Effect of Steam Curing on the Compressive Strength of Concrete with Blast Furnace Slag

Chung-Hao Wu, Kao-Hao Chang, and Huang Hsing Pan

Abstract This study aims to experimentally research the effect of steam curing on the compressive strength of concrete. The test variables included the compressive strength of concrete, two presteaming period (1.5 and 3 h), three curing temperatures (room temperature, 50 and 70 °C), and three blast furnace slag replacement ratios (0, 30, and 60%). Test results showed that with increase of the replacement ratio of blast furnace slag, it needed to increase the superplasticizer to achieve the required workability of concrete. At room temperature curing, the strength of control concrete was higher than that of concrete containing blast furnace slag before 28 days. With the increase of slag content, the growth rate of compressive strength tended to be slower. For the steam curing, the strength at 3 days was higher than that of the room temperature curing, and the strength at 28 days is lower than that of the room temperature curing. Longer presteaming period (3 h) and higher steam-curing temperature (70 °C) were helpful to the strength development of concrete with blast furnace slag at various ages. The concrete containing 30% blast furnace slag had the highest strength at all ages after 3 h presteaming period and 70 °C steam curing.

Keywords Blast furnace slag · Concrete · Steam curing · Presteaming period · Compressive strength

1 Introduction

Curing methods have a profound impact on the hardened properties of concrete. As far as the current curing technology is concerned, the high-temperature steam curing used in precast concrete is relatively complicated. The presteaming period before steam curing, the heating rate, the highest curing temperature, and the curing time, as well as the mineral admixtures, etc., may affect the properties of precast concrete

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[1]. Therefore, the subject of high-temperature steam curing has always been the focus of relevant research.

Escalante-Garcia and Sharp [2] reported that the microstructure of cement paste cured at 60 °C was more porous than those cured at 10 °C. Rosenbach et al. [3] observed that at higher temperatures, the hydrate phase distribution is more inhomogeneous and shorter needle-shaped ettringite crystals are formed. Chen et al. [4] showed that low curing temperature prolongs the hydration process. Low temperature does not change the types of hydrates, but reduces their amount. Low curing temperatures favor the formation of coarse ettringite crystals. Cao and Detwiler [5] found that the microstructure of silica fume cement paste cured at 23 °C was homogeneous. This cement paste has a less porous structure and the same degree of cement hydration as cement paste without silica fume.

Yang et al. [6] adopted 4 h presteaming period, and then, curing temperature was increased from 20 to 60 °C within 2 h by steam and maintained for 6 h. After that, the temperature was decreased to 20 °C using a 3 h ramp and maintained at 20 °C and 60% RH until the testing date. The test results showed that replacement ratios of blast furnace slag from 50 to 60% were optimal in maximizing the compressive strength of steam-cured high strength concrete with various water-to-binder ratios (0.25, 0.275 and 0.30).

Jung and Choi [7] investigated the effect of the high-temperature curing methods on the compressive strength of concrete containing high volumes of blast furnace slag (up to 60% replacement ratio of Portland cement). The curing parameters included the presteaming period (2, 3, and 4 h), temperature rise (10, 15, and 20 °C/h), peak temperature (55, 65, and 75 °C), peak period (3, 4, and 5 h), and temperature down (5, 10, and 15 °C/h). Test results showed that the compressive strength of the concrete with peak temperatures of 65 and 75 °C was about 88% higher than that of the samples with a peak temperature of 55 °C after 1 day curing.

Moreover, autogenous shrinkage and drying shrinkage easily occur in concrete during and after steam curing [8]. Zulu et al. [9] used two fineness of granulated blast-furnace slag cements to estimate the mechanical and shrinkage properties of concrete with water curing and steam curing. Their steam-curing procedures included 3 h presteaming period, heating to 65 °C, then maintained for 3 h, and finally cooling. The test results indicated that the difference in the fineness of blast-furnace slag cement was not significant in compressive strengths of concrete, especially at 28 days. They also found that the addition of gypsum provided slightly lower shrinkage, which may help to reduce cracking of concrete.

Li et al. [10] reported that raising the steam-curing temperature was more favorable for concrete incorporating high volume fly ash, which can conduct the higher demold strength and more entirely pozzolan reaction of fly ash compared with prolonging the steam-curing time. Although concrete incorporating fly ash can obtain satisfactory demold strength with steam curing at 80 °C, the later strength development of concrete is slow for the same curing conditions. The effect of the later performance of resistance to chloride ion permeability improved by fly ash is better than that of the effect improved by blast furnace slag. The risk of damaging the concrete incorporating high volume fly ash or blast furnace slag due to delayed ettringite formation is minimal when specimens were cured by steam at 80 °C.

