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Influence of superplasticizers on the early-age crack resistance of concrete

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Abstract: In order to improve the early-age cracking resistance of concrete, different types of superplasticizers are used. Two types of polycarboxlic salt/acid superplasticizers and one retarding naphthalene superplasticizer are selected to investigate the influence of superplasticizers on the early-age cracking resistance of the concrete by using the slab test and the temperature-stress test. The results show that the polycarboxlic salt/acid superplasticizer cannot always improve the cracking resistance capacity of the concrete compared with the naphthalene superplasticizer, which is related to the chemical structure of the polycarboxlic salt/acid superplasticizer. High plastic tensile strength and dynamic elastic modulus at the early stage are beneficial to avoid cracking, and low hydration heat is also helpful. The evolutions of the drying shrinkage stress and the hydration heat temperature stress varying with time can be comprehensively evaluated by means of the slab test and the temperature stress test.

Key words: superplasticizer; crack resistance; slab test method; temperature-stress test method

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With the development of social economy, durability and crack control of concrete have been valued more and more. And with the increased use of high performance concrete, micro-cracks often appear after concrete pouring and then gradually expand along the aggregate to the surface during the hardening of the concrete. The main factors causing deterioration and durability reduction in concrete[1] are cracks and the development of micro-cracks under various conditions which may lead to the intrusion of harmful media. The early cracks will certainly provide access for the intrusion of corrosive substances and accelerate the damage to the concrete. These cracks occur in the early hardening of the concrete with no load in structure and they are due to shrinkage cracks. According to the survey, 20% of the cracks are load cracks and the other 80% are deformation cracks which mainly occur in shrinkage cracks. The polycarboxlic salt/acid superplasticizer is a kind of surfactant in the comb-like molecular structure of graft copolymers with carboxyl[2]. This superplasticizer has a high water-reducing ratio and good performance in maintaining the liquidity of the concrete mixture. Besides, it also shows better improvement to concrete performance compared with the traditional plasticizers.

The concrete stress mainly consists of two parts under the constraints. One is the temperature stress caused by the constraints of temperature shrinkage with change of temperature; the other is the tensile stress caused by the constraints of drying shrinkage [3−5]. The ring constrained method and the slab test method are always adopted in the cracking evaluation. However, it is difficult to evaluate the crack resistance under constraints and objectively predict the cracking tendency of the concrete. In this paper, the influence of polycarboxlic salt/acid superplasticizers on crack resistance is comprehensively evaluated by the slab test method and the temperature-stress test method.

1 Experiment

1.1 Raw materials and mix proportion

P·O 42.5 cement, Grade Ⅰ fly ash, medium sand (M_x = 2.7) and graded gravel (5 to 25 mm) are chosen. Polycarboxlic salt/acid superplasticizers J1 and J2 (water-reducing ratio: about 35%) and retarding naphthalene superplasticizer N1 (water-reducing ratio: about 15%) are used and the dosages are adjusted by keeping the concrete slump as 180 to 200 mm. The mix proportion is shown in Tab. 1.

Tab. 1 Mix proportion of C50 kg/m^3

w(water)	w(cement)	w(fly ash)	w(sand)	w(gravel)
157	370	80	730	1 095

1.2 Methods

1.2.1 Slab test method

As concrete slabs are not easy to crack, stones which were larger than 5 mm are sieved out from the mixed concrete in the slab test. The test is taken indoors with a temperature of (20 ± 3) ℃ and a relative humidity of (60 ±

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5)%. The specimens are illuminated for 4 h, winded for 24 h; and then, the cracking situation is measured. The initial cracking time, the crack width and length are recorded. Finally, the crack index and area are calculated. This test procedure is conducted according to JC/T 951—2005.

1.2.2 Hydration heat

The 20℃ hydration heat curves of cement paste (containing fly ash) are directly measured by an isothermal calorimeter. The hydration heat is measured for 3 d after the addition of water.

