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Scaling and corrosion resistance of steam-cured concrete

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Abstract

In this paper, effects of various factors such as steam temperature, precuring time, air content, and fly ash (FA) on the deicer-scaling resistance and corrosion resistance of steam-cured concrete were investigated. Results showed that the deicer-scaling resistance and corrosion resistance of steam-cured concrete without FA were much lower than those of concrete cured in 20 °C under the same condition, and became worse with the increase in steam temperature and with the reduction of precuring time. The deicer-scaling resistance of steam-cured concrete was also improved with the increase in the air content, but the corrosion resistance of steam-cured concrete with 4.5% air content was a little lower than that of steam-cured concrete without SJ-2. The deicer-scaling and corrosion resistances of steam-cured concrete with FA were better than those without FA. Moreover, these results are discussed by analysing air-void parameters, 3-day-intake evaporable water, and compressive strength of concrete.

Keywords: Steam-cured concrete; Deicer; Freeze–thaw cycle; Corrosion; Fly ash

1. Introduction

In the north of China, concrete bridge beams and decks are usually produced with the steam-curing process in order to enhance the produced efficiency. The typical condition of the steam-curing process is a precuring time of 3–5 h, a heat rate of 22–33 °C/h, a maximum steam temperature of 60–90 °C, and a constant temperature of 6–18 h [1]. The total curing time, except for the precuring time, is about 18 h.

In the point of strength development, the above condition is positive even though the final strength of concrete is lower than that of concrete cured in 20 °C. However, the deicer-scaling resistance and corrosion resistance of steam-cured concrete are worse than those of common-cured concrete in severe environments such as in the combined action of deicer and freeze–thaw cycle together [2] and, therefore, the severe scaling of steam-cured concrete usually occurs after about two-winter service. In winter, deicers such as NaCl and $CaCl_2$ are commonly used to thaw ice and snow on pavements or bridges automatically in the north of China.

According to the works of many authors, such as Langlois et al. [3], Johnston [4], and Jacobsen and Sellevold [5], steam curing has a negative influence on the deicer-scaling resistance of concrete. The detrimental impacts of steam curing on precast concrete may be due to the fact that it tends to coarsen the pore structure [6], to enhance the microcracking [7], and to cause delayed ettringite formation [8]. Consequently, it is important to improve the durability of steam-curing concrete for the safe service of constructions such as bridges.

2. Experimental

2.1. Mix proportions

Ordinary Portland cement (OPC) no. 525 with a specific area of 340 m^2/kg, standard quartz sand according to GB178-1977, 4–12 mm limestones, and SJ-2 saponin air-entraining agent [9] were used. Class II fly ash (FA) according to GB 1596-91 was used. Small specimens with the size of 4 × 4 × 16 cm were manufactured. Compositions of OPC and FA are shown in Table 1.

The mix proportion of concrete is water:cement:sand:aggregate = 0.50:1:1.63:2.90. For concrete without SJ-2, its air content and slump are about 0.95% and 16 cm, respectively.

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Table 1
Compositions of cement and FA

Type	Chemical compositions (%)								Mineral compositions (%)			
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	C_2S	C_3S	C_3A	C_4AF
OPC	65.1	21.4	3.4	4.4	0.85	0.64	0.11	2.21	22.4	52.9	1.46	13.8
FA	2.72	48.71	31.26	7.24	1.14	0.42	0.67	1.06	Ignition loss at 950 °C = 5.76%			

For air-entrained concrete, its air content and slump are about 4–6% and 20–22 cm, respectively. For concrete with FA, the FA replacement of cement is 20%.

2.2. Curing condition

There are two curing methods for this test (i.e., common curing and steam curing). Common curing means that the concrete specimens are demoulded 1 day after casting and then stored in water at 20 ± 2 °C for 28 days. For steam-cured concrete, the specimens with moulds are stored during steam curing. The maximum steam temperatures are 45, 60, 75, and 90 °C and the constant time at this temperature is 12 h. The heating and cooling rates are 20 and 15 °C/h, respectively. The precuring times in air before steam curing are 0, 4, 7, 10, and 24 h. Steam-cured specimens after demoulding are also stored in water at 20 ± 2 °C for 28 days.

