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Analysis on the Anti-cracking and Anti-permeability Performance of Polypropylene Fiber-Reinforced Concrete in Subway Retaining Structure

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In this paper, regarding the problems of subway and tunnel retaining structures such as cracking and seepage, we study the stress, strain and temperature changes of the new polypropylene fiber-reinforced concrete (PFRC) through laboratory test and engineering measurement. The results show that mixing polypropylene crude and fine fiber into concrete can greatly improve the tensile strain and deformation performance of basic concrete. The amount of polypropylene fiber added has something to do with the aggregate composition of the concrete, and polypropylene fiber has little effect on the tensile modulus of the concrete. Compared with the purely crude fiber and fine fiber concrete, the blended fiber-reinforced concrete has the greatest increase in the tensile strength over the basic concrete. The results show that, after crude and fine fiber is added into the ordinary concrete, cracks on the concrete surface are greatly reduced and the width of the cracks is also within the standard, which is in accordance with the intended anti-cracking and anti-permeability target. Concrete is mostly likely to have cracks 1 week after being placed, so the internal temperature of concrete must be strictly controlled.

1. Introduction

The cracking and seepage problems of subway station and tunnel retaining structures have become great challenges in subway construction. With the increase in the buried depth of subway tunnels, the difficulty in groundwater seepage prevention for subway construction is also increased. Therefore, it is of great practical significance to study how to prevent cracking and seepage of subway retaining structures.

The main building material for subway interior is concrete structures. In the process of pouring, it is avoidable that concrete will have natural pores, bubbles and cracks. After the concrete is put into service, these original minor defects will gradually become large cracks, and with the opening of these cracks, the bearing capacity of the concrete will be reduced, and groundwater will seep into subway tunnels and stations. The anti-seepage performance of concrete is also known as impermeability. In recent years, it has been found that the addition of fibers into concrete can significantly improve its anti-cracking and anti-permeability performance.

At present, in subway engineering, there are two common types of fiber-reinforced concrete materials - steel fiber and non-steel fiber. The former is widely applied in construction, but it is also costly; the latter is being rapidly developed in recent years. Currently, there are two kinds - high-elastic and low elastic fiber. Synthetic fiber, as a representative of low-elastic fiber, has the advantages of corrosion resistance, high strength and low cost, and thus it has been extensively applied (Altoubat and Lange, 2001; Banthia and Nandakumar, 2003; Bentur and Kovler, 2003; Song et al., 2005; Wang et al., 2001; Usman et al., 2016). Regarding the addition of synthetic fiber into concrete, through continuous lab analysis and engineering applications, there have been several development stages – fine synthetic fiber (Choi and Yuan, 2005; Gopalaratnam et al., 1991), steel synthetic fiber (Najm and Balaguru, 2002), polypropylene fiber-reinforced concrete (Oh et al., 2007; Bui, Voigt and Shah, 2004; Feng et al, 2016), polypropylene crude fiber-reinforced concrete (Malmgren, 2007; Ladanchuk and Nehdi, 2004) and polypropylene blended fiber-reinforced concrete (Ding et al., 2009; Qian and Stroeven, 2000), producing a number of research results.

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In this paper, regarding the problems of subway and tunnel retaining structures such as cracking and seepage, we study the stress, strain and temperature changes of the new PFRC through laboratory test and engineering measurement.

2. Performance analysis on multi-scale PFRC

2.1 Testing materials and process

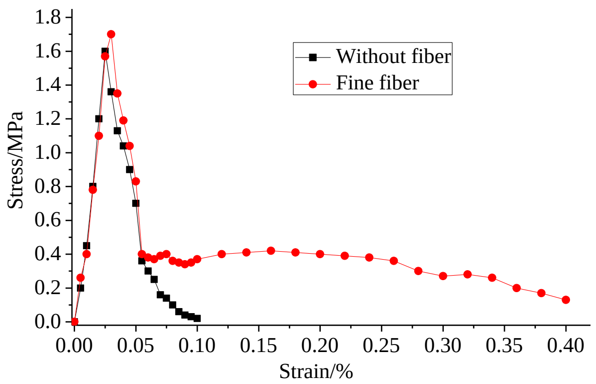
The concrete strength is 42.5R; the fineness modulus of fine aggregate is 0.73; the coarse aggregate mainly consists of macadam, with a particle size of 7-18mm; the polypropylene fiber has a density of 0.9g/cm, an average elasticity modulus of 6.2GPa, a tensile strength of 569MPa, a fiber length of 32mm and a diameter of 0.03-0.7mm; the design strength of concrete is C30; the ratio of cement: sand: stone: water = 405: 549: 1220: 210. The fiber is added according to the testing and engineering experience.

