



High temperature mechanical performance and micro interfacial adhesive failure of textile reinforced concrete thin-plate*

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Abstract: The mechanical performance of textile reinforced concrete (TRC) thin-plate under high temperature conditions was investigated using three-point bending tests. The influence of polypropylene (PP) fiber addition on the out-of-plane load capacity of TRC thin-plate after high temperature treatment was also studied. The results showed that the thermostability of TRC thin-plate with textile impregnated with epoxy resin was not good, but that the out-of-plane load capacity of TRC thin-plate after high temperature treatment could be improved by increasing the plate thickness or the textile distribution rate. Under normal temperature and a high temperature of 120 °C, the out-of-plane load capacity of specimens could be increased and cracks better distributed by mixing the TRC with PP fiber. However, the out-of-plane load capacity of TRC thin-plate under a continuous high temperature of 200 °C was not much affected by the addition of PP fiber. The result of a microcosmic scanning electron microscope (SEM) test showed that the main reason for the interfacial adhesive failure between the textile and the original concrete substrate was the degradation of the epoxy resin under high temperature.

Key words: Textile reinforced concrete (TRC) thin-plate, Epoxy resin, Thermostable performance, Three-point bending test

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1 Introduction

Textile may sometimes be used in place of the rebar in a reinforced concrete (RC) member. Because the covered layer of textile meets the requirements of bonding and anchoring, it is applied widely in thin-wall construction. Compared with common fiber concrete which has a disordered distribution of chopped fiber, continuous fiber roving can be arranged in the major principal stress direction in a textile reinforced concrete (TRC) member, which greatly increases the reinforcing efficiency (Li and Xu, 2006). Furthermore, a TRC structure has advantages like high out-of-plane load capacity, high tenacity, and magnetization prevention. Thus, it is currently considered as one of the most promising construction materials. TRC panels

have been applied in retrofit engineering and new construction practical engineering in Germany and the Netherlands. In 2004, 25 mm-thick TRC thin-plates were applied to a curtain wall structure of a concrete laboratory at Aachen University (Hegger *et al.*, 2008). In 2006, a TRC passenger foot-bridge designed by Dresden University of Technology was constructed in Ossac, Germany (Schneider and Bergmann, 2008). As an important component of buildings, the fire resistance performance and high temperature mechanical properties of TRC panels have to be guaranteed, or else the requirements for combustion performance and fire endurance (GB50016-2006) will not be satisfied. However, under high temperature conditions, when the covering layer of the TRC member is thin, its protective effect on the fiber material is weak (Reinhardt *et al.*, 2008). Therefore, a study on the effect of temperature on the performance of TRC is necessary.

So far, most research on the fire resistance of fiber concrete structures has been aimed at the strengthening component of the fiber reinforced

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polymer (FRP) (Bisby *et al.*, 2004). Wu and Wan (2009) studied the fire resistance of a RC beam flexural strengthened by a carbon fiber sheet, and compared the bearing capacities of concrete beams with either geopolymer or carbon fiber sheet adhered by epoxy adhesive (Wu *et al.*, 2012). Liu *et al.* (2011) investigated the failure mode and fire endurance of a carbon fiber sheet RC beam using an open-fire test. However, studies on the fire resistance properties of TRC members are rare. Reinhardt *et al.* (2008) studied the fire resistance properties, including fire endurance, of I-shaped beams reinforced by glass fiber and carbon fiber mesh grid. More experimental results are needed to evaluate thoroughly the thermostability of TRC members.

The crack behavior and out-of-plane load capacity of TRC members depend mainly on the adhesion between the fiber and the concrete (Xu *et al.*, 2004). Studies aimed at improving the adhesion between the fiber and the concrete (Xun *et al.*, 2005; Diltney *et al.*, 2006; Li *et al.*, 2008; Yin and Xu, 2010) indicate that adhesion could be effectively improved by impregnating the woven fiber net with epoxy resin. To investigate the thermostability of a TRC member impregnated with epoxy resin, we tested such a member at high temperature using a three-point bending test. Then we examined the influences of temperature and high temperature duration on crack behavior and out-of-plane load capacity. Using microscopic scanning electron microscope (SEM) observation, we analyzed the mechanism of interfacial adhesion damage between the woven fiber net and the concrete substrate.