1.2.3 Plastic tensile strength

"8"-shaped wooden molds [6] are used to measure the tensile strength of cement mortar during the plastic stage. Before testing, the rubberized fabric must be cut at the interface; otherwise, the specimen must be canceled if the surface has obvious cracks. A half mold is kept static, and a barrel is tied to the thread through the other half mold. Sands are poured into the barrel at a uniform speed, and stopped when the "8"-shaped wooden mold breaks. The weight of the barrel and sand is weighed (m_1), and then the barrel is tied to the other half. Stop pouring when this half moves, and the weight of the barrel and sand is recorded (m_2). The fracture area A is also measured. Only if the fracture happens in the middle of the mold, the data cannot be canceled. Then the tensile strength of the mortar during the plastic stage can be calculated by the formula $P = (m_1 - m_2)/A$.

1.2.4 Dynamic elastic modulus

The ultrasonic pulse method [7] is used to measure the dynamic elastic modulus. It can be used to measure the time, the velocity of the ultrasonic wave through the concrete and so on, and the measured parameters can be used to calculate the elastic modulus of the concrete. The calculation formula is

$$E_d = \rho_c V^2 (1+\nu)(1-2\nu)/(1-\nu) \tag{1}$$

where E_d is the dynamic elastic modulus of the concrete, GPa; ρ is the concrete density, kg/m^3; V is the speed of ultrasonic waves in the concrete, m/s; ν is the Poisson ratio.

1.2.5 Temperature-stress test method (TSTM)

The temperature-stress testing machine [8-9] can be used to measure the stress development of the concrete specimen in different constraint degrees (0 to 100%, adjustable) and different temperature environments (adiabatic, semi-adiabatic, isothermal, simulation of temperature history of the structural concrete) by the high-precision load sensor. And the influence of superplasticizers on crack resistance is studied by this method in a fully constrained state and the adiabatic temperature rise mode.

2 Results and Discussion

2.1 Evaluation of plastic crack resistance by slab tests

During the first several hours after concrete pouring, the pastes may shrink as the evaporating velocity of the surface water is greater than the bleeding velocity inside. During this stage, concrete has a very low strength. When the shrinkage stress generated by the capillary pressure is greater than the tensile strength of the concrete, the plastic cracks begin to appear on the surface of the concrete. Cracks expand in the first few hours of concrete curing. Besides, the number of cracks increases, and both the length and width of cracks become larger. The higher environment and concrete temperature, the lower environment humidity and the greater air flow rate will lead to the larger water evaporation of the concrete, and then the plastic shrinkage cracks become more serious.

The results of the slab tests are shown in Tab. 2. It shows that the initial cracking time of the concrete slab with N1 takes longer than that of the other two, but the maximum crack width, the crack index and the crack area are larger. Because the concrete slab with J1 has the lowest crack index and crack area, the polycarboxlic salt/acid superplasticizer J1 can greatly improve the plastic crack resistance of the concrete.

Tab. 2 Results of slab tests

Superplasticizer	Initial cracking time/min	Crack numbers	Maximum crack width/mm	Crack index/mm	Total crack area/mm^2	Ratio of crack area to total area/10^{-4}
N1	45	5	1.7	683	520.9	9.54
J1	30	5	1.2	331	179.3	3.28
J2	30	6	1.6	611	517.5	9.48

2.2 Hydration heat

Hydration heat curves can reflect the hydration of cementitious materials. Fig. 1 shows the normalized heat flow and heat development with different superplasticizers during the first 3 d. In the normalized heat flow curves, the high peaks at the beginning may be caused by the dissolving heat but not the hydration heat. From Fig. 1, the hydration of sample J1 is slower than that of J2. However, N1 delays cement hydration obviously and can be used to speculate the existence of retarding components. N1 can reduce shrinkage at early ages but with lower plastic tensile strength, and its ability to resist cracking is weaker.

