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Effect of Polypropylene Fibers on the Long-term Tensile Strength of Concrete

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Abstract: The influence of low volume fraction of polypropylene(PP) fibers on the tensile properties of normal and high strength concretes was studied. The experimental results indicate that the addition of PP fibers in concrete leads to a reduction in tensile strength during the age of 28 d. Whereas, after 28 days, there is a notable effect in tensile strength due to PP fibers restraining the formation and growth of microcracks in concrete, which improves the continuity and integrality of concrete structure. Thus, a low volume fraction of PP fibers is beneficial to enhancing the long-term tensile strength of concrete materials and improving the durability of concrete structures.

Key words: polypropylene fiber; concrete; tensile strength; microcrack

1 Introduction

Concrete is a kind of composite materials with a low tensile strength and a low tensile strain limit. With the increase of different kinds of shrinkage (*e g*, chemical shrinkage, thermal shrinkage, plastic shrinkage, drying shrinkage and autogenous shrinkage), microcracks are formed during the period of concrete's hardening process. Such microcracks may have a little effect on the compressive strength of concrete, thus, after 28 days, the compressive strength of concrete increases slowly. However, the tensile strength hardly increases, sometimes it may decrease after 28 days. The decrease of the tensile strength to compressive strength ratio with ages will definitely lead to the increase of concrete brittleness, and thus the potential failure fatalness without any symptom in concrete structures increases.

In order to improve the concrete tensile strength, it is necessary to decrease the amount of microcracks and control its growth effectively. Recently, many researches [1-5] have shown that by adding a low volume fraction of polymeric fibers, such as polypropylene (PP) fibers, the plastic shrinkage cracks of concrete at early ages reduced obviously, and the PP fibers can also distinctly reduce the surface bleeding and the settlement of aggregate of fresh concrete, which can prevent the formation of settling cracks. Moreover, adding the PP fibers is also helpful to reduce the shrinkage of matured concrete. The average crack width of PP fiber reinforced concrete in confined shrinkage decreases greatly with volume fraction increasing. Compared with plain concrete, not only the number of cracks decreases, but also the size of the microcracks reduces greatly for PP fiber reinforced concrete.

The decrease of initial defects, especially the reduction of amount and size of microcrack of PP fiber reinforced concrete, is helpful to the improvement of tensile properties. Thus, the trend of tensile strength at early age, standard age and up to 100 days, respectively, for PP fiber reinforced concrete with a low fiber volume fraction was studied in this paper. The concrete considered in the paper included normal and high strength concretes. The influences of low volume fraction of fibers on the microstructure and the interface characteristics of concrete were discussed, and the mechanism of the PP fiber's anti-cracking and its supplement effect on concrete tensile properties were analyzed.

2 Experimental

2.1 Materials

Ordinary Portland cements (P.O. 32.5 and P.O. 42.5), fine ground slag (specific surface area is 500 m^2/kg), river sand (fineness modulus is 2.80), gravel (the maximum aggregate size is 10 mm), PP

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Table 1 The basic physical properties of PP fibers

Length /mm	Diameter /μm/	Density (g/cm³)	Elastic modulus /GPa	Tensile strength /MPa	Melting point /°C	Fracture prolongation ratio /%
15	45	0.91	8.0	400	165	8.2

fibers (the physical properties are shown in Table 1), superplasticizer were used in the experiment.

2.2 Mixing proportions

Mixing proportions for normal and high strength concretes are shown in Table 2 and Table 3, respectively. The trend of tensile strength for both normal and high strength concretes was investigated with four series comparing specimens. The slump of 150 mm was kept by adjusting the dosage of superplasticizer.

2.3 Methods

The test of compressive and tensile strengths was referenced to GBJ 81-85 (Chinese Code), and the tensile strength was measured by splitting tensile test. In order to obtain the stable splitting tensile stress *vs* strain curve, a closed-loop servo-hydraulic universal testing system was used in the test at an approximately constant rate of strain. The clip gauges were fixed at the middle of the specimen, and the measurement span was 50 mm, as shown Fig.1. The values of load and strain were measured by a load sensor and clip gauges simultaneously, and the load *vs* strain curve was recorded and output by a computer at the same time.

Table 2 The mixing proportions of normal strength concrete

Series	Water-binder ratio	Cement¹	Fine ground slag	Coarse aggregate	Fine aggregate	PP fibers²
NC1	0.44	1.0	---	2.27	1.51	---
NC2	0.44	0.6	0.4	2.27	1.51	---
NC3	0.44	1.0	---	2.27	1.51	0.2%
NC4	0.44	0.6	0.4	2.27	1.51	0.2%

Note 1：P. O 32.5 Portland cement was used in the above mixtures. 2：In volume percent.