2 Materials and methods

2.1 Woven fiber net

The fiber adopted in this experiment was a 2D woven net made by mixing carbon fiber bundles and E-glass. The two fiber bundles were made of multifilaments which were not twisted, and the meshing size was 10 mm×10 mm (Fig. 1). The mechanical properties of the monofilament fibers are listed in Table 1. The ultimate tensile strength of the glass fiber was lower than that of the carbon fiber, but the cost was higher. Thus, the carbon/glass mixed fiber not only had a reinforcing effect, but also had a better economic efficiency.

The mechanical parameters of the zonal carbon fiber bundle (Table 1) were measured according to GB/T3362-2005. A woven fiber net impregnated with epoxy resin was adopted in this experiment. A certain amount of diluent was added to the epoxy resin to improve the impregnation effect of the woven fiber net. A tensile strength test of the fiber bundle (Table 2) indicated that the strength of the carbon fiber bundle was greatly improved by epoxy resin impregnation.

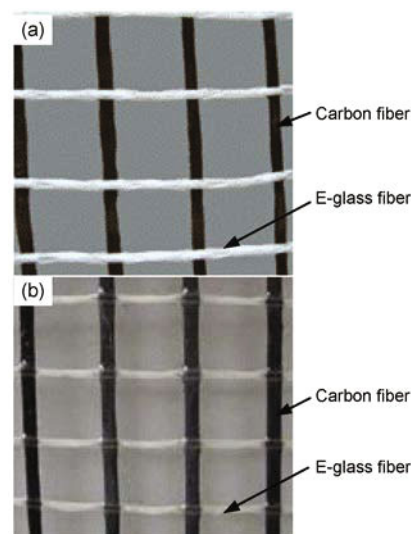


Fig. 1 Carbon/glass woven fiber net
(a) Non-impregnated with the epoxy resin; (b) Impregnated with the epoxy resin

Table 1 Mechanical properties and geometric parameters of monofilament fiber

| Fiber type | Carbon fiber | E-glass |
|---------------------------------|--------------|---------|
| Fiber model | 12K | 12K |
| Tensile strength (MPa) | 4900 | 3100 |
| Young's modulus (GPa) | 230 | 72 |
| Elongation at break (%) | 1.35 | 4.5 |
| Mass per unit length Tex (g/km) | 800 | 800 |
| Density (g/cm ³) | 1.82 | 2.55 |

Table 2 Mechanical properties and geometric parameters of fiber bundles

| Fiber type | Carbon fiber | Carbon fiber (EP) |
|-------------------------------------|--------------|-------------------|
| Fiber model | 12K | 12K |
| Tensile strength (MPa) | 2055 | 3621 |
| Strength utilization rate (%) | 42 | 74 |
| Theoretical area (mm ²) | 0.44 | 0.44 |
| Mass per unit length Tex (g/km) | 800 | 800 |
| Density (g/cm ³) | 1.82 | 1.82 |

Note: EP was the expression for the fiber bundle impregnated with epoxy resin

2.2 Concrete substrate

The raw material of the fine concrete substrate included Portland cement (PII 52.5R), coal ash, silica fume, water reducing agent (3rd generation of Sika), and sand in the proportions listed in Table 3. Experimental tests showed that the prepared fine concrete satisfied the working performance requirements of self-compacting concrete (Li and Xu, 2006). The influence of temperature on its mechanical properties is shown in Fig. 2.

Table 3 Mix proportions of fine concrete substrate

| Material | Content |
|-----------------------------|---------|
| Portland cement (PII 52.5R) | 472 |
| Coal ash | 168 |
| Silica fume | 35 |
| Water | 262 |
| Water reducing agent | 4.0 |
| Water binder ratio | 0.4 |
| Fine sand (0–0.6 mm) | 460 |
| Coarse sand (0.6–1.2 mm) | 920 |

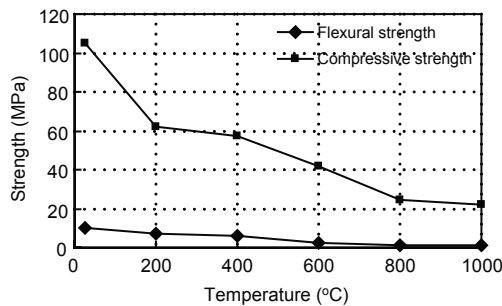


Fig. 2 Influence of temperature on the mechanical properties of fine concrete substrate

2.3 Polypropylene (PP) fiber

To control effectively the microcracking of the concrete during temperature changes, and to prevent the formation and development of cracks, some of the specimens were mixed with high-strength PP monofilament short fiber at a volume ratio of 0.09% (Yin and Xu, 2010). The mechanical and geometrical parameters of the PP monofilament short fiber are listed in Table 4.

