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Influence of fly ash on early-age cracking behavior of high-flowing concrete

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Abstract: The effects of quality and content of fly ash on the early-age cracking behavior of high-flowing concrete (HFC) were investigated. The early-age cracking behavior of the HFC was analyzed by combining the tests of evaporation capacity and electrical resistivity of the HFC. In these tests, a modified flat-type specimen was adopted. The results show that the HFC will have a lower evaporation capacity when it is mixed with fine fly ash, while it will have a higher evaporation capacity when grade III fly ash is used as mineral admixture. And the electrical resistivity rate of HFC reduces with the increase of the content of fly ash. A nonlinear relationship exists between the cracking time of HFC and the minimum electrical resistivity. The early-age cracking behavior of HFC with fly ash can be enhanced by appropriately increasing the fine particle content and MgO, K_2O, and SO_3 contents of fly ash. The optimal content of fly ash, which makes a satisfied early-age cracking behavior of HFC, is obtained. And when the content of fly ash exceeds a critical value, the early-age cracking behavior of HFC will rapidly decrease.

Key words: high-flowing concrete; fly ash; cracking behavior; electrical resistivity

1 Introduction

With the development of concrete technology, high-flowing concrete (HFC) is widely applied. But many problems still exist, especially cracking. Lots of experiments show that cracks will appear in a few days after HFC is poured in the structure, and some of them even happen only in a few hours after HFC is poured [1]. The crack may affect not only the appearance or serviceability of the structure, but also the safety and durability of the structure in many cases. To obtain a satisfied workability of fresh HFC, mineral admixtures with high volume fractions are needed. Fly ash, as a mineral admixture, is widely used for its abundant resource, excellent performance and low cost. Many previous studies showed that fly ash, as a pozzolanic material, is effective for improving various properties of concrete [2−4]. It has also been reported that fly ash can reduce the hydration shrinkage of cement paste effectively [5]; damage due to autogenous shrinkage can be significantly reduced in concrete or cement paste when fly ash is added [6−7]; the fly ash with different fineness has a marked effect on the drying shrinkage [8]; and the cracking behavior of concrete increases with the fly ash content added [9−11]. There are only a few papers about the effect of the quality and amount of fly ash on the cracking behavior of HFC. In this work, the effects of the quality and amount of fly ash on the early-age cracking behavior and electrical resistivity of HFC with equivalent workability of fresh concrete and strength were studied. And an optimized fly ash content of HFC with different quality of fly ash was obtained.

2 Experimental

2.1 Materials

A grade 42.5 ordinary Portland cement and four kinds of fly ash were used in the experiment. The fly ash samples were as follows. Grade Ⅰ fly ash, the product from Houshi Coal-fired Electric Power Station, China (HSⅠ) and Songyu Coal-fired Electric Power Station, China (SYⅠ); grade Ⅱ fly ash, the product from Houshi Coal-fired Electric Power Station, China (HSⅡ) and Huaneng Coal-fired Electric Power Station, China (HN Ⅱ); grade Ⅲ fly ash, the product from Houshi Coal-fired Electric Power Station, China (HS Ⅲ). The chemical composition and particle size distribution of the cement and the fly ash are listed in Tables 1 and 2, respectively. The crushed coarse aggregate and natural river sand were used. The fineness modulus of sand was 2.7, and the maximum size of coarse aggregate was 25 mm. A naphthalene-based superplasticizer was used. The mixture parameters of concrete are listed in Table 3.

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2.2 Test specimens

In a traditional test method, a large number of small cracks are formed. As a result, the measurement of cracks is difficult, and also a significant error is created. Therefore, a modified flat-type specimen was adopted to test the early-age cracking behavior of concrete (see Fig.1). A steel plate was used to induce and accelerate the development of the crack of the concrete, which made the cracks observed more easily with a lower error.

