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Thermal-Resistivity Characteristics of Carbon Fabric Reinforced Cementitious Matrix

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Abstract. *The thermal-resistivity effect of the carbon fiber reinforced cement (CFRC) has been successfully applied to monitor the temperature of concrete structures. There are insufficient studies on the thermal-resistivity effect of the carbon fabric reinforced cementitious matrix (CFRCM). In this paper, the resistance change of CFRCM from room temperature to 120℃ and the thermal-resistivity characteristics during repeated heating have been studied. It was showed that during the heating process, with the continuous increasement of the carrier concentration, the specimen exhibited obvious negative temperature coefficient (NTC) effect, and a temperature rise of 10℃ lessened relative resistance change by about 0.4%. However, some carriers stayed in the conduction band after the first cooling. Then, the resistance cannot return to the original value, and the curves of subsequent heating processes had a good repeatability.*

Keywords: *Thermal-resistivity effect; Carbon fabric reinforced cementitious matrix (CFRCM); Carbon fiber reinforced cement (CFRC); Thermal-resistivity characteristic; Repeated heating*

1 Introduction

The carbon fabric reinforced cementitious matrix (CFRCM) is a composite material composed by carbon fiber textile and cement matrix, which has low cost, good permeability, nonflammability, variable geometry of fibers and excellent compatibility with concrete (ACI 549.4R-13, Ai et al. 2015, Awani et al. 2017). The existing researches (Ai et al. 2015) have verified that humidity has little effect on its mechanical property, and it is can be used in low temperature and water immersed environments. CFRCM has been proved to be reinforce and repair structures (Arboleda 2014).

China has a vast territory, and the climate varies greatly between different longitude and latitude. In some parts of the Northeast, the temperature remains below 0 ℃ in winter, and even below -30 ℃ in extreme cases. In the south, the temperature may sometimes exceed 40 ℃ in summer, and the ground temperature can reach as high as 50 ℃ (Wang 2017). The hydration heat generated by the concrete itself can reach up to 70 ℃ (Chen 2022). However, the center temperature of the concrete structure is different from its surface temperature due to its poor thermal performance, which causes concrete cracks (Li et al. 2016). In addition, the temperature affects the mechanical property of the concrete and the safety of a structure (Wen and Chung 1999, Li et al. 2016). Therefore, monitoring the temperature of concrete structure can provide early warning information in time to ensure its safety.

The thermal-resistivity effects are divided into the positive temperature coefficient (PTC) effect and the negative temperature coefficient (NTC) effect, according to the relationship between the resistance and the temperature. The researches (Sauder et al. 2002, Zheng et al.

2012) show that the carbon fiber has an NTC effect. Based on this, the electrical resistance of the carbon fiber can be measured to realize the monitoring and evaluation of the temperature of carbon fiber and its composites.

Carbon fibers are usually made into composites to strengthen structures, such as the carbon fiber reinforced cement (Chung 2000, Wen and Chung 2001) (CFRC), the carbon fiber reinforced polymer (Okuhara and Matsubara 2005, Liu et al. 2016) (CFRP) and CFRCM (Awani et al. 2017, Arboleda 2014). In most studies (Wen and Chung 1999, Guan et al. 2005, Yao et al. 2006, Yao and Wang 2007, Xu et al. 2021), the resistance of CFRC decreased with the increasing temperature. On the contrary, some scholars (Guan et al. 2005, Chen et al. 2006, Liu et al. 2011) found that the resistance first decreased when the temperature is low and then increased. Therefore, the temperature range of the specimens which only had the NTC effect was usually small, generally below 50 °C, and their resistance may be increase if they continue to be heated. Yao et al. (2006) studied thermal-temperature characteristics of CFRC during repeated heating. CFRC had an NTC effect for the first time, and then PTC effect existed in the subsequent heating. When Schulte K and Baron C (1989) studied the resistance change of CFRP laminates under the fatigue load, the temperature also increased and was related to the load frequency. The resistance increased erratically during the loading, which may be caused by temperature. In relevant studies, both CFRP plates (Zheng et al. 2012) and CFRP bars (Ping 2018) show PTC effect, which is different from CFRC.

In general, the current research on the thermal-temperature characteristics on the carbon fiber mainly focuses on CFRC and CFRP, while research on CFRCM remains limited. CFRCM has a reinforcement similar to CFRP and a matrix similar to CFRC, which may lead to some similar thermal-temperature characteristics of CFRCM with both of CFRC and CFRP. In this paper, CFRCMs with different lengths were heated to study the thermal-temperature characteristics. Based on these test results, the mechanism of temperature affecting resistance was analyzed.

2 Experimental setup

2.1 Materials

The carbon fibers were provided by Wuxi Youtejia New Material Co., Ltd, whose properties are shown in Table 1.