2.4 Specimens and test method

Specimens for the three-point test included two specifications: 450 mm×100 mm×15 mm for the monolayer woven fiber net, and 450 mm×100 mm×25 mm for the bilayer woven fiber net. The top and bottom cover layer thickness was 5 mm. The curing time was 28 d after casting of the specimens.

Table 4 Mechanical properties and geometric parameters of polypropylene fiber

| Item | Description |
|------------------------------|--------------|
| Material type | Fiber bundle |
| Melting point (°C) | 160 |
| Tensile strength (MPa) | >280 |
| Tensile ratio (%) | 15 |
| Specific weight | 0.91 |
| Ignition point (°C) | 580 |
| Young’s modulus (MPa) | >3900 |
| Electric conductivity | Low |
| Content (kg/m ³) | 0.7–0.9 |

The high-temperature test was conducted by putting the specimens in a muffle. The temperature started from 15 °C, and reached 120 °C or 200 °C with a heating rate of 7 °C/min. The length of time that the specimens were in the muffle was 30 min or 90 min. A load test was then conducted after all the specimens were cooled naturally.

The specimens were placed on two pin supports with 300 mm clear span. Experimental tests were conducted with a 250 kN Instron universal testing machine. The loading method is shown in Fig. 3a. The load *P* was measured by a load transducer. The mid-span deflection of the thin plate was measured by two displacement sensors (LVDTs). The loading device is shown in Fig. 3b. Displacement control was adopted in the loading test with a velocity of 0.5 mm/min.

An FEI Quanta FEG650 electron microscope and energy disperse spectroscopy were used to observe the damaged sections of the samples after high temperature treatment. The adhesion between the woven fiber net impregnated with epoxy resin and the substrate concrete was investigated microscopically after the high temperature treatment.

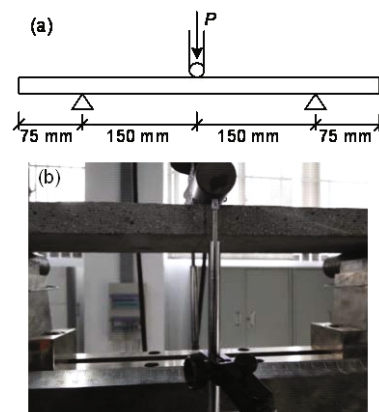


Fig. 3 Three-point bending test (a) Loading schematic diagram; (b) Loading system

3 Results and analysis

3.1 First cracking, ultimate state, and damage process

The load-midspan displacement curves for the TRC thin plate after treatment at different temperatures and duration times are given in Fig. 4. The first cracking load, ultimate state load, and mid-span deflection under the three-point bending test are shown in Table 5. The temperature and duration time of the process were set on the muffle furnace, and all the

woven fiber nets of the specimens were impregnated with the epoxy resin. The specimen type P denotes a specimen mixed with PP fiber; 1 denotes a monolayer woven fiber net member; and 2 denotes a bilayer woven fiber net member. The first cracking loads of specimens B, D, and E were not related closely to the temperature, in contrast to the results shown in Fig. 2. This suggests that the factors influencing the first cracking load of TRC specimens after high temperature are complicated, and not simply related to the strength of the concrete substrate.