After being cast, the specimen was exposed to an environment of (23±3) ℃ and (60±5)% relative humidity. The crack was monitored by cracking observation meter with 40 times of magnification. The specimen was observed every 5 min until the crack pronged the specimen, and then observed every 2 h. To test the evaporation capacity, the concrete was poured into the cylinder with a diameter of 150 mm and a height of 50 mm. The mass of the cylinder was weighed every 1 h for the first 3 h, and then every 1.5 h. The evaporation capacity (E_t) of the concrete can be calculated according to the following equation: $E_t=(m_t-m_0)/A$, where m_t is the mass of the cylindrate concrete at time t, m_0 is the initial mass of the cylindrate concrete, and A is the area of the cylinder. A non-contacting electrical resistivity apparatus was used to measure the electrical resistivity of the concrete.

3 Results and discussion

3.1 Result

3.1.1 Electrical resistivity

The development of the electrical resistivity vs time of HFC is presented in Fig.2, which shows that the initial electrical resistivity of HFC basically increases with the increase of fly ash content, while the electrical resistivity rate of HFC decreases. As a result, at late age the electrical resistivity of HFC decreases with the increase of fly ash content. It also shows that with the increase of fly ash content, the occurrence time of the minimum electrical resistivity is retarded. When the fly ash content is lower than 40%, the occurrence time of the first peak of the electrical resistivity rate is about 500 min, compare with 753 min for HFC with 70% fly ash content.

Table 1 Chemical compositions of fly ash and cement (mass fraction, %)

Material	SY Ⅰ	HS Ⅰ	HS Ⅱ	HS Ⅲ	HN Ⅱ	Cement
SiO_2	47.24	53.18	49.48	47.27	51.65	19.99
CaO	6.14	7.13	6.87	4.93	7.93	62.72
Al_2O_3	34.00	27.02	30.42	35.19	23.86	5.22
Fe_2O_3	5.83	6.29	6.96	5.06	9.35	3.87
MgO	0	0.53	0	0	0.69	1.06
SO_3	0.81	0.64	0.74	0.61	0.96	3.48
K_2O	0.86	1.89	1.16	0.74	1.51	0.98
Bal.	3.36	2.04	1.94	2.29	1.74	0.53
Loss	1.76	1.27	2.43	3.90	2.30	2.19

Table 2 Particle size distribution of fly ash and cement (mass fraction, %)

Material size/μm	SY Ⅰ	HS Ⅰ	HS Ⅱ	HS Ⅲ	HN Ⅱ	Cement
0.8	0	0	0	0	0	0
3.0	44.92	23.28	7.00	6.79	15.99	16.48
5.4	56.47	34.64	11.84	10.32	24.93	25.06
9.7	70.11	54.53	23.48	18.73	42.15	38.82
15.1	81.44	68.43	35.88	28.60	57.70	51.56
20.4	87.92	75.83	44.55	35.75	66.45	62.20
31.8	97.15	88.91	63.47	52.32	81.12	81.63
42.7	99.23	94.74	76.10	63.64	89.33	90.59
66.5	100	98.07	83.55	68.84	94.07	96.51
103.3	100	100	97.01	94.12	99.30	100
120.0	100	100	100	100	100	100

Table 3 Mixture proportions, fresh properties and compressive strength of concrete mixtures