2 Experimental Program

To understand the effect of steam curing on the compressive strength of concrete containing blast furnace slag, this study adopted the 28 MPa design strength of concrete, three replacement ratios of cement by blast furnace slag (0, 30, and 60%), two presteaming period (1.5 and 3 h), and three curing temperatures (room temperature, 50, and 70 °C).

2.1 Materials

1. Water: general tap water, which meets the requirements of CNS mixing water.
2. Cement: Type I Portland cement with a specific gravity of 3.15.
3. Blast furnace slag: 120 grade ground-granulated blast furnace slag from local company, with a fineness of 431 m^2/kg and a specific gravity of 2.9.
4. Coarse and fine aggregates: natural river stone and sand were used, the specific gravity of coarse and fine aggregates is 2.6 and 2.5, the water absorption rates were 1.2% and 1.9%, the D_{max} of coarse aggregates is 19 mm, the bulk density is 1470 kg/m^3, and the fineness modulus of fine aggregate is 2.2.
5. Superplasticizer: Taiwan Sika Type G high-performance water-reducing retarder was used, the specific gravity is 1.2 ± 0.02 kg/l, the pH value is 7.0 ± 1.0, and its properties meet the requirements of CNS or ASTM.

2.2 Mix Design

The mix design of concrete was according to ACI 211.1-91. The replacement ratio of cement by blast furnace slag was 0%, 30%, and 60%, respectively. The design compressive strength of concrete was 28 MPa, and test ages were 3, 7, and 28 days. The mix designs of concrete were given in Table 1.

2.3 Specimen Preparation and Test Method

After concrete specimens were cast into cylindrical mold (100 mm diameter, 200 mm height), part of them were placed indoors for curing in the air, and the others were

Table 1 Mix design of concrete (m^3)

Specimen no.*	w/cm	Water	Cement	Blast furnace slag	Fine aggregate	Coarse aggregate	Superplasticizer
		kg					
S00	0.60	205	340	0	835	900	0
S30	0.60	205	238	102	830	895	3.4
S60	0.60	205	136	204	825	890	5.1

*S00 means that the blast furnace slag replacement ratio is 0%, S30 is 30% replacement ratio, and S60 is 60% replacement ratio

steam cured, while selecting two presteaming period of 1.5 and 3 h remaining at room temperature. The steam temperature rise was 20 °C/h, peak temperature was 50 and 70 °C, peak period was 6 h, and temperature down was 20 °C/h. The steam-cured specimens were placed indoors for curing in the air and were taken out at the test age for compressive strength tests.

The compression test was conducted according to ASTM C192. The test ages were 3, 7, and 28 days. In terms of steam-curing equipment, a self-designed steam-curing box was used, as shown in Fig. 1. Its internal dimensions are 1500 mm × 470 mm × 610 mm, which can simultaneously steam cure 24 cylindrical specimens, providing uniform and stable temperature and humidity (Fig. 2). The temperature range was from room temperature to 80 °C, and the relative humidity was 20–98%.

Fig. 1 Steam-curing box

Fig. 2 Steam-curing specimens

3 Test Results and Discussion

3.1 Slump of Concrete

The results of slump test were given in Table 2. It is seen that the slump of concrete ranged from 180 to 190 mm. When the slag replacement ratio increased, the superplasticizer was relatively increased to ensure the appropriate workability of concrete.

3.2 Compressive Strength of Concrete

Room Temperature Curing. Table 2 and Figs. 3, 4, 5, 6 and 7 show the test results of the compressive strength of concrete and the strength development. It is seen from Table 2, the 3-day age strength of control concrete S00 cured at room temperature was the highest of 13.6 MPa, and the concrete S60 (60% slag replacement ratio) presented the lowest strength of 8.8 MPa. At the age of 7 days, the strength of S30 (30% slag replacement ratio) was 22.8 MPa, which has exceeded the 20.6 MPa of S00. At the age of 28 days, the strength of S30 presented the highest of 30.5 MPa, and the strength of S60 was still the lowest of 24.8 MPa, while it was close to the design strength of 28 MPa.