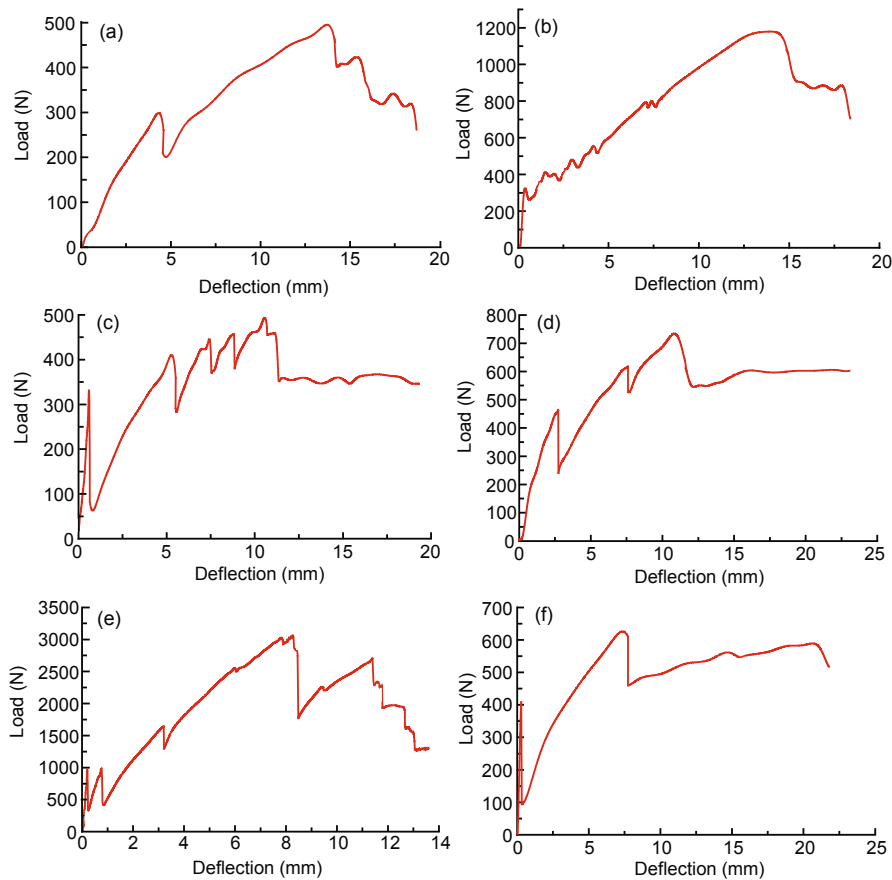


Fig. 4 Load-displacement relation of three-point bending test

(a) Specimen A (room temperature); (b) Specimen B (room temperature); (c) Specimen C (120 °C, 30 min); (d) Specimen D (120 °C, 30 min); (e) Specimen E (120 °C, 30 min); (f) Specimen F (200 °C, 30 min)

Table 5 Results of three-point bending test

| Condition | Type | Specimen | Crack deflection (mm) | Cracking load (N) | Ultimate deflection (mm) | Ultimate load (N) |
|------------------|------|----------|-----------------------|-------------------|--------------------------|-------------------|
| Room temperature | C-1 | A | 1 | 40 | 15 | 500 |
| | CP-1 | B | 0.5 | 320 | 15 | 1190 |
| 120 °C, 30 min | C-1 | C | 3 | 280 | 10.5 | 350 |
| | CP-1 | D | 2.5 | 450 | 11 | 710 |
| 120 °C, 30 min | CP-2 | E | 0.5 | 1000 | 8.5 | 3100 |
| | CP-1 | F | 1 | 400 | 10.5 | 500 |
| 200 °C, 90 min | C-1 | G | 0.1 | 500 | 0.1 | 500 |
| | CP-1 | H | 0.1 | 300 | 5 | 410 |

Comparison of the bearing capacities between specimens A and B, and C and D showed that under normal temperature and 120 °C, the addition of PP could greatly increase the ultimate out-of-plane load capacity of the thin plate. This was likely to have been the result of the bridging and load transfer effects of the short fibers on the crack development sites. As the first crack of the plate occurred, the bridging effect of the PP fiber may have delayed crack development, reduced the crack width, and optimized the stress transfer between the woven fiber net and the concrete substrate. The failure modes of specimens A and B are shown in Fig. 5. The concrete on the upper edge of the thin plate was crushed. However, the PP fiber mix may have helped the member present a multi-crack failure mode. The fracture interval was between 2 and 4 cm, and the distribution was uniform.