2.3. Deicer-scaling test

The deicer-scaling test used here is similar to the RILEM 117-FDC/CDF test method [10]. However, one freeze–thaw cycle consists of freezing at − 20 ± 2 °C for 3 h and then thawing at 20 ± 5 °C for 3 h. The deicer solution is 4% NaCl. After being cured in water for 28 days, the single surface of the specimen is immersed into a 4% NaCl solution into a depth of about 4 mm in a plastic container that is covered by a tight lid during the test. The deicer solution is changed about every seven cycles.

Under the test condition, the scaling of the specimen is very severe before 25 cycles, over 1 kg/m^2 for most of the steam-cured specimens. Even though the scaling increases with the increase in the number of cycle, the orders for the scaling resistance of different concretes are not changed, and therefore the scaling test is ended before 25 cycles.

2.4. Corrosion test

During casting, a steel bar with a diameter of 5 mm and a length of about 166 mm was embedded in the middle of a specimen. The weight of the steel bar (W_0) was measured before casting. After demoulding, two exposed ends of the steel bar were covered with epoxy resin.

The corrosion of steel bar in the specimen is accelerated by the drying–wetting cycle. The condition of the cycle is that the specimens are dried at 60 ± 2 °C for 3 days and then soaked in a 10% NaCl solution for 1 day after being cooled.

The mass loss of the steel bar was measured after some cycles. According to the Chinese standard JTJ 228-87, "The fast corrosion test of steel bar in marine concrete," the rust of the steel bar is firstly removed by an acid solution, consisting of 12% HCl and 0.3% hexamethylene tetramine $(CH_2)_6N_4$, and then the steel bar is neutralized with a 3% Na_2CO_3 solution and rinsed with distilled water. Finally, after the treatment, the steel bar is dried at 105 °C for 2 h and then weighed (W_N). The mass loss of the steel (M) due to corrosion is calculated as follows:

$$M = \frac{W_0 - W_N}{W_0} \times 100\%$$

3. Results and discussions

3.1. Maximum steam temperature

The effect of maximum steam temperature (T_{max}) on the deicer-scaling resistance of steam-cured concrete is displayed in Fig. 1. From Fig. 1, it can be seen that for the steam-cured concrete precured for 7 h, its scaling is obviously enhanced with the increase in T_{max}. The negative effect of steam curing on the deicer scaling of concrete with the air content of 4.0% is much higher than that on the deicer scaling of concrete without SJ-2. For example, after 15 freeze–thaw cycles, the scaling of nonair-entrained concrete steam-cured at 45, 60, 75, and 90 °C is 2.0, 3.0, 4.1, and 5.5 times that of nonair-entrained concrete under common curing at 20 °C, respectively, and for the air-

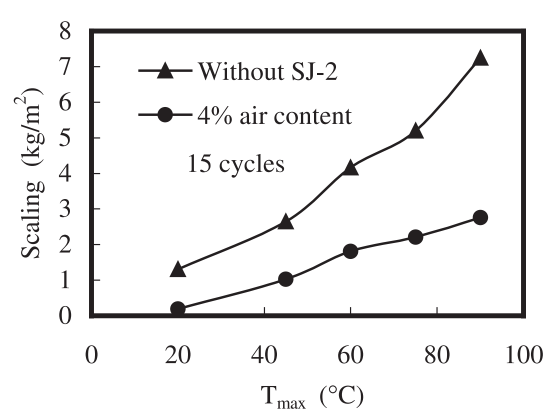

Fig. 1. Effects of T_{max} on the deicer-scaling resistance of concrete at a PT of 7 h.

entrained concrete, this scaling is 6.4, 9.5, 11.6, and 16.2 times that of air-entrained concrete under common curing, respectively.

Effects of maximum steam temperature on the corrosion resistance of concrete without SJ-2 are shown in Fig. 2. They clearly show that the corrosion resistance of steam-cured concrete without FA is lower than that of concrete at common curing, and is reduced with the increase in T_{max}, especially after 40 °C. For the steam-cured concrete with 20% FA, its corrosion resistance is improved with the increase in T_{max} when T_{max} is lower than 60 °C, but it is reduced with the increase in T_{max} beyond 60 °C.

