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Study on the hydration heat of binder paste in high-performance concrete

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Abstract

High-performance concrete (HPC) is a type of new concrete materials developed in the recent 10 years. Compared with normal strength concrete (NSC), HPC is made with lower water–binder ratio (W/B), larger dosage of superplasticizer and addition of different types of mineral admixtures. The objective of the article was to evaluate the effect of W/B, superplasticizer and mineral admixtures on the hydration heat of the binder paste in HPC. The testing results showed that the hydration heat reduced with the decrease of W/B of the binder paste. The total hydration heat did not decrease with the incorporation of superplasticizer containing retarding component, however, the hydration exothermic process was delayed. Mineral admixtures greatly reduced the hydration heat and the exothermic rate and prolonged the arrival time of the highest temperature, particularly when two or three types of mineral admixtures were added at the same time (double adding and triple adding). The influence of these three factors on hydration heat may counteract the deficiency of high hydration heat at early stage due to high cement content and high-strength cement usually used in HPC. This way, the influence of temperature stress is alleviated and the durability of concrete is enhanced.

Keywords: Binder paste in HPC; Water–binder ratio (W/B); Superplasticizer; Mineral admixtures; Hydration heat

1. Introduction

High-performance concrete (HPC) is a new type of concrete materials developed in the recent 10 years. Due to good workability, high mechanical properties and excellent durability, HPC has been applied in many building constructions across the world [1–4].

Portland cement (PC) in concrete releases a lot of heat during the process of hydration, which greatly influences durability of concrete. Hence, many work [5–8] has been conducted to investigate the hydration exothermic process. However, most of it focused on normal strength concrete (NSC).

Compared to NSC, HPC has its own special characteristics:

(a) The content and strength grade of cement is higher. In general, 28-day compressive strength of cement is 52.5 MPa or greater.
(b) Water–binder ratio (W/B) is lower.
(c) More dosage of superplasticizer is required to attain good workability of fresh concrete with lower W/B.
(d) Different types of mineral admixtures are used to partly replace the PC.

Those four characteristics result in a great difference in the process of hydration heat liberation between HPC and NSC. Therefore, in order to further develop and apply HPC in civil engineering, many studies are in great need to investigate the influence of W/B, superplasticizer and mineral admixtures on the hydration exothermic process of binder paste in HPC.

The study was initiated to investigate the influence of W/B, superplasticizer and mineral admixtures involving adding approaches, amount and types of mineral admixtures on the hydration exothermic process of binder paste in HPC. The work provided important insight in reducing the hydration heat of binder paste in HPC.

2. Method

2.1. Materials

Graded 52.5 Portland Cement supplied by Hua Xin Cement in Hu Bei province, PR China, was used, complying with Chinese Standard GB175-85, similar to ASTM C150 Type II cement.

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Table 1
Compositions and physical properties of materials

Materials	Chemical compositions (%)								Specific surface (m^2/kg)	Water demand ratio (%)
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	SO_3	LOI		
Cement	21.47	5.80	4.04	–	59.64	3.24	2.08	2.44	310	–
Fly ash	45.38	33.53	5.29	4.71	3.16	2.81	0.43	5.3	345	95
Slag	34.76	15.39	1.20	–	35.86	9.07	0.81	–	530	99
Silica fume	94.48	0.27	0.87	–	0.54	0.91	–	1.9	20000	–

Water demand ratio denotes the ratio of water content of paste incorporated with 30 wt.% of mineral admixtures to that of reference paste under the condition of the same fluidity.

Graded I fly ash, ground blast furnace slag and silica fume were employed for mineral admixtures to replace partial cement.

Naphthalene sulfonate-based superplasticizer FDN-9001 (powder) supplied by Huao Yuan Additive Plant was incorporated. FDN-9001 contains retarding component. The water-reducing rate was approximately 25%.

The chemical compositions and physical properties of materials were listed in Table 1.

2.2. Mixture proportions

Table 2 summarizes the mixture proportions of the 16 investigated binder pastes. The W/B was varied from 0.20 to 0.60 (no. 2 to no. 6) in order to determine the detailed effect of W/B on the hydration exothermic process of binder paste. SF to SF + SL were designed to investigate the influence of the types, adding amount and adding approaches of mineral admixtures on hydration exothermic performance. In order to decide the influence of superplasticizer containing retarding component, two types of binder pastes, one without superplasticizer (no. 1) and the other with superplasticizer, (Pure) were prepared.