The relation between the shear tensile strength of the epoxy resin and the temperature under 140 °C was studied. The shear tensile strength of the epoxy resin at 140 °C was only 15.4% of that at normal temperature. However, in this experiment, compared with specimens A and B, which were not treated with high temperature, the ultimate bearing capacities of specimens C and D, which were treated with the high temperature of 120 °C for 30 min, were reduced by 30% and 40%, respectively. This may have been because the epoxy resin inside and outside of the woven fiber net was protected by the concrete substrate and thus did not reach 120 °C. After treatment with high temperature, the ultimate out-of-plane load capacity of specimen E with bilayer woven fiber net could still reach 3100 N, which was 3.4 times that of the specimen D. This was probably because first, the heat was blocked by the increased plate thickness; second, the ultimate tensile strength of carbon fiber decreases a little with increasing temperature under 900 °C (Kleineberg *et al.*, 2004). However, under the high temperature in this study, the ultimate tensile strength of the carbon fiber woven net did not decrease much, thus the ultimate out-of-plane load capacity of the member could be effectively increased by increasing the network distribution rate. In other words, it may be useful to increase the network distribution rate within a certain range to improve the performance of TRC to that of reinforced concrete structures in bending failure mode at room temperature. However, it is probably useless to increase the rate in concrete

crushing failure mode. The formed macro-crack number was 3, as specimen E was damaged. The width of the third crack reached 1 mm and a transverse crack was found on the sublayer of the woven fiber net on the side of the specimen. This indicated that the woven fiber net and the concrete substrate had separated. As more loading was added, two horizontal fractures were found, which led finally to shear failure of the specimen. The failure mode is shown in Fig. 6.

Compared with specimen B without high temperature treatment, the ultimate out-of-plane load capacity of specimen F treated at 200 °C for 30 min decreased by 58%. The reason for the specimen damage

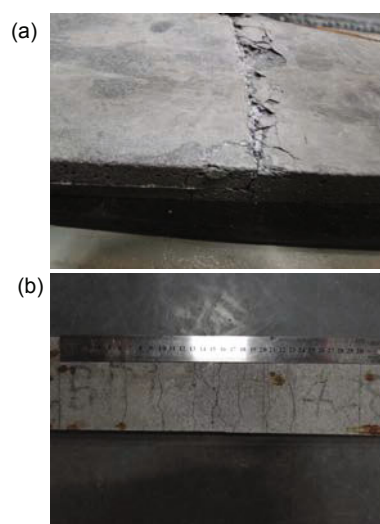


Fig. 5 Failure mode of TRC specimens
(a) Specimen A; (b) Specimen B

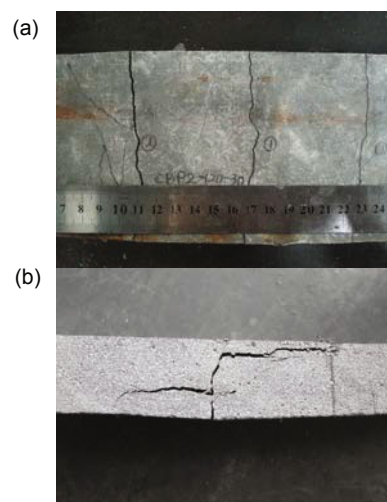


Fig. 6 Failure mode of specimen E
(a) Crack width; (b) Transverse cracks

was the early separation of the woven fiber net and the concrete substrate. After treatment at 200 °C for 90 min, the integrity of the thin plate was maintained, but its ultimate out-of-plane load capacity was only 400–500 N. The out-of-plane load capacity of specimen G was lost quickly during the initial stage of the loading, which showed its obvious brittle failure characteristic. Regardless of whether the TRC was mixed with PP fiber, the crack number was 1, as the specimen was damaged. The reasons were: first, the PP fiber had already melted under 200 °C. Thus, the influence of the mixed PP on the out-of-plane load capacity of the plate was not big; second, the color of the epoxy resin on the surface of the woven fiber net had already turned from transparent to deep yellow (Fig. 7). This indicated that the performance of the epoxy resin had already degenerated and the fragility had increased greatly. This damaged the adhesion between the woven fiber net and the concrete substrate, and they quickly became separated.