Mixture	m(Cement)/kg	Fly ash			m(Sand)/kg	m(CA)/kg	m(Water)/kg	w(SP)/%	Slump/mm	Compressive strength/MPa	
		Variety	Content/%	Amount/kg						3-day	28-day
M1	420	−	−	−	706	1 059	170	0.40	180	38.2	54.0
M2	396	HS Ⅰ	10	44	704	1 056	173	0.45	190	36.3	50.9
M3	360	HS Ⅰ	20	90	704	1 056	173	0.45	200	34.8	49.7
M4	338	HS Ⅰ	25	112	704	1 056	173	0.45	210	33.8	50.3
M5	315	HS Ⅰ	30	135	704	1 056	173	0.50	140	31.0	46.3
M6	305	HS Ⅰ	35	165	704	1 056	165	0.53	150	31.4	50.6
M7	282	HS Ⅰ	40	188	704	1 056	160	0.64	190	30.5	49.3
M8	270	HS Ⅰ	45	220	704	1 056	170	0.60	210	27.0	49.4
M9	245	HS Ⅰ	50	245	696	1 044	170	0.60	230	22.4	48.7
M10	200	HS Ⅰ	60	300	696	1 044	170	0.60	230	16.8	45.6
M11	150	HS Ⅰ	70	350	696	1 044	170	0.60	200	9.2	35.4
M12	396	HS Ⅱ	10	44	704	1 056	173	0.45	190	27.6	50.0
M13	360	HS Ⅱ	20	90	704	1 056	173	0.45	200	29.7	51.7
M14	315	HS Ⅱ	30	135	704	1 056	173	0.45	170	28.9	46.3
M15	282	HS Ⅱ	40	188	704	1 056	160	0.70	170	29.0	51.8
M16	396	HS Ⅲ	10	44	704	1 056	173	0.45	180	28.5	47.1
M17	360	HS Ⅲ	20	90	704	1 056	173	0.60	180	27.9	46.6
M18	396	SY Ⅰ	10	44	704	1 056	173	0.40	180	32.5	51.1
M19	360	SY Ⅰ	20	90	704	1 056	173	0.45	210	33.9	53.3
M20	315	SY Ⅰ	30	135	704	1 056	173	0.40	210	29.5	51.4
M21	282	SY Ⅰ	40	188	704	1 056	160	0.40	180	29.5	51.6
M22	396	HN Ⅱ	10	44	704	1 056	173	0.45	190	27.6	50.0
M23	360	HN Ⅱ	20	90	704	1 056	173	0.45	200	29.7	51.7
M24	315	HN Ⅱ	30	135	704	1 056	173	0.45	170	28.6	47.0
M25	282	HN Ⅱ	40	188	704	1 056	160	0.70	170	29.1	51.8

Note: CA stands for coarse aggregate; and SP stands for superplasticizer.

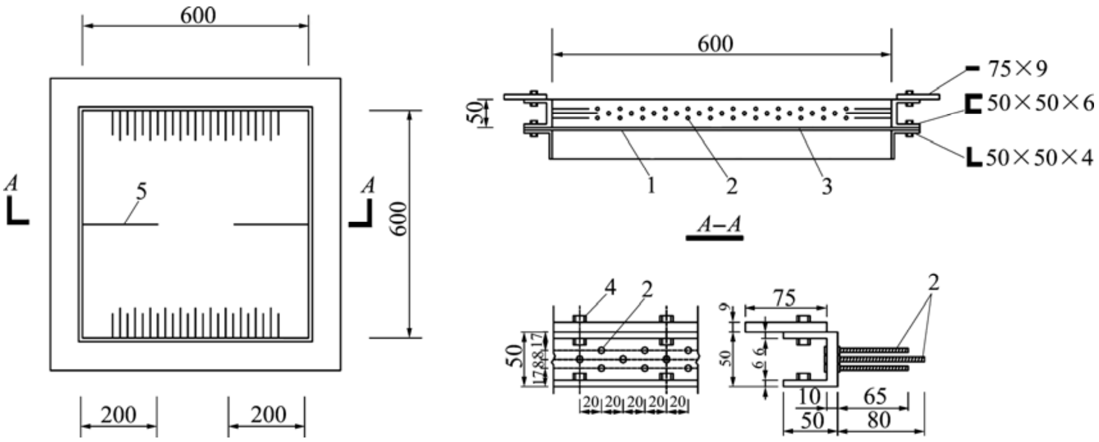

Fig.1 Details of modified flat-type specimen (unit: mm): 1—Motherboard; 2—*d*6 Bolt; 3—Olefin paper, teflon paper; 4—*d*9 Bolt; 5—Steel plate