All binder pastes were proportioned to preserved the following parameters: the contents of cementitious materials were fixed to 250 g. Except no. 1, the other 15 mixtures were made with 1.2 wt.% of superplasticizer FDN-9001 (accounting for the total binder weight).

2.3. Test procedures

All 16 binder pastes proportioned according to Table 2 were mixed by hand. The mixing sequence consisted of homogenizing the cement and mineral admixtures for 1 min, then introducing water along with superplasticizer, following 3 min of agitation. After that, the binder pastes were casted into 100 × 200 mm cylindrical container, and thermocouples were inserted into the pastes, then the cylinder containers were immediately stored in a large box insulated with styrofoam to simulate semiadiabatic conditions. The temperature was monitored and recorded at 20-min intervals in the first 3 h, and at 1-h intervals in the rest of the 69 h.

The temperature rise corresponded to the recorded temperature minus the initial temperature of the fresh binder paste, which was 20 °C.

2.4. Calculation of hydration heat and exothermic rate

2.4.1. Hydration heat

Firstly, heat-dissipating coefficient of heat-preserving box (K) is measured, and thermal capacity of the box

Table 2
Mixture proportions and mechanical properties

No.	Composition of binder (%)				W/B	Superplasticizer (%)	Compressive strength in 28 days (MPa)
	Cement	Silica fume	Fly ash	Slag			
1	100				0.30	0	66.8
2	100				0.20	1.2	90.3
Pure	100				0.30	1.2	67.2
3	100				0.38	1.2	60.1
4	100				0.42	1.2	56.7
5	100				0.50	1.2	51.5
6	100				0.60	1.2	45.9
SF	90	10			0.30	1.2	89.1
FA10	90		10		0.30	1.2	67.0
FA20	80		20		0.30	1.2	64.9
FA30	70		30		0.30	1.2	60.4
SL30	70			30	0.30	1.2	73.8
FA + SL	70		10	20	0.30	1.2	71.7
SF + FA + SL	60	10	10	20	0.30	1.2	87.3
SF + FA	60	10	30		0.30	1.2	75.0
SF + SL	60	10		30	0.30	1.2	80.6

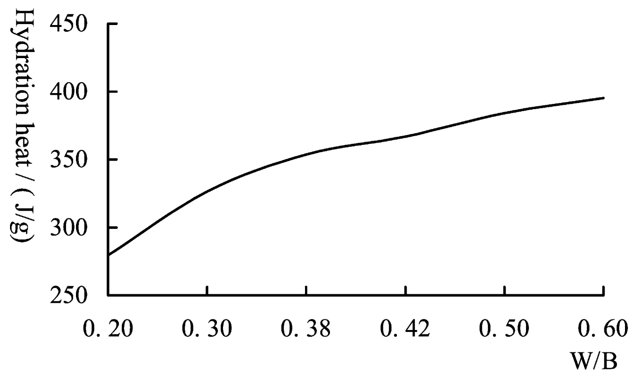

Fig. 1. Effect of W/B on the 3-day hydration heat of binder pastes.

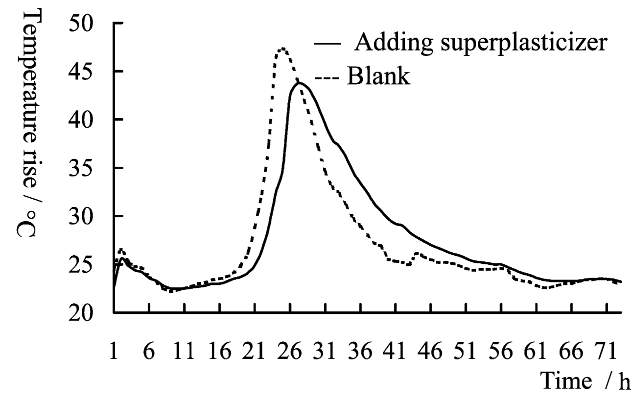

Fig. 3. Effects of superplasticizer on the temperature rise of binder pastes.

including the binder paste in it (C_p), is calculated before the hydration heat test.

Secondly, the hydration heat test is carried out and the temperature rise–time cure is plotted. Area values $\sum F_{0\sim t}$ (where t is time) is acquired through the integral of the temperature rise–time curve.

Thirdly, the total liberation heat of the binder paste at t hours is calculated: $Q_t = C_p(T_t - T_0) + K\sum F_{0\sim t}$, where T_t is the temperature at t hours and T_0 is the initial temperature.