2.3 Tensile properties

The plastic tensile strength and the dynamic elastic modulus can reflect the tensile properties of the concrete

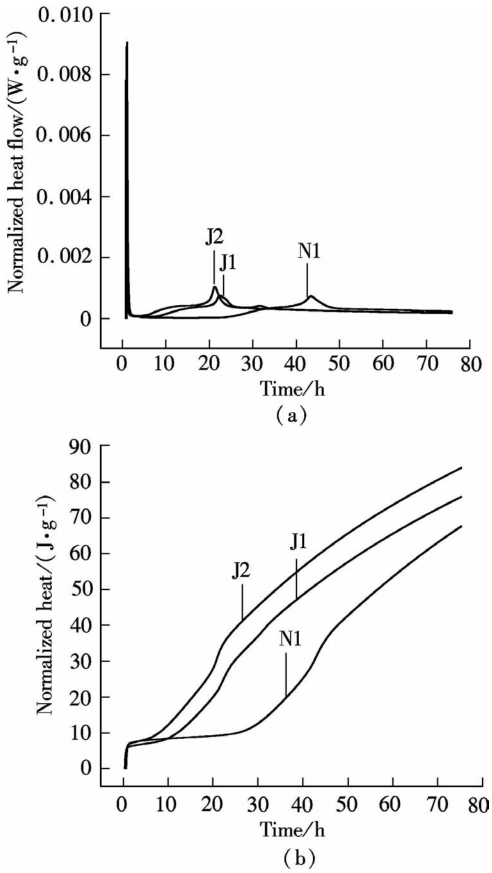

Fig. 1 Normalized heat flow and heat development with different superplasticizers during the first 3 d. (a) Heat flow; (b) Heat

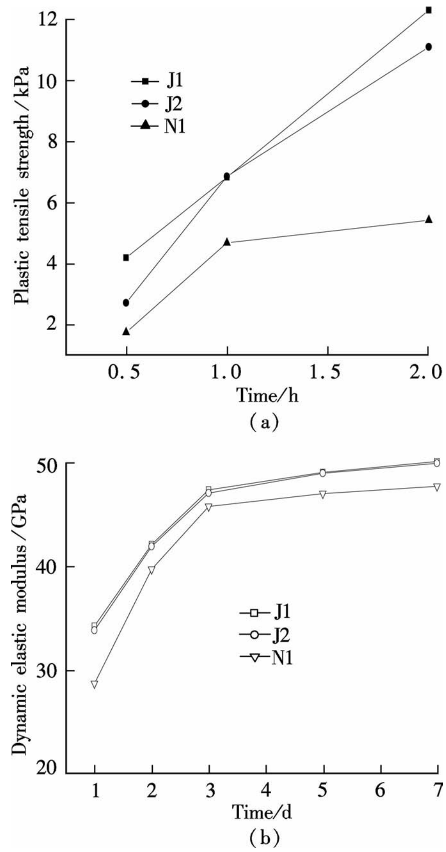

Fig. 2 The curves of plastic tensile strength and dynamic elastic modulus by the time. (a) Plastic tensile strength; (b) Dynamic elastic modulus

in different stages. The higher plastic tensile strength and the dynamic elastic modulus mean the better performance in deformation resistance. Certainly, to evaluate the crack resistance of concrete, one should take into consideration not only the deformation resistance but also the value of shrinkage. In Fig. 2, from the curves of the plastic tensile strength and the dynamic elastic modulus, the deformation resistance of specimen N1 is weaker than others, especially, during the early plastic stage. In spite of the inhibition of the early-age shrinkage by retarding components, it is not beneficial to the crack resistance for the poor tensile properties. But J1 and J2, especially the former, show the better performance in deformation resistance.

2.4 Temperature-stress test method

The stress development histories of the concrete specimen with three superplasticizers are studied in the fully constrained state and the adiabatic temperature rise mode. With consideration of the influences of constraint degree and temperature history, the crack resistance can be described more reliably and correctly. All the data can be measured real-timely after concrete pouring, and a large number of data are recorded in the whole test. These are the advantages of the TSTM to study the crack resistance of the concrete.

The shrinkage stress and the temperature history are recorded real-timely throughout the whole test. From Fig. 3, the experimental process can be described as three stages. Stage 1 is the temperature rise stage with cement hydration; stage 2 is the constant temperature stage at the temperature peak; and stage 3 is the temperature dropping and cracking. The test parameters in the TSTM are shown in Tab. 3.