3.1.2 Evaporation capacity

Fig.3 shows the evaporation capacity of HFC at different contents of fly ash. For the HSⅠ and HNⅡ, when the fly ash content is lower than 20%, the evaporation capacity of HFC has no obvious difference; when the fly ash content is higher than 20%, the evapora-

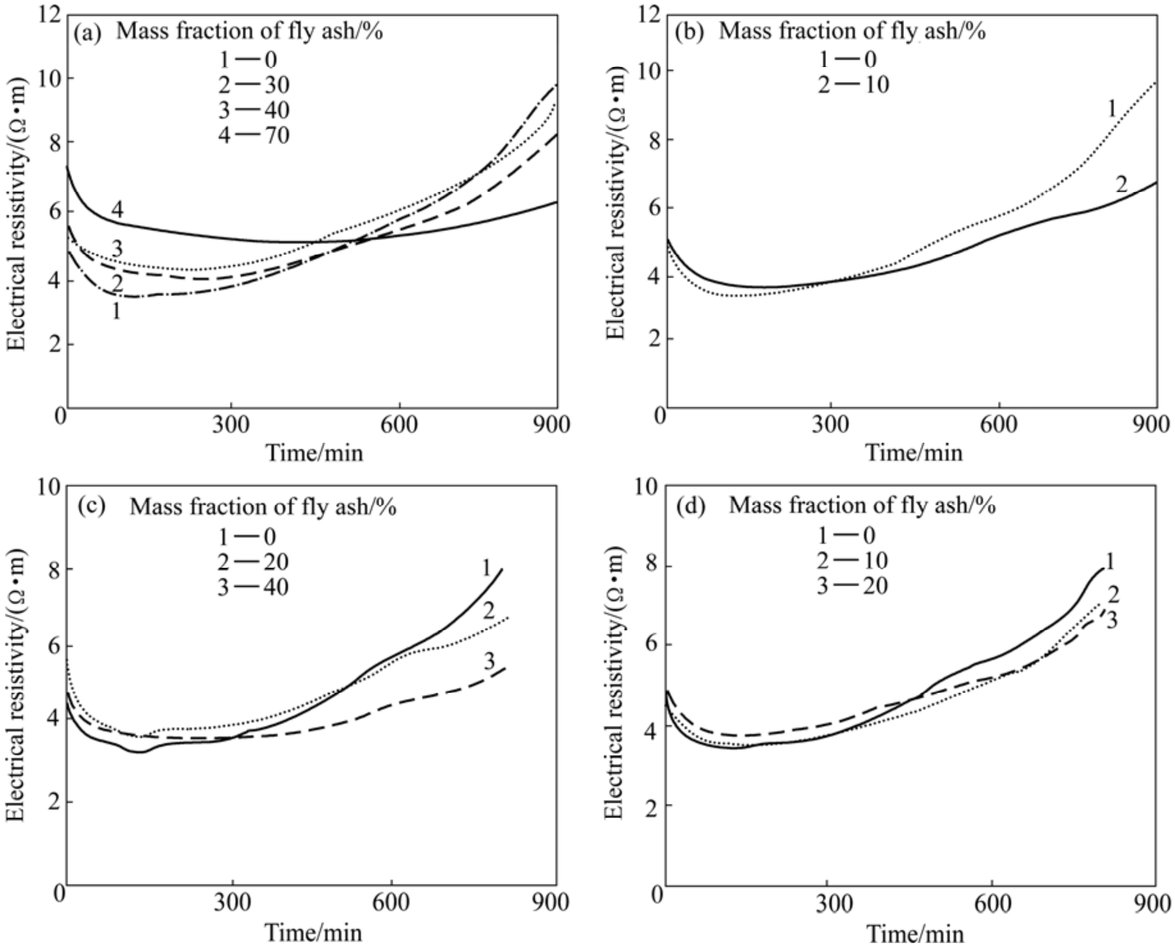

Fig.2 Electrical resistivity development of concrete: (a) HS Ⅰ; (b) SY Ⅰ; (c) HS Ⅱ; (d) HN Ⅱ

tion capacity of HFC decreases with the increase of fly ash content. The evaporation capacity of HFC with SYⅠ decreases with increase of fly ash content. The test result also shows that the evaporation capacity of HFC mixed with HS Ⅱ has no distinct difference when the content of HS Ⅱ changes. While the evaporation capacity of HFC mixed with HS Ⅲ is enhanced, especially at early age.