Finally, hydration heat is calculated: $q = Q_t/G$ Where, G is the mass of the binder pastes.

2.4.2. Exothermic rate

The exothermic rate can be obtained through differential of the hydration heat–time curve.

3. Results and discussion

3.1. The influence of W/B

The w/c of cement is 0.38 in theory, while W/B of HPC commonly applied in building constructions ranged from 0.20 to 0.35. Such lower W/B greatly impacted the hydration exothermic process in HPC. The effect of W/B on the hydration exothermic process of binder pastes in HPC was plotted in Figs. 1 and 2.

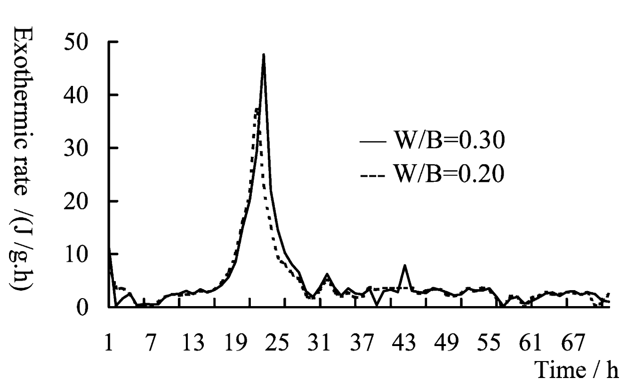

Fig. 2. Effect of W/B on the hydration exothermic rate of binder pastes.

According to Fig. 1, it was observed that the 3-day hydration heat of binder paste in HPC with low W/B exhibited much less heat liberation than that of the paste in NSC with higher W/B. For example, the binder paste with W/B of 0.3 only generated 326.4 J/g of hydration heat in 3 days. However, the 3-day hydration heat of binder pastes with W/B of 0.42 and 0.60 were 366.7 and 393.2 J/g, respectively. The results confronted with the findings of Cook et al. [9], who reported that for adiabatic 1 × 1 × 1 m cubic specimens, HPC containing 470 kg/m^3 of cement with w/c of 0.30 had comparable highest temperature rise and hydration heat liberation as that containing 540 kg/m^3 of cement with w/c of 0.25. It was obvious that the concrete with W/B of 0.25 had lower hydration heat per unit cement than that with w/c of 0.30.

It can be seen from Fig. 2 that the binder paste with W/B of 0.20 exhibited slightly greater hydration exothermic rate than that with W/B of 0.30 during the period of 0–22 h. After that, with the development of hydration, the hydration exothermic rate in the binder paste with W/B of 0.30 exhibited a more rapid drop, compared with the binder paste with W/B of 0.20 at the middle stage (22–31 h). The W/B had small effect on the hydration exothermic rate at a later stage (31–72 h).

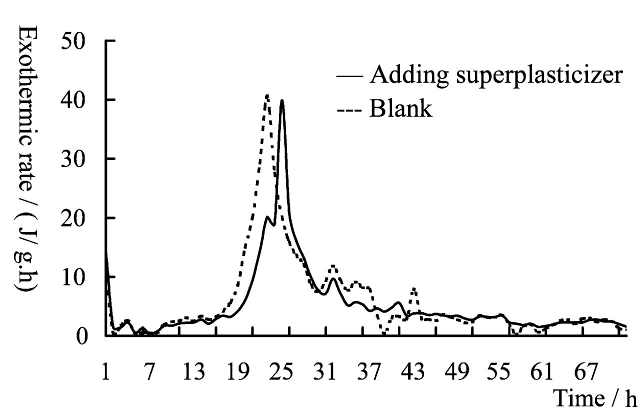

Fig. 4. Effects of superplasticizer on the hydration exothermic rate of binder pastes.

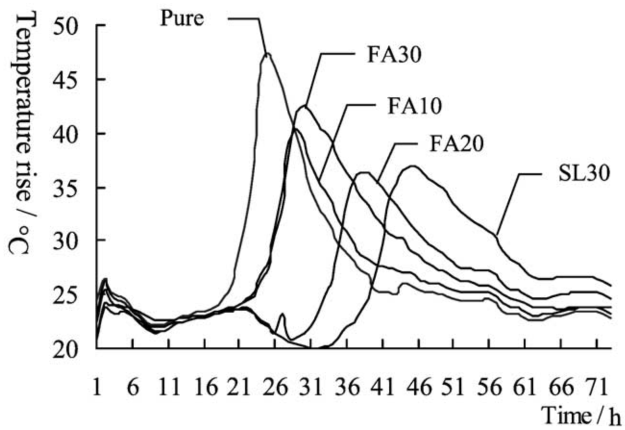

Fig. 5. Curves of temperature rise–time for single-adding samples.