Table 3 The mixing proportions of high strength concrete

Series	Water-binder ratio	Cement¹	Fine ground slag	Coarse aggregate	Fine aggregate	PP fibers²
HSC1	0.36	1.0	---	2.0	1.32	---
HSC2	0.36	0.5	0.5	2.0	1.32	---
HSC3	0.36	1.0	---	2.0	1.32	0.2%
HSC4	0.36	0.5	0.5	2.0	1.32	0.2%

Note 1：P. O 42.5 Portland cement was used in the above mixture；2：In volume percent.

Considering that there exist two kinds of fracture mechanisms in the splitting tensile behavior[6,7], as shown in Fig.2, especially to the load *vs* strain curve of fiber reinforced concrete, the second peak is generally higher than the first peak. In order to ensure the validity of testing data, the tensile strength was calculated by selecting the corresponding load at the first peak load instead of the maximum load.

3 Results and Discussion

The results of the compressive and tensile strengths of normal and high strength concretes are shown in Table 4 and Table 5, respectively. It is found that the compressive strength of all series of concretes increases with ages. The compressive strengths of series NC2 and HSC2 containing fine ground slag are the highest in their groups, while series NC3 and HSC3 containing no fine ground slag but fibers are the lowest in compressive strength.

In both normal and high strength concretes, the trend of the tensile strength development of all series is widely divergent. A remarkable difference took place at the age of 28 days. Although at the age of 7 days and 28 days, the tensile strengths of series NC2 in normal strength concrete group and series HSC2 in high strength concrete group were the highest, while those of series NC3 and HSC3 were the lowest, after 28 days, the tensile strengths of series NC1, NC2, HSC1 and HSC2 containing no fibers decreased to a different degree, but the tensile strengths of series NC3, NC4, HSC3 and HSC4 containing fibers continued to increase. Moreover, the tensile strengths of series NC4 and HSC4, in which the fibers and fine ground slag were added together, were the highest respectively in each group.

The tensile strength to compressive strength ratio is one of the indexes that can indicate the brittleness of concrete.

Fig.3 shows the trend of the tensile strength to

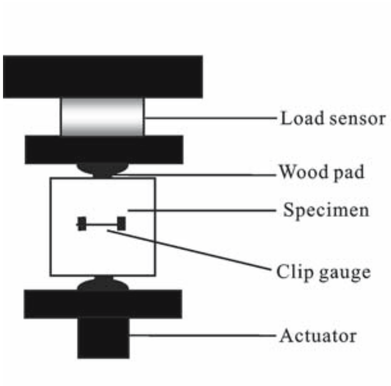

Fig.1 Setup of splitting tensile test

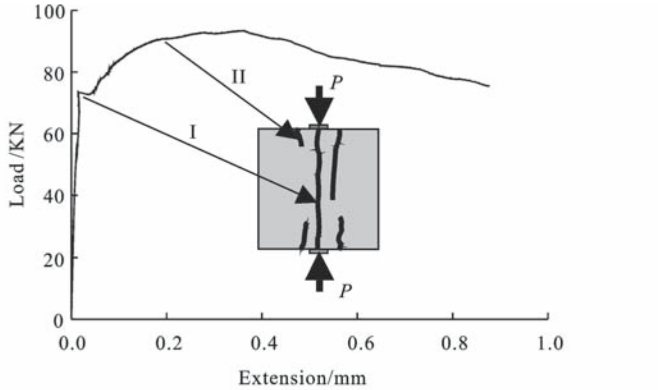

Fig.2 load-extension curve and two fracture mechanisms of concrete

compressive strength ratio of all series of concretes with the age. It can be seen from the figure that the tensile strength to compressive strength ratio descended faster for concretes with no fibers compared with those concretes containing fibers. It is also found that the tensile to compressive ratio of series HSC4 increases slightly with increasing in ages.

As we have known, there are two independent populations of pores in the cement-based material: (i) open pores with no “length” but volume; (ii) closed pores with length but no volume. The former population affects the compressive strength and elastic modulus, whereas the latter determines the fracture stress, *i e*, the tensile strength or the flexural strength. With age increasing, the number and volume fraction of open pores decrease greatly, thus, the compressive strength gradually increases. Especially when the lower water to binder ratio is adopted and some active supplementary cementitious materials with a larger specific surface area are added in high performance concrete, a denser complex cementitious system is formed, which can improve the compressive strength notably. However, the amount of shrinkage cracks of concrete increases with ages and the number of closed pores increases frequently, which leads to the descending trend of the tensile strength.