3.1.3 Early-age cracking behavior

Fig.4 shows the test results of the early-age cracking behavior of HFC specimens. For Ⅰ and Ⅱ grade fly ash, with the increase of fly ash content, the appearance of cracks retards. For HS Ⅰ, when the fly ash content is lower than 30% of binder, with the increase of fly ash content, the crack area of specimen reduces. When the fly ash content is between 30% and 50% of binder, the fly ash content hardly affects the crack area of HFC specimen. And the crack area of specimen decreases by 53.4% at fly ash content of 45%. But when the content of the fly ash is higher than 50% of binder the crack area of specimen increases rapidly with the increase of fly ash content. Crack area of HFC specimen with 60% fly ash content is 1.93 times of that with 50% fly ash content. For SYⅠ and grade Ⅱ fly ash, when the content of fly ash is lower than 20%, the crack area of HFC specimen decreases with the increase of fly ash content. When the content of SYⅠ is higher than 20% of binder the crack area of HFC specimens increases slowly with the increase of fly ash content. However, for grade Ⅱ fly ash, when the fly ash content is higher than 30%, the crack area of specimen increases rapidly. Incorporation of grade Ⅲ fly ash in HFC makes the crack area of specimen increase, but has little effect on the age of crack appearance.

3.2 Discussion

The electrical resistivity of concrete is determined by the pore property, the ion concentration and the mobility in the liquid phase [12]. According to the development of the electrical resistivity of concrete, the hydration progress of concrete can be described as three periods: the dissolving period, the setting period, and the hardening period [13]. The initial electrical resistivity of concrete is determined by the ion concentration in the dissolving period. And the electrical resistivity rate of concrete reflects its hydration rate. For the pozzolanic property of fly ash, the ion concentration and the hydration rate of concrete reduce with the increase of fly ash content. Therefore, with the increase in fly ash