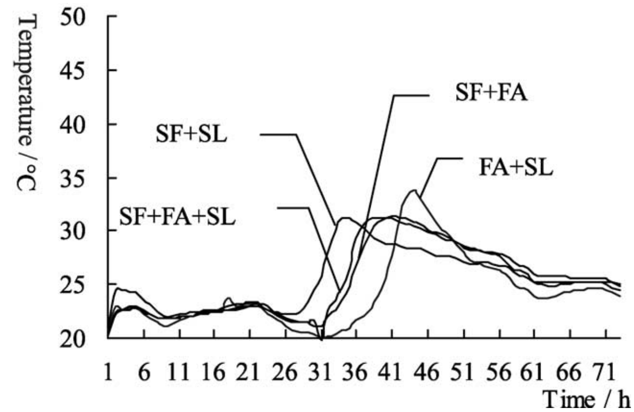

Fig. 7. Curves of temperature rise–time for double-adding and triple-adding samples.

3.2. The influence of superplasticizer

Superplasticizer is a key constituent to the preparation of HPC. The superplasticizer used in this article comprised 10% of retarding agent (citrate type) to reduce the slump loss. The effect of the superplasticizer on the temperature rise–time curve and the hydration exothermic rate–time plot were shown in Figs. 3 and 4, respectively.

As observed from the two figures, the point at which the exothermic rate showed rapid increase and the arrival time of the highest temperature rise were delayed, although the 3-day hydration heat of the two binder pastes had nearly compatible values. The 3-day hydration heat of binder pastes without superplasticizer was 332.5 J/g, while the value was 326.4 J/g for the binder paste with superplasticizer. However, with the development of hydration, the film will progressively be destroyed, and rapid hydration will resume. As a result, the 3-day hydration heat of binder paste without superplasticizer was nearly equal to that of the binder paste with superplasticizer.

3.3. The influence of mineral admixtures

Mineral admixture is one of the necessary components in the preparation of HPC. Inclusion of mineral admixture can reduce hydration heat. The hydration exothermic process, however, is significantly influenced by types, adding amount and adding approaches of mineral admixtures.

The temperature rise, exothermic rate and 3-day heat liberation of binder pastes in HPC caused by the hydration of cement were shown in Figs. 5–9. The following phenomena were observed from Figs. 5–9.

When 10–20 mass% of cement was replaced by fly ash, a decreasing trend in the highest temperature rise, maximum hydration exothermic rate and 3-day hydration heat, with an increase in the adding amount of fly ash, was seen. For example, as for the binder paste in FA10, the highest temperature rise, arrival time of the highest temperature rise, maximum hydration exothermic rate and 3-day hydration heat were 40.3 °C, 29 h, 27.80 J/h g and 287.1 J/g, respectively. However, as for the binder paste in FA20,

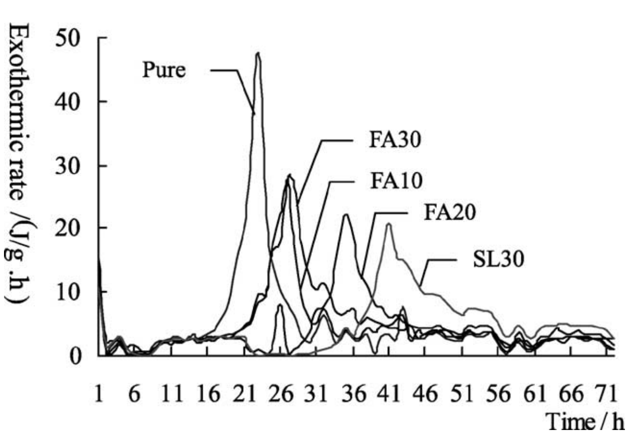

Fig. 6. Curves of the hydration exothermic rate for single-adding samples.