Concrete mixing process: put the sand, stones and polypropylene fiber into an agitator and stir the mixture well for 5min; add cement and stir it for 3min; pour water into the mixture and stir it for 2min. When polypropylene fiber is evenly distributed in the formed concrete, the mixing is completed.

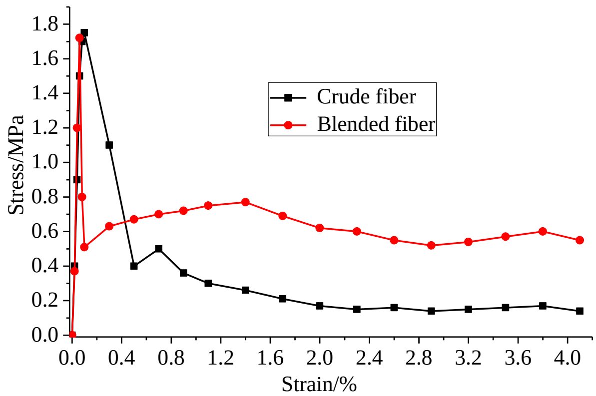
Prepare concrete specimens into cuboids with a size of 150mm×100mm×250mm. Fabricate 5 test pieces from each kind of concrete cuboid. Let them sit for 48h and maintain them in the curing room for 10d. Dry and polish the surfaces of the test pieces.

2.2 Analysis on the tensile strain of PFRC

The tensile stress-strain curves of ordinary concrete and PFRC are shown in Figure 1. Figure 1(a) shows the stress-strain comparison of fiber-free concrete and polypropylene fine fiber concrete. It can be seen from the figure that when fiber is not added in the concrete, the stress decreases very fast and the descending section of the curve is short. When the strain is 0.1, the stress is close to 0MPa, and the concrete exhibits obvious brittleness. When polypropylene fiber is added into concrete, the decrease in the stress-strain curve slows down obviously at 0.07, and a slow downward trend is shown, indicating that the addition of polypropylene fiber can obviously improve the brittleness of concrete.



(a) Ordinary concrete and polypropylene fine concrete



(b) Polypropylene crude and blended fiber concrete

Figure 1: Stress-strain curve of multi-scale polypropylene fiber concrete

Figure 1 (b) shows the stress and strain curves of the crude fiber and blended fiber added to the concrete. When the test piece is cracked, the bearing capacity instantly decreases sharply from the highest value, but with the continued effect of the external load, the carrying capacity of the test piece rises after hitting the local minimum value, and when the external load is further applied to the test piece, breaking the fiber, the test piece gradually loses its bearing capacity, and the descending section of the curve of the test piece is long and gentle. It can also be seen from Figure 1(b) that the blended fiber concrete can better exert the tensile strength and fracture resistance of polypropylene fiber in different stress stages than the crude fiber concrete, and significantly improve the anti-cracking and anti-permeability capabilities and toughness of the concrete.

There are natural defects like pores and bubbles inside the concrete. When an external load is applied, stress will be concentrated in the weak area of concrete. When the external load is greater than the tensile strength of the material, cracks will appear in the concrete and gradually expand. With the stress concentrated at the concrete defect increasing, microcracks develop slowly into macrocracks and rapidly expand, finally leading to concrete instability and damages. When polypropylene fiber is added into the concrete, fiber constrains the further expansion of microcracks and applies a stress field to the microcrack tips to offset the cracks, which in this way improves the tensile strength of the concrete.

3. Analysis on the anti-cracking and anti-permeability performance of subway station retaining structures

3.1 Addition of polypropylene fiber into concrete and field test

Based on the laboratory analysis on PFRC in the above section, in this section, we further study the application of PFRC in actual engineering and analyze its anti-cracking and anti-permeability performance in subway tunnel and station retaining structures. In the field test, we select an actual subway section under construction. The main framework of the station consists of single-span, double-wall and double-box structures. The test section is divided into two parts – one part of the wall retaining structure is made of ordinary concrete and the other part is the concrete structure added with polypropylene fiber. The two parts are divided into five monitoring sections, where Section 1, 2 and 3 are in the PFRC structure while Section 4 and 5 in the ordinary concrete structure. The detailed monitoring chart is shown in Figure 2.