Tab. 3 Test parameters in the TSTM

Parameters	J1	J2	N1
Test time/h	121.12	103.00	99.72
The first zero-stress temperature/℃	18.50	17.40	18.10
Maximum compressive stress/MPa	0.31	0.39	0.45
Second zero-stress temperature/℃	51.38	48.96	43.24
Temperature peak/℃	51.50	49.10	43.24
Room temperature stress/MPa	−2.96	−2.87	−2.50
Cracking stress/MPa	−3.23	−2.88	−2.82
Cracking temperature/℃	11.77	18.62	9.60

2.5 Analysis of test parameters

2.5.1 Compressive stress

Shrinkage appears after concrete mixing with cement hydration, but the shrinkage value is not so large. With the temperature rise, the expansion of the concrete specimen leads to the compressive stress. And the maximum compressive stress among the three groups are nearly the same.

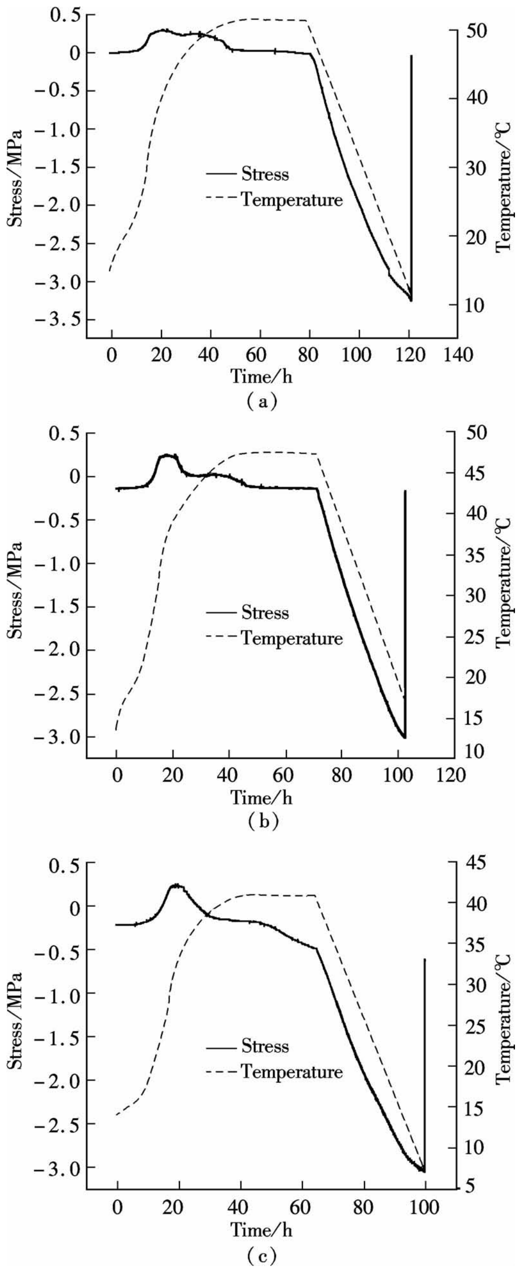

Fig. 3 The shrinkage stress and temperature history with different superplasticizers. (a) J1; (b); J2; (c) N1

2.5.2 Temperature rise caused by cement hydration

The temperature rise depends on the hydration speed. In the experiment, plasticizer N2 contains the retarding component which delays cement hydration and lowers the temperature peak. J1 and J2 are polycarboxylic salt/acid superplasticizers and their temperature rise is nearly the same.

The temperature rise is not a direct factor on the level of cracking capacity. The greatest advantage of the TSTM is that the development process of the temperature and the stress of the constrained concrete members can be studied and simulated in the laboratory.

2.5.3 The second zero-stress temperature

The second zero-stress temperature is the temperature when the stress of the specimen changes from the compressive stress to the tensile stress. Before this time, the expansion by cement hydration plays a major role and the stress status is reflected in the compressive stress. Then, the shrinkage stress increases, which leads to the tensile stress status. The second zero-stress temperature is not only associated with the temperature rise caused by cement hydration, but it is also influenced by the development of concrete strength. With the effect of temperature rise caused by cement hydration, the second zero-stress temperatures of the J1 and J2 groups are higher than that of the N2 group.

