing UFA with or without slag. The experimental results indicated that the concrete containing UFA has low early strength after 13-h steam curing and that the difference between the 28-day compressive strength of concrete through 13-h steam curing and that of moist-cured concrete is large, but the concrete with UFA and $CaSO_4$ or $Ca(OH)_2$ has a high early strength, thus, the reactivity of fly ash must be accelerated. Concrete containing UFA and ground slag was prepared, whose compressive strengths were improved.

Keywords: Fly ash; Slag; $CaSO_4$; $Ca(OH)_2$; Steam curing; Compressive strength

1. Introduction

Fly ash has been widely used as a partial replacement of cement in concrete for over half a century. The benefits include saving cement and lowing the heat of hydration in mass concrete. Fly ash has a larger output in China, the production is more than 100 million tons/year [1]. Because of critical contamination, the development of fly ash as supplementary cementitious materials in China is the first priority. The fly ash has been used in concrete for long time; it was found that the workability of concrete was improved, and the high-performance concrete with grade C70–C80 was achieved [2], whose compressive strength is above 78 MPa [3].

The hardening process and strength-gaining rate of concrete under normal conditions are slow; they affect the production rate of concrete plants. Therefore, it is beneficial to provide a desired strength level for concrete in a short time by accelerating its hardening process using various methods. Heat treatment is among the methods widely used for this purpose. At present, some concrete plants in China adopt ordinary high-strength concrete. The strength grade of concrete is C50–C60 [3], the content of cement in concrete is as high as 500 kg/m^3.

Several studies were published in the last decade on the reactivity of fly ash by various chemical activators ($CaSO_4$, Na_2SO_4, $CaCl_2$, Alkali, Waterglass, etc. [4–9]). The use of fly ash together with Portland cement causes a reaction between the glassy phase of fly ash and the calcium hydroxide generated from the hydration of Portland cement, which leads to the formation of additional C-S-H gel and results in higher density and strength. The fly-ash-blended cement has well adaptability of steam curing [10], and curing temperatures above 20 °C improves the strength of a cement mortar containing 20% fly ash more than it improved the strength of the control Portland cement concrete [11].

Research by Ma et al. [4] on the hydration behavior of low-lime fly-ash-blended cement over the temperature range of 10 to 55 °C at the early stage has shown that low-lime fly ash is relatively inert at these temperatures and that its presence may actually retard the hydration of Portland cement. But the data from Maltais and Marchard [5] indicated that an increase of the curing temperature is

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Table 1
Chemical composition and finenesses of cementing materials

Compound	Ordinary portland cement	UFA	GGBFS
SiO_2	24.3	52.7	28.3
Fe_2O_3	3.8	9.7	1.5
Al_2O_3	4.8	25.8	13.6
CaO	55.3	3.7	38.4
MgO	4.2	1.2	7.2
SO_3	2.2	0.2	2.4
K_2O		1.6	
Na_2O		0.7	
IL	2.4	2.4	0.4
Blaine fineness (m^2/kg)	330	500	590

much less detrimental for fly ash mixtures and that it can, in certain cases, even have a beneficial influence on the long-term compressive strength of the material.

Kjellsen et al. [12] described the results of experiments in which the pore structure of plain cement hydrated at different temperatures. They concluded that, for plain cement pastes of equal water/cement ratios hydrated to approximately the same degree of hydration, the higher the curing temperature, the greater the total porosity. Campbell and Detwiler [13] examined the compressive strength of cylinders after 18-h steam cure and 1-day moist cure. The conclusion is that, compared with control concrete, the compressive strength was increased by as much as 33% for concretes by incorporating appropriate quantities of silica fume with or without slag. Paya et al. [14] presented that the influence of fly-ash grinding on the strength development of fly ash/cement mortars cured at 20 and 40 °C was a significant increase of compressive strength for fly ash mortars found at early age, when curing temperatures is raised.

In current study, ultrafine fly ash (UFA) and slag were used as a replacement for cement; steam curing was used to accelerate hydration of fly ash with or without chemical activators. This paper presents the influence of steam curing on the compressive strength of concrete containing UFA with or without slag.

2. Experimental procedure

The cement used is 525 ordinary portland cement and complies with Chinese National standard GB175-92 [15]; its 28-day compressive strength is 56.4 MPa. The fine aggregates came from the Xiangjiang River, and its fineness modulus is 2.88. The coarse aggregates are broken gravel, with nominal maximum size of 25 mm, and its crushed index is 8.0%. A superplasticizer of sulfonated naphthalene formaldehyde base is used in the mix and complies with Chinese National Standard specified by GB8077-87 [16], whose commercial name is TQN. The ultrafine powder is UFA. The ground granular blast furnace slag (GGBFS) came from Xiangtan steel plant. Table 1 gives the chemical compositions and finenesses of cement, UFA and GGBFS. Table 2 gives the results of granulometry tests of cement and UFA.