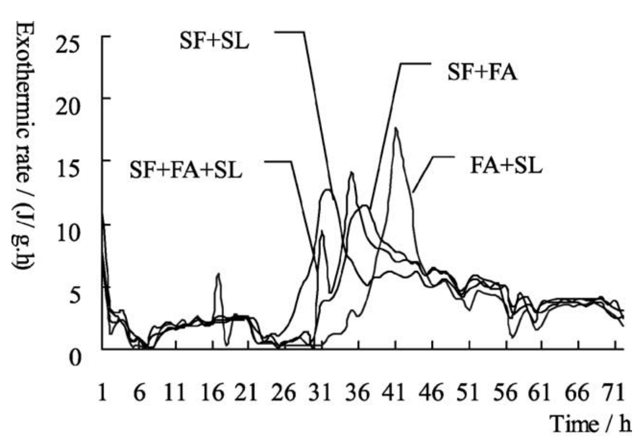

Fig. 8. Curves of the hydration exothermic rate for double-adding and triple-adding samples.

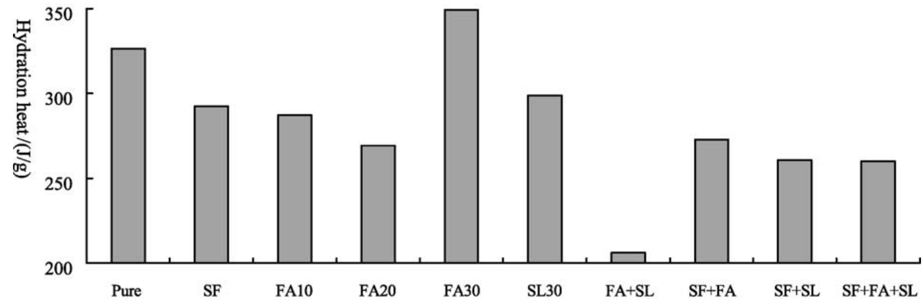

Fig. 9. Effect of types, adding amount and adding approaches of mineral admixtures on 3-day hydration heat.

corresponding values were 36.4 °C, 38 h, 22.15 J/h g and 269.2 J/g, respectively. It was important to note that hydration exothermic process was accelerated when 30% of fly ash was added. As a result, the highest temperature, maximum hydration exothermic rate and 3-day hydration heat reached 42.6 °C, 28.17 J/h g and 349.7 J/g, respectively, which were 80.5 J/g, 6.02 J/h g and 6.2 °C higher than those in FA20. The results were inconsistent with the views from the literature [10]. The phenomenon could be explained by noting that fly ash diluted cement particles at early age, resulting in the increase of actual W/B and the improvement of the hydration environment of cement. As a result, the hydration process of cement was accelerated and a great deal of heat was released. This phenomenon was true only to HPC with low W/B.

When slag was included, the highest temperature rise, maximum hydration exothermic rate and 3-day hydration heat were reduced, which was similar to fly ash. For example, as for SL30, the highest temperature rise, maximum hydration exothermic rate and 3-day hydration heat were 298.8 J/g, 20.88 J/h g and 37.0 °C, respectively.

As for the binder paste made with double-adding and triple-adding mineral admixtures (FA + SL, SF + FA, SF + SL, SF + FA + SL), the 3-day hydration heat and maximum hydration exothermic rate were much lower than those of pure and single-adding samples (FA30 and SL30). The arrival time of the highest temperature rise was also significantly delayed. For example, the highest temperature rise, 3-day hydration heat and maximum hydration exothermic rate of double-adding and triple-adding samples were 13.6–16.1 °C, 53.6–119.7 J/g and 30.04–36.18 J/h g lower than the pure sample. The arrival time of the highest temperature rise was also delayed from 9 to 19 h. It was interesting to point out that FA + SL sample had the lowest highest temperature rise, 3-day hydration heat and maximum hydration exothermic rate. Additionally, these curves of temperature rise–time showed a very slow fall as time passes. These leads us to believe that the temperature gradient inside concrete made with double-adding and triple-adding mineral admixtures should be small. As a result, the probability of cracks caused by high-temperature gradient will be reduced to some extent.

4. Conclusion

Based on the data presented in this paper, the following conclusions were obtained:

1. W/B had great impact on the hydration of the binder paste in HPC. The 3-day hydration heat of binder pastes decreased with the decrease in W/B.
2. The 3-day hydration heat of binder pastes was not reduced in the presence of superplasticizer containing retarding component (citrate type), but the hydration heat liberation process was delayed.
3. The addition of mineral cementitious components greatly reduced the 3-day hydration heat and exothermic rate and retarded the arrival time of highest temperature of the binder paste in HPC, which was especially true to double- and triple-adding approaches.

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