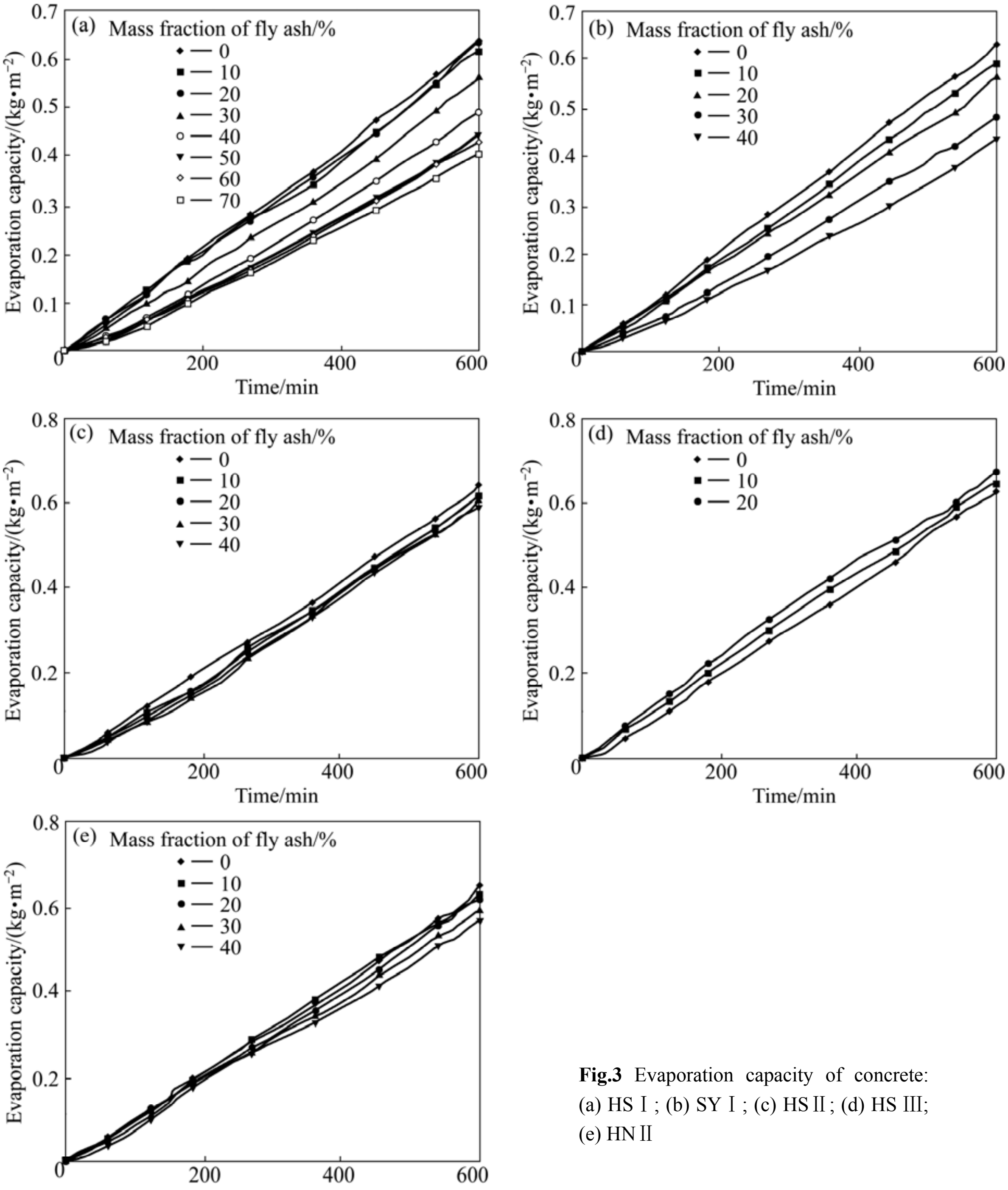

Fig.3 Evaporation capacity of concrete: (a) HS Ⅰ; (b) SY Ⅰ; (c) HS Ⅱ; (d) HS Ⅲ; (e) HN Ⅱ

content, the initial electrical resistivity of the concrete increases and the rate of electrical resistivity decreases.

Based on Raoult rule the water vapor pressure increases with the decrease of ion concentration [14]. And the evaporation rate is elevated with increase of the vapor pressure. The vapor pressure of HFC increases with the increase of fly ash content. However, HFC mixed with fine fly ash has a higher water-holding capacity. According to all these factors, the evaporation capacity of HFC varies when HFC is mixed with different quality and quantity of fly ash. Because of its finer particle size compared with other types of fly ash, the HFC mixed with SY Ⅰ has a lower evaporation capacity even with low content of fly ash. And the evaporation capacity of HFC mixed with HS Ⅲ is higher than that of control HFC, as the particle size of HS Ⅲ is larger than that of Portland cement.

An increase in the fly ash content can retard the initial setting time of HFC for the pozzolanic property of fly ash, which is confirmed by the electrical resistivity test. It was reported that the initial setting time extended with the increase of the occurrence time of the minimum