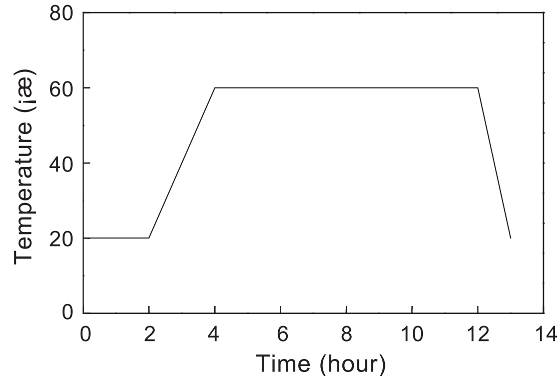

Fig. 1. Heat treat cycle applied.

The specimen used for cubic compressive strength in this paper has a measurement of 100 × 100 × 100 mm. The heat treat cycle applied is illustrated schematically in Fig. 1. The treatment temperature and its duration together have a profound effect on the evolution of hydration reaction and the products. In this study, heat treatment cycle has a total duration of 13 h, the preheating duration is 2 h, the heating duration is 2 h, the treatment duration is 8 h, and the cooling duration is 1 h. The treatment temperature was chosen to be 60 ± 5 °C, and the humidity in the steam-curing box was above 90%.

Mixing and specimen preparation was performed at room temperature. After steam curing, the specimens were removed from their moulds, and some were used to measure the compressive strength (named as f_{sc}) at once. The others were put in the standard curing room, with its 28-day compressive strength named as f_{sc28}. The 28-day compressive strength of concrete with moist curing after moulding is named as f_{mc28}.

3. Results and discussion

3.1. Compressive strength of steam-cured concrete containing UFA

Table 3 illustrates the variation of compressive strength of concrete cured at different conditions. The

Table 2
Particle size distribution of cement and UFA

Size (μm)	0–2.8	2.8–3.9	3.9–5.5	5.5–11	11–16	16–31	31–88	88–92.5
Cement	2.3	4.8	6.7	19.6	1.9	27.2	32.2	4.6
UFA	6.8	7.4	6.1	11.6	13.4	52.4	1.9	0

Table 3
The mix proportions and experimental results of concrete containing UFA after steam curing

Specimen	Mix proportions (kg/m^3)				Compressive strength (MPa)			$f_{cuz}/f_{cuz,28}$ (%)	$f_{cuz,28}/f_{cu,28}$ (%)
	C	UFA	W	TQN	f_{cuz}	$f_{cuz,28}$	$f_{cu,28}$		
1	300	200	130	4	44.6	63.2	78.1	70.6	80.9
2	300	200	130	4	43.3	70.6	82.3	61.3	85.8
3	300	200	130	4	48.0	62.3	76.3	77.0	81.7
4	300	200	130	4	47.8	61.7	72.1	77.5	85.6
5	350	150	140	4	49.5	61.5	72.2	80.5	85.2
6	300	200	120	6	46.5	58.4	78.3	79.6	74.6
7	300	200	110	6	49.1	64.3	73.2	76.4	87.9
8	500	–	135	4	55.2	72.9	70.3	75.7	103.7
9	500	–	150	5	50.8	70.9	76.3	71.7	92.9

The slump of mixture is about 10–30 mm.

experimental results indicate that steam-cured concrete with UFA has lower 28-day compressive strength after demoulding, but the specimens with UFA exposed to moist curing exhibited a greater increase in compressive strength. The ratio of early strength after 13-h steam curing and 28-day strength is about 0.7, but the compressive strength of steam-cured concrete is lower than that of moist curing at 28 days, which predicates that the strength-gaining rate of concrete is lower after steam curing and that steam-cured ordinary concrete has this problem too [17]. At higher temperatures, the hydration rate of cement increases quickly, the generation speed of gel increase, and the hydration results in the formation of gel around each of the cement particles. The hydration rate of cement and the diffusion rate of hydration product are fast, but the dissolving rate is slow, hence, the gel layer becomes thick and dense gradually. The penetration of water into gel layer is counteracted, and the hydration of unhydrated cement particle is retarded; the later compressive strength has lesser increment. The higher the temperature is, and the longer the steam curing time is, the lower the later strength-gaining ratio.