3.2. Precuring time

Effects of precuring time (PT) on the deicer-scaling resistance of steam-cured concrete at 75 °C are shown in Fig. 3. It indicates that the deicer-scaling resistance of steam-cured concrete is significantly improved with the increase in PT, especially for air-entrained concrete. The deicer-scaling resistance of steam-cured concrete with the air content of 4.0% is even lower than that of steam-cured concrete without SJ-2 when PT is zero (i.e., the concrete is directly steam-cured after casting). When PT is 24 h, the scaling of steam-cured concrete with the air content of 4.0% is obviously reduced, approaching that of concrete under common curing. For example, after 15 freeze–thaw cycles, the scaling of nonair-entrained concrete with PT of 0, 4, and 24 h is 5.4, 4.3, and 1.6 times that of nonair-entrained concrete under common curing, respectively. For concrete with an air content of 4.0%, this scaling is 41.4, 14.2, and 2.4 times as that of air-entrained concrete under common curing, respectively.

From Fig. 4, it can be seen that the corrosion resistance of concrete is significantly improved with the increases in PT. When PT is 24 h, the corrosion resistance of steam-cured concrete with 20% FA is higher than that of concrete with 20% FA at common curing, but that of steam-cured concrete without FA is still lower than that of concrete without FA at common curing.

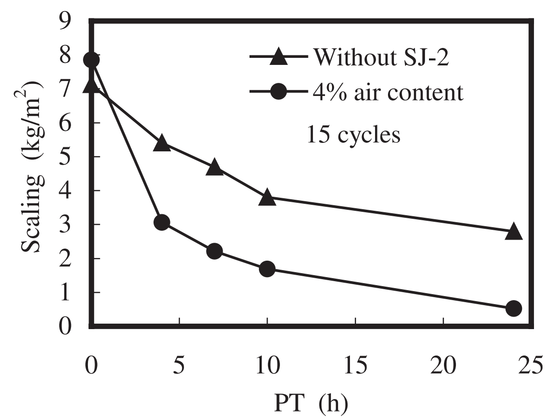

Fig. 3. Effects of PT on the deicer-scaling resistance of concrete at 75 °C.

3.3. FA and air content

Results on the effects of FA and air content on the deicer-scaling resistance of concrete are shown in Fig. 5. It is clearly demonstrated that for steam-cured concrete at 75 °C and with enough-long precured time such as 7 h, air entraining is also an effective measure to improve the deicer-scaling resistance even though it is obviously lower than that of concrete under common curing. The deicer-scaling resistance of steam-cured concrete with 20% FA is somewhat higher than that of steam-cured concrete without FA, but that of common-cured concrete with 20% FA is a little lower than that of common-cured concrete without FA.

From Figs. 2 and 4, it can be seen that the corrosion resistance of concrete with 20% FA is obviously higher than that of concrete without FA, especially for steam-cured concrete. Steam curing has a negative influence on the corrosion resistance of concrete without FA, but that of steam-cured concrete with 20% FA is improved when T_{max} is lower than 60 °C. Consequently, adding FA has a strong positive effect on the corrosion resistance of steam-cured concrete. However, the corrosion resistance of steam-cured

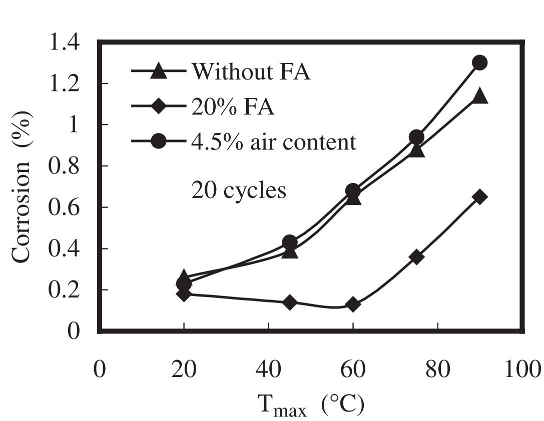

Fig. 2. Effects of T_{max} on the corrosion of concrete at a PT of 7 h.