By adding a low volume fraction of PP fibers, a three-dimensional cross supporting network comes out. Although a larger specific surface area of PP fibers increasing the air content in concrete leads

Table 4 Results of tensile and compressive strengths of normal strength concrete

Series	Compressive strength/MPa				Tensile strength /MPa			
	7 d	28 d	60 d	100 d	7 d	28 d	60 d	100 d
NC1	23.4	37.8	45.7	51.3	2.53	3.62	3.58	3.71
NC2	29.0	42.9	49.5	53.5	2.95	3.98	3.85	3.71
NC3	22.1	32.8	42.1	48.0	2.31	3.23	3.79	4.03
NC4	24.9	39.4	46.6	49.5	2.36	3.90	4.40	4.62

Table 5 Results of tensile and compressive strengths of high strength concrete

Series	Compressive strength/MPa				Tensile strength/MPa			
	7 d	28 d	60 d	100 d	7 d	28 d	60 d	100 d
HSC1	33.6	54.8	66.0	73.2	3.26	4.06	4.01	3.95
HSC2	42.0	63.5	72.1	77.5	3.52	4.76	4.52	4.40
HSC3	31.7	46.9	61.0	69.5	2.81	3.86	4.25	4.82
HSC4	36.1	56.9	67.2	71.8	2.82	4.54	5.26	5.98

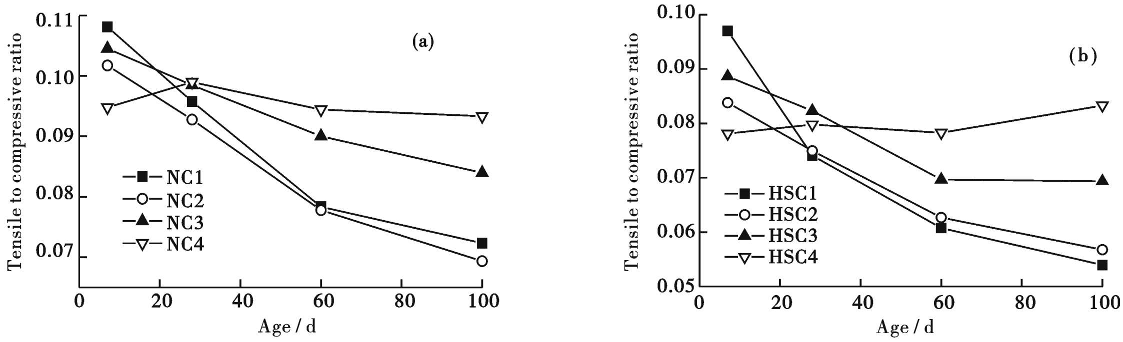

Fig. 3 Trend of tensile to compressive ratios of (a) normal strength concrete and (b) high strength concrete

to descending of compressive strength (*e g*, the compressive strengths of NC3 and HSC3 are lower than those of NC1 and HSC1, respectively; the compressive strengths of NC4 and HSC4 are lower than those of NC2 and HSC2), a remarkable anti-cracking effect exists with the smaller diameter of PP fibers and smaller fiber distribution span to prevent the plastic shrinkage cracking effectively due to the higher elastic modulus of the PP fibers compared with that of plastic cement-based material at early age.

Adding PP fibers and fine ground slag together into concrete can improve the interface bonding stress between fiber and matrix materials. As we know that PP fiber is hydrophobic, the water to cement ratio at the interface zone of fiber and matrix material is usually higher than that of matrix materials themselves, which forms a weak interface effect harmful for concrete strength. Adding some fine ground slag can increase the contact area between fiber and matrix, improve the interface characteristies and increase the interface bonding strength between fiber and matrix. Table 6 shows the debonding strength of single fiber by pull-out test (the embedded length of fiber was 10 mm, the water to binder ratio was 0.36).

What should be pointed out is that it is a kind of

Table 6 The debonding strength of single PP fiber by pulling out from different pastes

Age /d	In cement paste /MPa	In cement paste with 50% fine ground slag/MPa
3	0.07	0.08
7	0.12	0.19
14	0.15	0.21
28	0.22	0.28

supplement effect rather than a increasing strength effect when adding a low volume fraction of PP fibers with a low elastic modulus to make the long-term tensile strength of concrete go up. As the elastic modulus of PP fibers is only one fourth of that of hardened concrete, according to the simple law of mixture, the PP fiber reinforced concrete will lose some strength compared with control concrete[4,5]. From the results of Table 4 and Table 5, we can find that at the early age, the strengthes of concretes containing PP fibers are all lower than that of the corresponding concrete with no fibers. However, after 28 days, with the increase of shrinkage and micro-defects of control concrete, the tensile strength sensitive to microcracks descends. For those concretes containing fibers, due to the anti-cracking effect of PP fibers, which reduce the formation and growth probability of microcracks, and keep the integrality of concrete, the tensile strength improves synchronously with the hydration process as the compressive strength.

4 Conclusions

The addition of a low volume fraction (0.2%) of PP fibers is helpful to improve the microstructure and restrain the formation and growth of microcracks in concrete. When the PP fibers are utilized with fine ground slag together, the interface characteristics and bonding stress between fibers and cement matrix will be enhanced, which increases the anti-cracking effect and strength supplement effect to a great degree, and reduces the brittleness of concrete. Moreover, the continuity and integrality of concrete will be improved and the long-term tensile strength will be developed, which is beneficial to safety and durability of concrete structures.

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