Numbers 6 and 7 shown in Table 3 are based on the increment of superplasticizer content, and the water–binder ratio is 0.22–0.24, but the compressive strength is not improved observably. And also, the difference of demoulding compressive strength between cement concrete and concrete containing UFA is remained. This result demonstrated that the concrete containing UFA has poor adaptability of steam curing. If the demoulding compressive strength needs to be enhanced, the fly ash must be improved.

3.2. Compressive strength of steam-cured concrete containing UFA and activators

The mix proportions are same as that of Number 1 shown in Table 3, but the chemical activators were used by mass; the results were shown in Figs. 2 and 3.

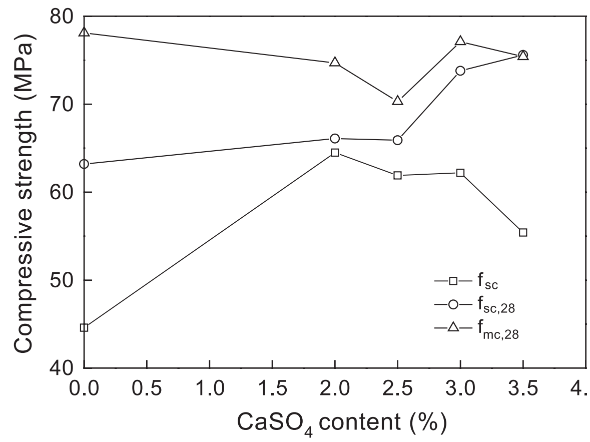

Fig. 2. Influence of $CaSO_4$ content on the compressive strength.

Compared with the results shown in Table 3, the results shown in Fig. 2 indicates that early compressive strength after 13-h steam curing is improved observably, but decreases when the content of $CaSO^4$ exceeds 2%. The difference between the 28-day compressive strength of steam-curing specimens and that of moist-curing specimens decreases gradually with the increment of $CaSO_4$ content, and there is less effect on the compressive strength of moist-cured concrete. Under steam-curing condition, the more the calcium sulphate content is, the more the produced ettringite is, which can expand and results in crack in concrete, then, the strength of concrete decreases. The results of $Ca(OH)_2$ influencing the compressive strength are shown in Fig. 3. Besides the early strength, the strengths decrease approximately with the increment of $Ca(OH)_2$ content. The early strength after 13-h steam curing is constant approximately. When the content of $Ca(OH)_2$ exceeds 2%, the effect of $Ca(OH)_2$ as an activator is less than that of $CaSO_4$ compared with the results shown in Fig. 2. Under steam-curing condition, fly ash has lower activity even if $Ca(OH)_2$ exists in

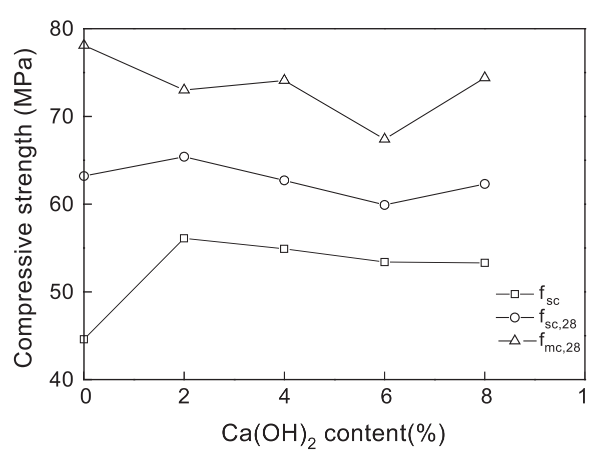

Fig. 3. Influence of $Ca(OH)_2$ content on the compressive strength.