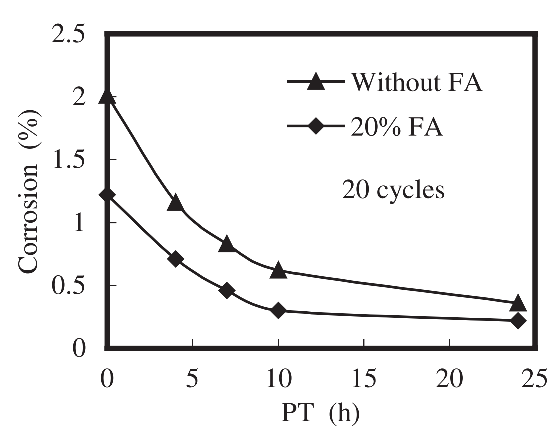

Fig. 4. Effects of PT on the corrosion of concrete at 75 °C.

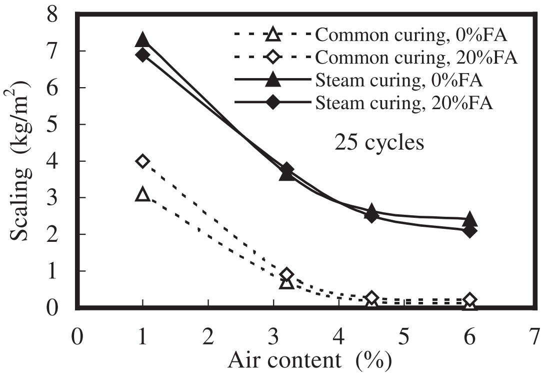

Fig. 5. Effects of air content and FA on the deicer-scaling resistance of concrete.

concrete with 4.5% air content is somewhat lower than that of steam-cured concrete without SJ-2.

3.4. Analysis

The curing conditions of concrete after casting, such as temperature and humidity, have a large influence on the quality and durability of the concrete, especially for pore structure and surface quality. For steam-cured concrete, the precuring time, maximum steam temperature, calefactive rate, and cooling rate are the most important factors that influence the quality of concrete. The hydration rate of cement is more accelerated with the increase in the steam temperature and, therefore, the development of strength becomes quicker. However, the possibility of microcracking due to thermal stress at the paste–aggregate interfaces [6], and the pore and hydrated crystal sizes become larger; moreover, the porosity and crystallinity of hydrates such as CSH and $Ca(OH)_2$ are enhanced at the same time [7]. These negative effects will cause the reduction in the ultimate strength, durability, and homogeneousness of steam-cured concrete, and ingression of water into the concrete more easily.

Obviously, steam curing has more negative effects on the structure and quality of air-entrained concrete because the microair bubbles will become larger and coalesce together. This tendency will make the good air bubble system become worse. The system will be damaged thoroughly when concrete is directly steam-cured after casting (i.e., without the precuring time).

In contrast, FA has a positive influence on reducing the above negative effects caused by steam curing because the pozzolanic reaction of FA is accelerated by increasing temperature. Thus, crystalline $Ca(OH)_2$ and CSH with high C/S ratio are transformed as CSH with low C/S ratio and crystallinity due to the pozzolanic reaction of FA, and therefore improves the pore structure and homogeneity and reduces the possibility of microcracking and porosity of concrete. Consequently, adding FA enhances the strength and durability of steam-cured concrete.

Results on the air-void parameters, compressive strength, and 3-day-intake evaporable water of concrete are summarized in Tables 2 and 3. Table 2 clearly shows that the air-void structure of concrete becomes worse after steam curing (i.e., the air-entrained pore becomes coarser and the air-void spacing factor is larger). These negative effects become more obvious when the steam-curing regime is not reasonable (such as the maximum steam temperature above 70 °C, or very short precuring time), but is mitigated by adding FA. However, the negative effects are not large enough to reduce the deicer-scaling resistance and corrosion resistance of steam curing significantly.