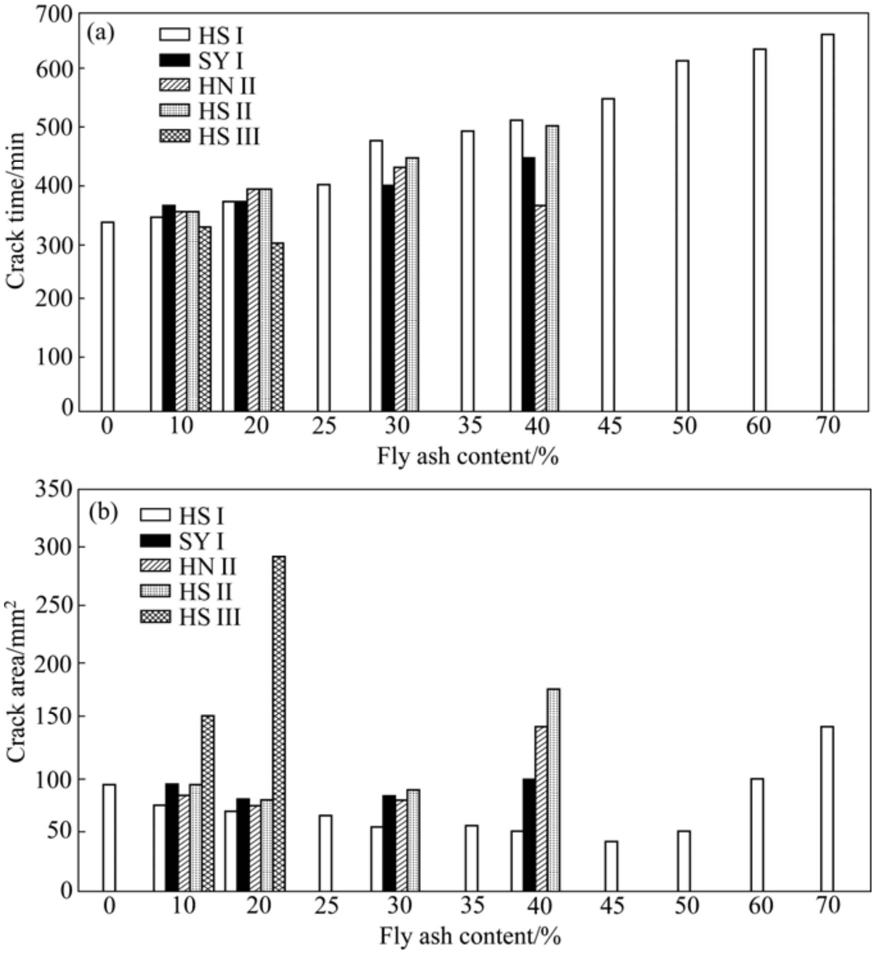

Fig.4 Comparison of early-age cracking behavior of HFC with various kinds of fly ash: (a) Crack time vs fly ash content; (b) Crack area vs fly ash content

electrical resistivity and the first peak of the electrical resistivity rate [13,15]. The electrical resistivity test results also reveal that the occurrence time of the minimum electrical resistivity of HFC is retarded with the increase of fly ash content. The results in Ref.[16] suggest that the onset of cracking is closely related to the setting time of concrete. Hence, the occurrence of concrete crack is retarded with the increase of fly ash content.

From the result of the electrical resistivity test and cracking behavior test, a conclusion can be drawn that the crack of HFC specimens appears between the occurrence of the minimum electrical resistivity and the first peak of electrical resistivity rate of HFC. The occurrence of the minimum electrical resistivity of concrete means that the solution of the paste reaches a supersaturated state, and ettringite (AFt), calcium hydroxide (CH), and calcium silicate hydrate (CSH) are formed. The first peak of electrical resistivity rate relates to the end of the setting period when the fluid paste starts to stiffen and gains strength [13]. The crack of HFC specimens appears between the initial setting time and final setting time. The minimum electrical resistivity of concrete indicates the hydration degree in the early age. From the test, the relationship between the age of the crack appearance and the minimum resistivity of HFC can be calculated using the following equation: $y=0.0498x^2-0.5306x+4.9159$, which is presented in Fig.5.