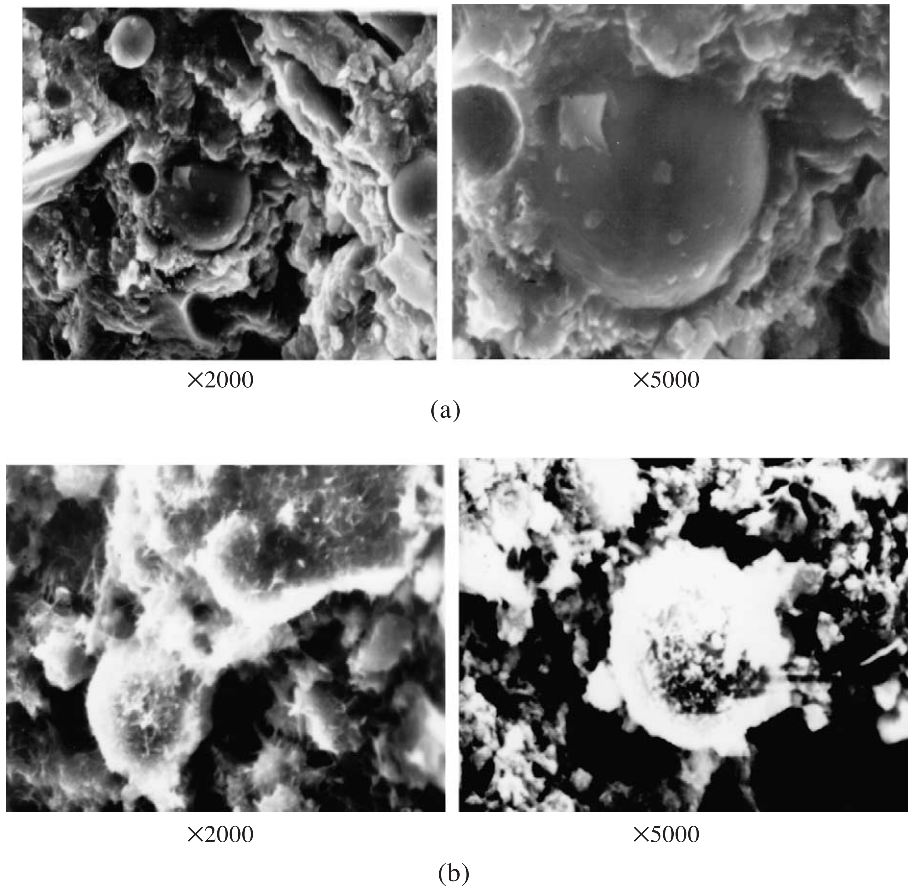

Fig. 4. Micrograph of SEM. (a) Concrete containing UFA after 13-h steam curing; (b)concrete containing UFA and $CaSO_4$ after 13-h steam curing.

concrete, thus, the produced hydration is less. When the content of $Ca(OH)_2$ is more than 2%, the influence is less.

Fig. 4 is a micrograph of concrete containing ultrafine powders. Most of the fly ash particles seen in Fig. 4a were well embedded in the paste and were round and smooth. In some cases, etching of glassy materials was rarely visible in Fig. 4a. This result is consistent with the moist-cured concrete [18]. But most of hydrating production can be seen in Fig. 4b: The degree of hydration of fly ash is increased in the presence of gypsum because the surface is activated by the destruction of the structure of the glass and crystalline phase caused by the dissociation of Al_2O_3 reacting with SO_4^{2-} [11]; then, the reaction between the glass phase of fly ash and calcium hydroxide generated from the hydration Portland cement is accelerated. The reason of two kinds of concrete having difference of compressive strength lies in hydration of fly ash.

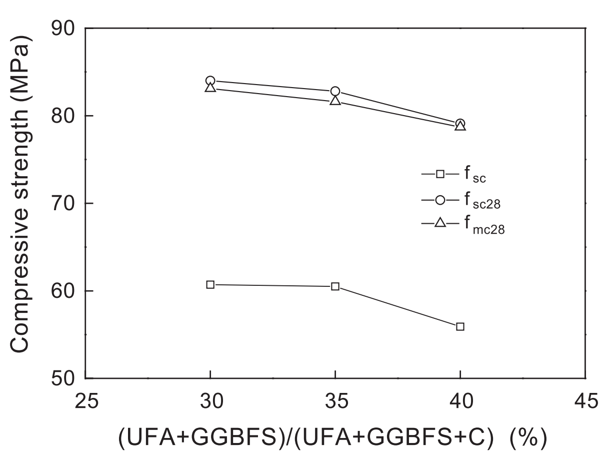

Fig. 5. Influence of GGBFS on compressive strength.

3.3. Compressive strength of concrete containing UFA and GGBFS

The UFA and GGBFS are added into the concrete, the ratio of UFA and GGBFS is 3:1, and the experimental results are shown in Fig. 5. The UFA and GGBFS as a substitute for cement can improve the adaptability of steam curing. The difference between f_{sc28} and f_{mc28} is little; the steam-curing concrete containing supplementary cementing materials has high strength-gaining ratio, and the development of later compressive strength is the same as the moist-cured concrete and solves the problem of lower strength-gaining rate.

4. Conclusion

1. The compressive strength of concrete containing UFA through steam curing after demoulding is low, and that of 28 days is low also, which indicates that the steam-curing adaptability of UFA is poor.
2. The chemical activators had distinct effect on the early compressive strength after 13-h steam cure and had less effect on the 28-day compressive strengths. The effect of $Ca(OH)_2$ as an activator is less than that of $CaSO_4$.
3. The addition of UFA and ground slag can increase the compressive strengths of concrete containing supplementary cementing materials and can solve the problem of lower strength gaining rate.

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