2.5.4 Room temperature stress

The compressive stress is formed after concrete mixing by expansion with the temperature rise, and it reaches the maximum value before the arrival of the temperature peak. Then the compressive stress decreases and the stress status becomes tensile. The room temperature stress reflects the tensile stress when the temperature of the concrete drops to room temperature. The room temperature stress reflects the influences of the temperature, deformation and constraint degrees of the concrete. And the cracking stress is the ultimate stress of crack resistance. The room temperature stresses of the J1 and J2 groups are high with fast cement hydration, but for the concrete of the J2 group, the room temperature stress is almost equal to the cracking stress, which means that the concrete of the J2 group is obviously influenced by temperature and constraint conditions.

2.5.5 Cracking stress and cracking temperature

The cracking stress reflects the mechanical properties of the concrete, and the higher the cracking stress means the better the tensile performance. The cracking temperature is a comprehensive cracking parameter to evaluate the cracking sensitivity of the concrete. The lower the cracking temperature means the better the crack resistance. The cracking stress of the J1 group is 3.23 MPa and it is higher than those of the other two groups, so it has a better tensile performance. The cracking temperatures of the J1 and N1 groups are 11.77℃ and 9.60℃, respectively, and they are obviously lower than that of the J2 group, which shows better crack resistance. N1 contains retarding components and it can delay cement hydration and reduce the tensile strength and shrinkage at early ages. However, in extremely poor conditions such as high-power illumination and long-time wind in slab tests, the crack area of the N1 group is larger in spite of good cracking sensitivity. With the lower strength in early ages, cracks expand more easily, which may obviously increase the cracking area. The concrete of the J1 group has a lower cracking temperature and a higher tensile strength. With the common cement hydration and mechanical properties, polycarboxlic salt/acid superplastizier J1 can obviously improve the crack resistance of the concrete compared to that of the J2 group. Besides, polycarboxlic salt/acid superplasticizers can reduce the surface tension of the pore solution and the capillary tension and then control the development of the early-age shrinkage.

So, in order to have a better crack resistance ability, the concrete should have lower shrinkage and higher tensile properties. According to the two aspects, an appropriate polycarboxlic salt/acid superplasticizer can be chosen to improve the crack resistance of the concrete.

3 Conclusions

1) Polycarboxlic salt/acid superplasticizer J1 shows better performance in plastic crack resistance tests with a lower crack index and crack area. To evaluate the crack resistance of concrete not only the tensile strength but also the value of shrinkage should be taken into consideration.

2) The higher tensile strength and the dynamic elastic modulus show the better performance in deformation resistance. The delay of cement hydration can reduce the early-age shrinkage.

3) The TSTM can study crack resistance caused by temperature stress. The ring test and the slab test can study drying shrinkage resistance. In the TSTM, the cracking stress reflects the tensile properties of the concrete and the cracking temperature is a comprehensive cracking parameter to evaluate the cracking sensitivity of the concrete. The appropriate polycarboxlic salt/acid superplasticizer such as J1 can obviously improve the crack resistance of the concrete as the concrete of the J1 group has a high cracking stress (3.23 MPa) and a low cracking temperature (11.77℃)

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减水剂对混凝土早期抗裂性的影响

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摘要: 为了提高混凝土的早期抗裂性能,使用了不同种类的减水剂. 采用平板法和温度应力试验法,研究了 2 种不同分子结构的聚羧酸减水剂和 1 种缓凝型萘系减水剂对混凝土早期抗裂性能的影响. 结果表明,与萘系相比,聚羧酸减水剂并非一定能提高混凝土的早期抗裂性能,这与聚羧酸的分子结构有关. 早期塑性抗拉强度和动弹性模量较高,将有利于抗裂,在此前提下,较低的水化热也有利于避免裂缝的产生. 温度应力试验法与平板法结合可综合反映混凝土的干缩应力和水化热温度应力随时间的演化.

关键词: 减水剂;抗裂性;平板法;温度应力试验法

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