It was reported that the shrinkage of concrete mixed

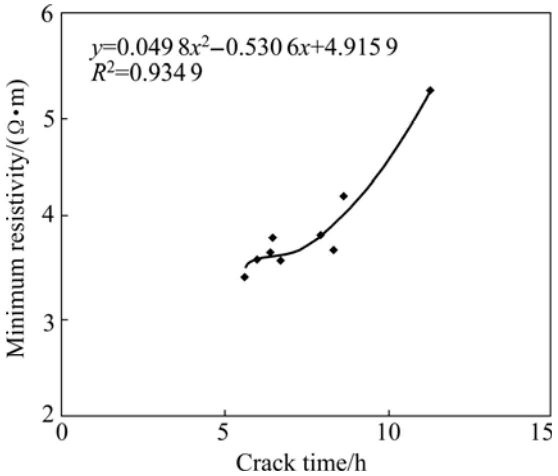

Fig.5 Minimum electrical resistivity vs crack time of HFC

with fine fly ash decreased with the increase of content of fly ash [17]. NELSON et al [18] and CENGIZ [19] also reported that the incorporation of fly ash in concrete decreased shrinkage. LEE et al [7] reported that the incorporation of fly ash in concrete decreased autogenous shrinkage; and the higher the fly ash content, the lower the rate of autogenous shrinkage. TANGTERMSIRIKUL [20] found that the increase of SO_3 content in the fly ash resulted in lower autogenous shrinkage rate, suggesting that chemical expansion of SO_3 plays an important role in reducing autogenous shrinkage. As shown in Table 1, the fly ash used in this work contains a small amount of SO_3. For the inert activity of fly ash, the chemical shrinkage of HFC in early age is reduced with the increase of fly ash content. The shrinkage reduction of HFC with fine fly ash is also resulted from less water evaporation and more free water. The tensile strength and elastic modulus of HFC decrease with incorporation of fly ash. So a balance of fly ash content should exist, with which a best early-age cracking behavior of HFC is obtained. When the content of fly ash is higher than a critical value, the balance is breached and the early-age cracking behavior of HFC decreases seriously.

Different types of fly ash have different chemical components and physical properties, and the influences of which on the early-age cracking behavior of HFC are different. The reactivity degree is greater in a fine fly ash than in a coarse fly ash [21]. The increase of the fine particle content of fly ash can increase the strength of concrete and decrease the evaporation capacity of concrete. So the optimal content of grade Ⅰ fly ash is higher than that of grades Ⅱ and Ⅲ fly ash. Though the optimal contents of SYⅠ and grade Ⅱ fly ash are the same, the early-age cracking behavior of HFC with SYⅠ decreases much slower than that of grade Ⅱ fly ash when the content is higher than the optimal content. The HFC mixed with grade Ⅲ fly ash enhances its evaporation capacity, and may decrease its early-age cracking behavior although the strength does not decrease. The chemical reaction of MgO and K_2O can cause volume expansion, which will mitigate shrinkage. HSⅠcontains small amount of MgO. The content of K_2O in HS Ⅰ is 1.91%, which is higher than that in SYⅠ (0.87%). Thus, the optimal content of HSⅠ is higher than that of SYⅠ.

4 Conclusions

(1) The crack of HFC specimen appears between the initial and final setting time. The relationship between the age of crack appearance and the minimum electrical resistivity of HFC is nonlinear.

(2) There is an optimal content of fly ash, and the content is related to the quality of fly ash. When the fly ash content is lower than the optimal content, the cracking behavior of HFC is enhanced with the increase of fly ash content. However, when the content of fly ash exceeds a critical value, the early-age cracking behavior of HFC rapidly decreases, and the critical value is closely related to the quality of fly ash. For grade Ⅱ fly ash, the critical value is 30%. But for grade Ⅰ fly ash, when the fly ash content exceeds 30%, the early-age cracking behavior of HFC does not decrease obviously, even some fly ash does not reach the optimal content. To ensure a satisfied early-age cracking behavior of HFC, grade Ⅰ fly ash is chosen when the fly ash content exceeds 30%.

(3) The incorporation of grade Ⅲ fly ash in HFC will decrease the early-age cracking behavior of HFC.

(4) An appropriate increase in the fine particle content and MgO, K_2O, and SO_3 contents of fly ash can enhance the early-age cracking behavior of HFC.

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