It shows from Fig. 3 that the strength of the slag concrete S30 presented a similar strength as the control concrete S00 at the ages from 3 to 28 days, while the strength

Table 2 Slump and compressive strength of concrete

Specimen no	Slump (mm)	Presteaming period (h)	Curing temperature (°C)	3 days	7 days	28 days
				Compressive strength (MPa)		
S00	180	0	Room temperature	13.6	20.6	29.3
S30	195			12.1	22.8	30.5
S60	190			8.8	15.3	25.8
S00	180	1.5	50	20.8	22.7	27.3
S30	195			19.3	24.1	29.5
S60	190			17.2	20.2	24.1
S00	180		70	18.8	21.8	25.6
S30	195			17.1	22.5	28.4
S60	190			15.7	19.4	23.2
S00	180	3	50	23.1	23.7	28.3
S30	195			21.8	26.8	30.2
S60	190			19.3	21.8	25.3
S00	180		70	21	22.1	27
S30	195			19.7	23.6	31.3
S60	190			18.1	20.3	24.8

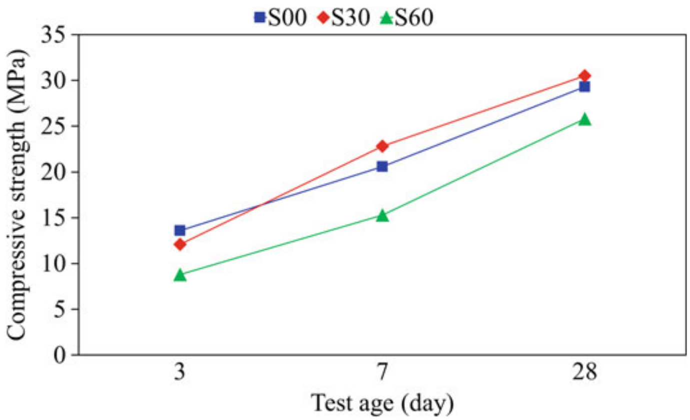

Fig. 3 Strength development of concrete cured at room temperature

of the slag concrete S60 had a distinct lower value of 3.8–5.7 MPa at each age compared to the control concrete S00. This indicates that the slag replacement ratio of under 30% may have insignificant effects to the strength of concrete.

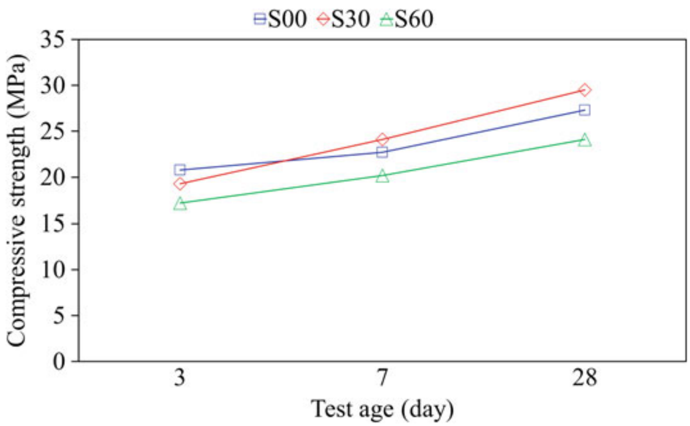

Fig. 4 Strength development of 50 °C steam-curing concrete with 1.5 h presteaming period

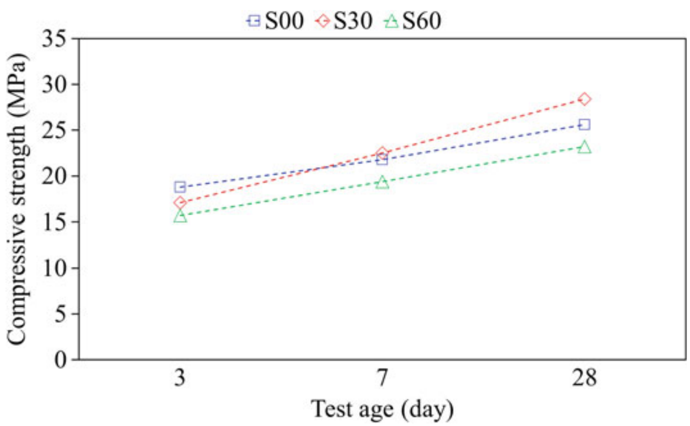

Fig. 5 Strength development of 70 °C steam-curing concrete with 1.5 h presteaming period

Steam Curing with 1.5 h Presteaming Period. Figures 4 and 5 show the compressive strength of concrete made with 1.5 h presteaming period and the steam-curing temperature of 50 and 70 °C. At 3 days, the strengths 20.8 and 18.8 MPa of concrete S00 after steam curing at 50 and 70 °C for 6 h soaking time are both higher than the 13.6 MPa of concrete S00 without steam curing. This reveals that steam curing can improve the early-age strength of concrete. Further at 7 days, it is seen from Figs. 4 and 5 that the compressive strength of S30 is 24.1 MPa and 22.5 MPa, respectively, which exceeds 50 and 70 °C steam-curing concrete S00 of 22.7 MPa and 21.8 MPa. This result is the same as that of room temperature curing. Similarly, at 28 days, the strength of concrete S30 is still the highest, and the strength of concrete S60 is the lowest, whether it is cured by steam at 50 or 70 °C, this result is also consistent with that of room temperature curing. In addition, comparing the effects of steam curing