According to test analysis and engineering experience, the amount of polypropylene added into the concrete can be calculated according to formula 1:

$$\Delta t_{\max} \leq \Delta t_D \quad (1)$$

Δt_{max} is the thermal limit for concrete; Δt_D is the damage limit temperature drop of concrete under the waterproof condition, expressed in the following formula:

$$\Delta t_D = t_0 + \gamma\left[\lambda\left(0.8-K\right)+\beta\left(1-H_w\right)+\theta\right] \quad (2)$$

The strain gauges and thermometers are embedded in the concrete subway retaining structures. The temperature correction coefficient for the fiber-reinforced concrete is as follows:

$$\varepsilon_m = k\Delta F + \left(b-\alpha\right)\Delta t = k\left(F-F_0\right)+\left(b-\alpha\right)\left(t-t_0\right) \quad (3)$$

ε_m is the strain of the concrete structure; α is the linear expansion coefficient; F_0 is the measured strain value; t_0 is the temperature reference value.

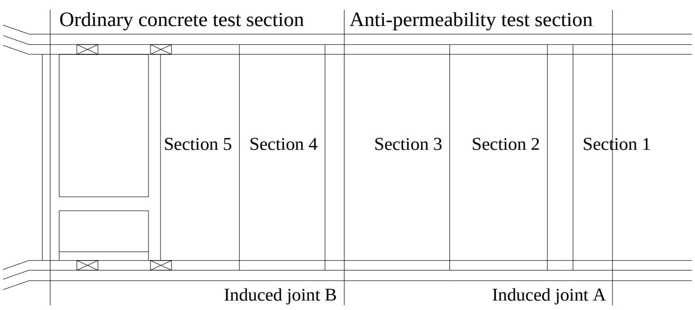
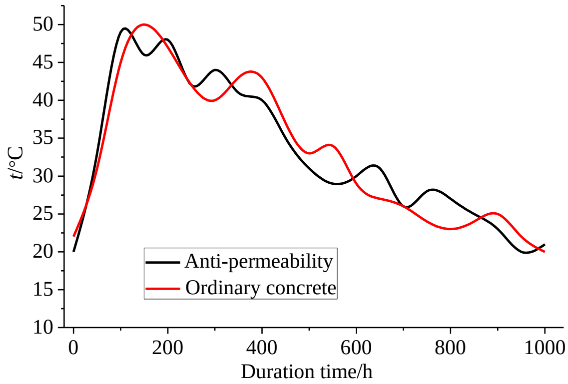


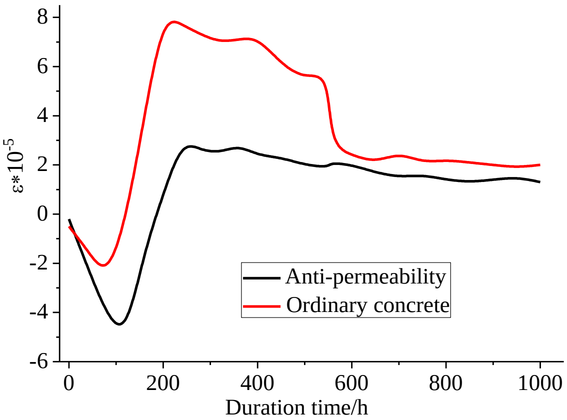
Figure 2: Layout chart for anti-permeability testing of concrete

3.2 Test results and analysis

We observe the concrete structures in the two parts for a long time. The temperature and strain results of the concrete in the two parts are shown in Figure 3. It can be seen from the temperature curves of ordinary concrete and PFRC in Figure 3(a) that the PFRC structure reaches the maximum temperature of 49℃ after 100-120h, which is much higher than the ambient temperature, because the concrete releases heat after hydration, significantly increasing the internal temperature of the structure. When the temperature reaches the maximum value, the temperature curve shows a decreasing trend with fluctuations. After 800-1000h, the temperature inside the concrete decreases to the ambient temperature - 20-25℃. The temperature changes of ordinary concrete are similar to that of PFRC. The general temperature curve trend is also a rapid rise within a short period of time and then a decline in oscillation and the final temperature also drops to the ambient temperature.