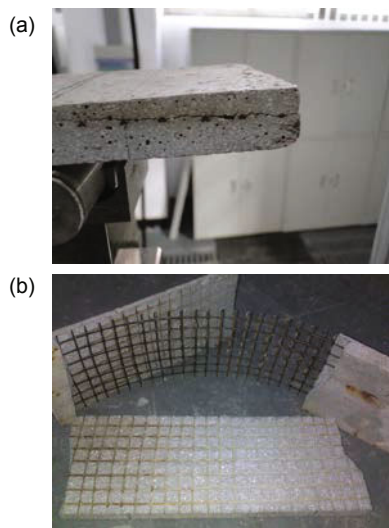


Fig. 7 Degradation of epoxy resin
(a) Epoxy resin interface crack; (b) Adhesion failure

3.2 Micro-structure analysis

To visualize the morphology of the woven fiber net, the epoxy resin, and the concrete substrate at high temperature, an FEI Quanta FEG650 electron microscope and energy disperse spectroscopy were adopted to observe the damaged section of the plate member. The existing form of the PP fiber treated with high temperature is shown in Fig. 8. PP fiber was still found in the thin plate after treatment at 200 °C

for 30 min. The melting point of the PP fiber was 160 °C (Table 4), indicating that the inner temperature of the concrete did not reach 160 °C. However, as the duration of the high temperature reached 90 min, the PP fiber melted, and only a few holes remained (Fig. 8). Thus, if the heating time of a plate member was long, the mixed PP fiber had little influence on the out-of-plane load capacity of the member. However, the porosity of the specimen could be increased with mixed PP fiber, favoring the elimination of vapor and heat from the concrete substrate, thereby reducing pore pressure.

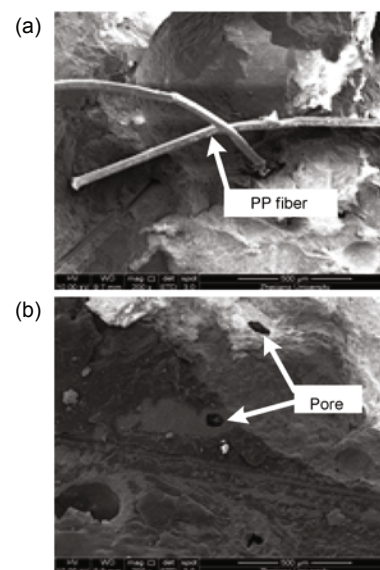


Fig. 8 Polypropylene (PP) fiber after exposure to high temperature for different durations
(a) 200 °C, 30 min; (b) 200 °C, 90 min

The morphology of the surface epoxy resin in the woven fiber net after high temperature treatment is shown in Fig. 9. As the temperature and the high temperature duration increased, the morphology of the epoxy resin changed greatly. At 200 °C for 90 min, the surface became uneven, and performance of the specimen was obviously degraded (Fig. 9c). The interfacial condition of the fiber surface and the substrate after treatment at 200 °C for 90 min is shown in Fig. 10. The fragility of the epoxy resin on the fiber net surface increased greatly, and obvious cracking was observed on the epoxy layer of the fiber surface. Unevenness was already apparent at the interface between the fiber and the concrete substrate, which would lead to the easy separation of the plate and a great drop in its out-of-plane load capacity.

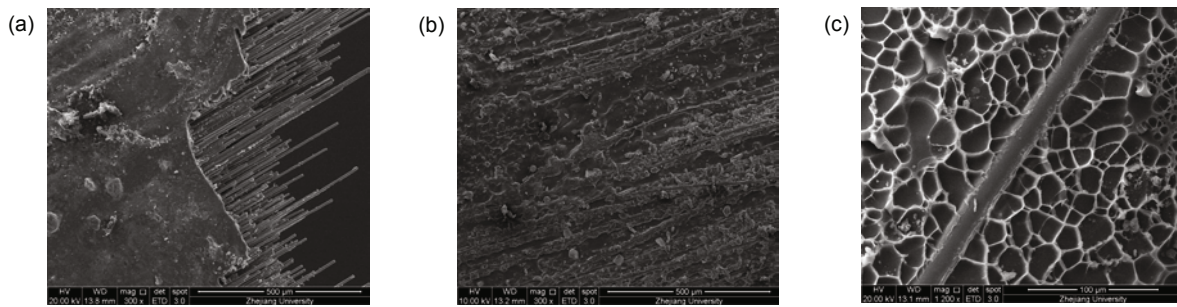


Fig. 9 Epoxy resin on the surface of fiber
 (a) Normal temperature; (b) 120 °C, 30 min; (c) 200 °C, 90 min