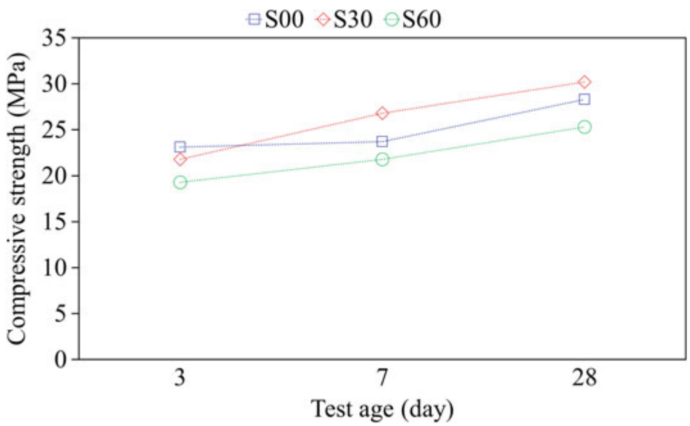

Fig. 6 Strength development of 50 °C steam-curing concrete with 3 h presteaming period

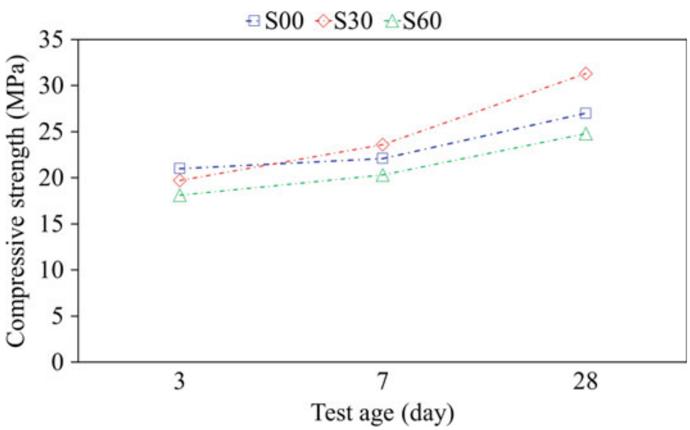

Fig. 7 Strength development of 70 °C steam-curing concrete with 3 h presteaming period

at 50 and 70 °C, it was found that at the age of 3 days, the strengths of the three steam-cured concretes were higher than those of concrete cured at room temperature, while at 28 days, the strengths of the three concretes were lower than those of concrete cured at room temperature. This indicates that steam curing may improve the early-age strength of concrete, but the strength improvement effect at the age of 28 days is lower than that of concrete cured at room temperature. This is true for the steam curing of concrete conducting with a 1.5 h presteaming period.

Steam Curing with 3 h Presteaming Period. Figures 6 and 7 show the compressive strength of concrete made with 3 h presteaming period and the steam-curing temperature of 50 and 70 °C. It is seen that at the age of 3 days, the strength of each concrete after steam curing at 50 or 70 °C for 6 h soaking time is higher than that of the related concrete cured at room temperature and that of the related steam-curing concrete with 1.5 h presteaming period. This reveals that making concrete with 3 h presteaming period before steam curing may attain higher early-age strength. Observing the strength of each concrete at different ages, it is found that regardless of the steam curing at 50 or 70 °C, the strength of concrete S30 exceeds that of concrete S00 at 7 days, and maintains the highest strength at the age of 28 days. These results reveal that longer presteaming period and a higher steam-curing temperature may significantly contribute to the development of compressive strength of concrete containing 30% blast furnace slag at the age of 28 days, while the compressive strength of concrete cured with steam at 70 °C and 3 h presteaming period is higher than that of other curing methods.

4 Conclusion

Based on the experimental results, the following conclusions can be drawn:

1. With the increase of the replacement ratio of blast furnace slag, it needs to increase the superplasticizer appropriately, so that the concrete can have an adequate workability.
2. Under room temperature curing, the slag replacement ratio of less than 30% may insignificant effects to the strength of concrete, exceeding 30% the strength of slag concrete tends to be lower.
3. Conducting with steam curing, the strength of concrete with or without slag at early age (3 days) may be higher than that of room temperature curing, the strength at 28 days is lower than that of room temperature curing.
4. The presteaming period before steam curing may benefit to the strength development of concrete with blast furnace slag.
5. The concrete containing 30% blast furnace slag present the highest strength at all ages after 3 h presteaming period and 70 °C of steam curing, compared to other slag concrete and curing method.

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