(a) Test section temperature



(b) Test section strain

Figure 3: Curve of concrete temperature and strain versus time

From the strain curves of PFRC and ordinary concrete in Figure 3(b), it can be seen that the maximum strain of PFRC is compressive strain, which is 4.8×10^{-5}. When the temperature inside the concrete gradually increases, the concrete at the test point suffers from thermal expansion and is pressed due to the stress concentration around it. When the temperature inside the concrete gradually decreases, the concrete at the test point shrinks, and the tensile stress occurs at the test point. From the figure, we can see that the maximum tensile strain is 2.7×10^{-5}. When the temperature further decreases, the tensile strain inside the fiber-reinforced concrete also decreases, and finally to 1.95×10^{-5} after 1000h. And the closer it is to the concrete surface, the greater drop there is in the tensile strain. For ordinary concrete, the maximum compressive strain is 2.03×10^{-5}, while the tensile strain is up to 7.9×10^{-5}, much higher than that of the PFRC. The concrete is more susceptible to tensile damage, so when the tensile strain exceeds the ultimate tensile strain of concrete, cracks will occur. Therefore, the addition of polypropylene fiber into the concrete can effectively prevent concrete cracking and avoid water seepage caused by concrete cracking.

Figure 4 shows the wall surface cracks of PFRC and ordinary concrete. As can be seen from the figure, there are two wall cracks in the PFRC wall, while there are 6 in the ordinary concrete wall. According to onsite construction experience, cracks mainly occur within 1 week after the concrete pouring. Table 1 shows the average width of the cracks in PFRC and ordinary concrete. As can be seen from the table, the maximum width of the cracks in PFRC is 0.16mm, and the average width of the two cracks is only 0.12mm, while in the ordinary concrete, the maximum width of cracks is 0.57mm, and the average width of the six cracks is 0.33mm. According to relevant subway design specifications, the maximum allowable width of concrete cracks is 0.2mm. The surface crack width of the ordinary concrete is much greater than this specification, while that of PFRC is within the allowable range.

Table 1: Average crack width of anti-permeability and ordinary concrete (mm)

	1	2	3	4	5	6
Ordinary concrete	0.47	0.19	0.36	0.57	0.15	0.24
Anti-permeability concrete	0.16	0.08				

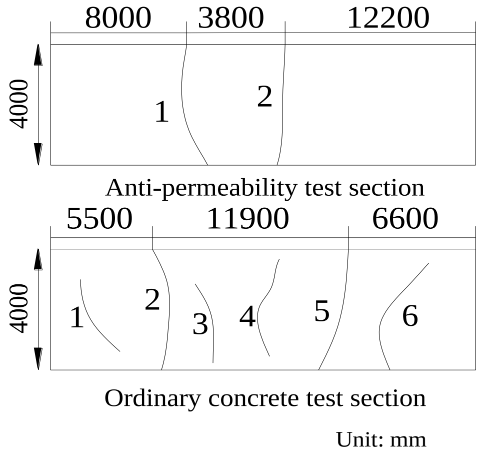


Figure 4: Crack distribution of different test concrete

4. Conclusions

In this paper, regarding the problems of subway and tunnel retaining structures such as cracking and seepage, we study the stress, strain and temperature changes of the new polypropylene fiber-reinforced concrete (PFRC) through laboratory test and engineering measurement. And the research conclusions are as follows:

(1) Mixing polypropylene crude and fine fiber into concrete can greatly improve the tensile strain and deformation performance of basic concrete. The amount of polypropylene fiber added has something to do with the aggregate composition of the concrete, and polypropylene fiber has little effect on the tensile modulus of the concrete. Compared with the purely crude fiber and fine fiber concrete, the blended fiber-reinforced concrete has the greatest increase in the tensile strength over the basic concrete.

(2) The results show that, after crude and fine fiber is added into the ordinary concrete, cracks on the concrete surface are greatly reduced and the width of the cracks is also within the standard, which is in accordance with the intended anti-cracking and anti-permeability target. Concrete is mostly likely to have cracks 1 week after being placed, so the internal temperature of concrete must be strictly controlled, and at the same time, waterproof work must be strengthened at the concrete joints.

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