Of course, steam curing also makes capillary pores of concrete coarser and the possibility of microcracking in concretes higher. Results on the 3-day-intake evaporable water and compressive strength in Table 3 indirectly prove them. Table 3 indicates that the compressive strength of steam-cured concrete without FA and SJ-2 or with 4.5% air content is significantly reduced with the increase in the maximum steam temperature and with the reduction of precuring time, but their 3-day-intake evaporable water is enhanced, especially for air-entrained concrete. However, the compressive strength of steam-cured concrete with 20% FA increases, and its 3-day-intake evaporable water decreases a little with the increase in the temperature when the maximum steam temperature is lower than 60 °C, and the evaporable water is enhanced with the reduction of precuring time. Furthermore, the strength of steam-cured concrete with

Table 2
Air-void parameters of hardened concrete

Curing condition		Without SJ-2 and FA			4.5% A			20% FA and 4.5% A		
T_{max} (°C)	PT (h)	A_h (%)	α (mm^{-1})	L (μm)	A_h (%)	α (mm^{-1})	L (μm)	A_h (%)	α (mm^{-1})	L (μm)
20[a]	7	0.86	15.2	742	4.6	28.8	189	4.3	27.4	208
45	7	0.94	13.8	788	4.8	25.5	210			
60	7	1.11	12.1	838	4.7	23.4	232	4.5	25.8	216
75	0	1.30	8.7	1091	5.2	17.2	301	4.6	25.1	220
	7	1.15	11.7	854	4.9	22.3	238			
	24	0.92	14.3	767	4.7	26.1	207			
90	7	1.24	11.2	864	5.0	21.7	243			

A, air content in fresh concrete; A_h, air content in hardened concrete; α, specific area; and L, average air-void spacing factor.

[a] Common curing.

Table 3
Results on compressive strength and 3-day-intake evaporable water of concrete

Curing condition		Compressive strength at 28 days (MPa)			Evaporable water[a] (%)		
T_{max} (°C)	PT (h)	Without FA and SJ-2	20% FA	4.5% A	Without FA and A	20% FA	4.5% A
20[b]	7	64.2	61.4	54.7	3.53	3.81	3.94
45	7	59.2	65.5	48.8	3.84	3.76	4.51
60	7	53.9	67.3	45.6	4.35	3.62	4.95
75	0	40.3	46.4	32.5	6.05	5.85	7.12
	7	48.1	56.7	42.3	4.94	4.57	5.68
	24	60.5	63.8	46.4	4.30	4.10	4.81
90	7	43.2	52.8	37.5	5.27	4.81	6.26

A, air content in fresh concrete.
[a] Intake water of concrete soaked in water for 3 days after drying at 105 °C for 1 day and after cooling.
[b] Common curing.

20% FA is obviously higher than that of steam-cured concrete without FA and the 3-day-intake evaporable water of steam-cured concrete with 20% FA is lower than that without FA. In fact, microcrackings are found during measurements of air-void parameters in steam-cured concretes, especially for those steam-cured at high temperature of over 70 °C and with very short precuring time.

From these data, it can clearly be seen that the air-entrained concrete is more sensitive to steam curing compared to concrete without the air-entraining agent.

These conclusions from Tables 2 and 3 prove above analyses. Also, they are indirectly consistent with the results on the deicer-scaling and corrosion resistance of concrete.

4. Conclusion

The deicer-scaling and corrosion resistances of steam-cured concrete are significantly lower than those of concrete at common curing. The resistances become worse with the increase in the steam temperature and with the reduction of the precuring time.

The deicer-scaling and corrosion resistances of steam-cured concrete are improved by adding a reasonable amount of FA, especially the corrosion resistance. The corrosion resistance of concrete with 20% FA steam-cured below 60 °C is even higher than that of concrete with 20% FA at common curing.

The deicer-scaling resistance of air-entrained concrete at steam curing is obviously higher than that of steam-cured concrete without SJ-2, but its corrosion resistance is a little lower than that of the latter. Moreover, the air-entrained concrete is more sensitive to steam curing compared to concrete without the air-entraining agent.

It is recommended that the concrete in bridges exposed to deicer be commonly cured, and with some air-entraining agent and pozzolanic materials such as FA, slag, silica fume, etc. If the steam-curing process has to be used for some reasons, the maximum steam temperature should be below 60 °C, and it is necessary to cure the concrete for a long-enough time at the common temperature before raising the steam temperature and to restrict the calefactive and cooling rates.

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