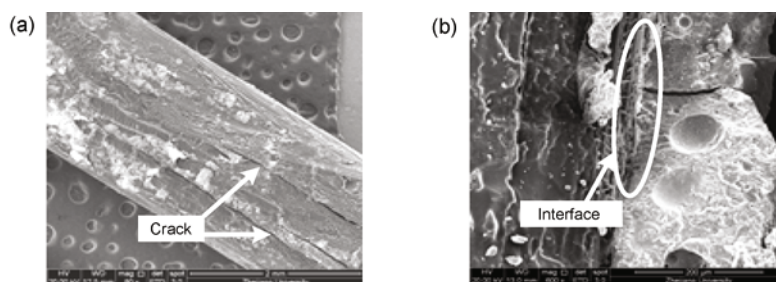


Fig. 10 Interface condition after treatment at a high temperature of 200 °C for 90 min
 (a) Cracks in epoxy resin; (b) Separation at the interface

4 Conclusions

1. At 120 °C for 30 min, the TRC member maintained structural integrity and basic out-of-plane load capacity. However, as the temperature duration increased to 90 min, while the integrity of the member remained, the out-of-plane load capacity was almost lost. The main reason for the separation of the woven fiber net from the substrate material was the degradation of the epoxy resin on the surface of the fiber.

2. The thermostability of the TRC member was improved to a certain degree by increasing the network distribution rate or the thickness of the concrete cover.

3. At normal temperature or at 120 °C, the out-of-plane load capacity of the TRC member could be increased greatly by mixing with PP fiber, but at 200 °C for a long time, the mixed PP fiber had no effect on the out-of-plane load capacity of the specimens. However, the fusion of the PP fiber may increase the porosity of the member, favoring the elimination of heat and vapor from the concrete. Thus, mixing an appropriate amount of PP fiber could help improve the thermostability of TRC members.

4. After treatment at a high temperature of 200 °C for 90 min, the degradation of the epoxy resin was serious, and led to unevenness in the surface layer,

interfacial adhesion damage between the fiber net and the cement substrate and finally, a great reduction in the out-of-plane load capacity of the member. Although the strength utilization rate of carbon fiber bundles is greatly improved with epoxy resin impregnation at room temperature, the interfacial adhesive performance of epoxy and concrete is not good at high temperature, and leads to premature damage of thin-plate and bonding failure. Therefore, the out-of-plane load capacity of TRC thin-plate without epoxy will be worse.

5. Taking into account all the uncertainties involved and the inadequate number of specimens, statistical analyses and modelling of the optimal amount of fibers will be carried out after conducting a large number of experiments with different amounts of fiber.

6. As a new type of cement based composite material, the TRC member has wide application prospects. However, the out-of-plane load capacity of TRC members with woven fiber net impregnated with the epoxy resin was not good under the high temperature condition. In future research, the function of the epoxy resin could be further optimized, or an inorganic glue with a stronger impregnation and adhesion ability, and better thermostability may be found to replace the epoxy resin.

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中文概要：

本文题目：织物增强混凝土薄板的高温力学性能与微观界面黏结破坏性分析

High temperature mechanical performance and micro interfacial adhesive failure of textile reinforced concrete thin-plate

研究目的：探讨不同温度和持续时间对织物增强混凝土（TRC）薄板裂缝行为和承载能力的影响。通过微观扫描电镜观测，分析纤维编织网与基体混凝土间的界面黏结破坏机理。

创新要点：明确了高温后纤维编织网与基体混凝土之间界面粘破坏的主要原因。以温度和持时为基本参数，对 TRC 构件的耐高温性能进行正确评价。

研究方法：通过三点弯曲试验（见图 3），对高温后试件的力学性能（见图 4、5）进行测试。通过微观扫描电镜观测（见图 8~10），了解高温下纤维编织网、环氧树脂及基体混凝土的形态。

重要结论：1. 环氧树脂在 200 °C 高温作用 90 min 时劣化严重，造成纤维网与基体之间的界面黏结破坏，这是导致试件破坏的主要原因；2. 在常温或 120 °C 作用下，掺加聚丙烯（PP）纤维可以较大幅度地提高 TRC 构件的承载能力；但在 200 °C、持续时间较长的高温作用下，PP 纤维的掺入对试件的承载力几乎没有影响。