Table 1. Mechnical and electrical properties of carbon fiber.

Number of filaments	Diameter of monofilament	Tensile modulus	Ultimate elongation	Tensile strength	Volume resistivity
12000	7 μm	230 GPa	1.5%	3530 MPa	1.7×10^{-2} Ω·mm

The impregnating adhesive was mainly composed of epoxy resin and other adhesives. The material and its main properties were provided by Shanghai Zhinuo Decoration Materials Co., Ltd., as shown in Table 2.

Table 2. Mechnical properties of impregnating adhesive.

Tensile strength	Tensile modulus	Ultimate elongation	Bending strength	Compressive strength	Curing time at 10-20 ℃
≥40 MPa	≥2500 GPa	≥1.5%	≥50 MPa	≥70 MPa	36 h

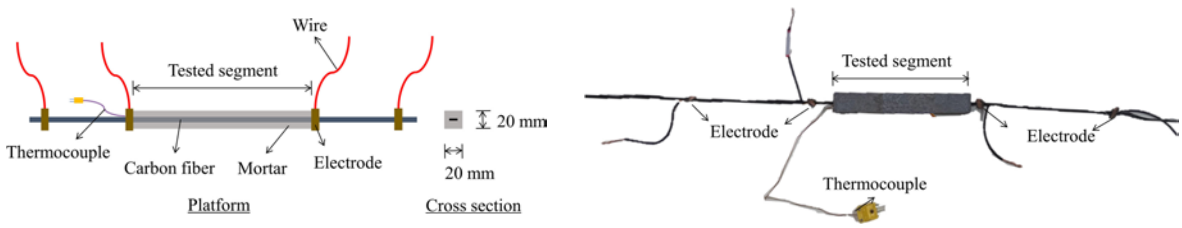
The mix proportion of the mortar is shown in Table 3. Three cube specimens of 70.7 mm × 70.7 mm × 70.7 mm were prepared for a 28-day compression test, according to the standard "Cement - Test methods - Determination of strength (IOS 679:2009)". The average 28-day compressive strength was 34.5 MPa and the coefficient of variation was 4.2%.

Table 3. Mix proportion of mortar.

Cement (P.O 42.5)	Water	Coarse sand (0.5-1 mm)	Fine sand (0-0.5mm)	Redispersible emulsion powder	Water-reducing admixture
100 g	45 g	133 g	67 g	1.5 g	0.15 g

2.2 Specimen preparation

Four electrodes were arranged on the specimen to measure its resistance, which were at both ends of the tested segment and both ends of the specimen. Then the impact of the electrodes' contact resistance was eliminated (Yao and Wang 2007). These electrodes were made of copper foil of 15mm×5 mm×0.08 mm, epoxy conductive adhesive and wires. The specimen was poured layer by layer. After the first layer of mortar was poured and vibrated, a carbon fiber and thermocouple were arranged. This thermocouple was applied to monitor the temperature inside CFRCM to ensure that the center temperature was basically consistent with the surface temperature. In this process, the specimen should be tensioned to avoid the loose filaments. The specimen is shown in Figure 1.



(a) Schematic diagram. (b) Finished product.

Figure 1. Specimen of CFRCM.

These specimens were divided into three groups, each with three specimens. The lengths of the tested segments were 100 mm, 150 mm and 200 mm, and the groups were numbered H-100, H-150 and H-200, respectively.

2.3 Heating and measurement

An electrothermal drier (101·2A), fabricated by Shaoxing Huyue Instrument Factory, China, was employed to heat the specimens, as shown in Figure 2. The temperature was raised and then lowered in steps between the room temperature and 120 ℃. The temperature was raised by 5 ℃ per 10 min and lowered by 10 ℃ per 30 min, as shown in Figure 3. During heating and cooling, the thermocouple was connected to the thermometer (TA612C), supplied by Suzhou Tasi Electronics Co., Ltd., to observe whether the center temperature of CFRCM reached the predetermined value. The center temperature was collected by the thermometer with a sampling rate of 1 Hz.

A constant current of 1 mA was input to the tested segment. Then a data acquisition instrument (DH5922N), fabricated by Donghua Measurement Technology Inc., China, was applied to measure the voltage of the tested segment. Then its resistance was calculated according to Ohm's law.

Figure 2. Heating system.

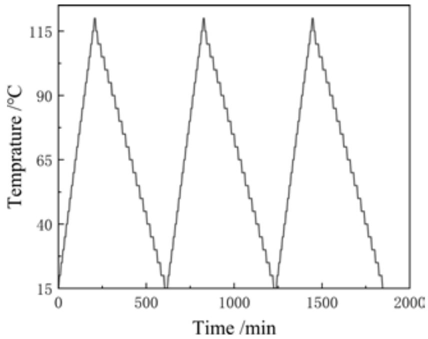


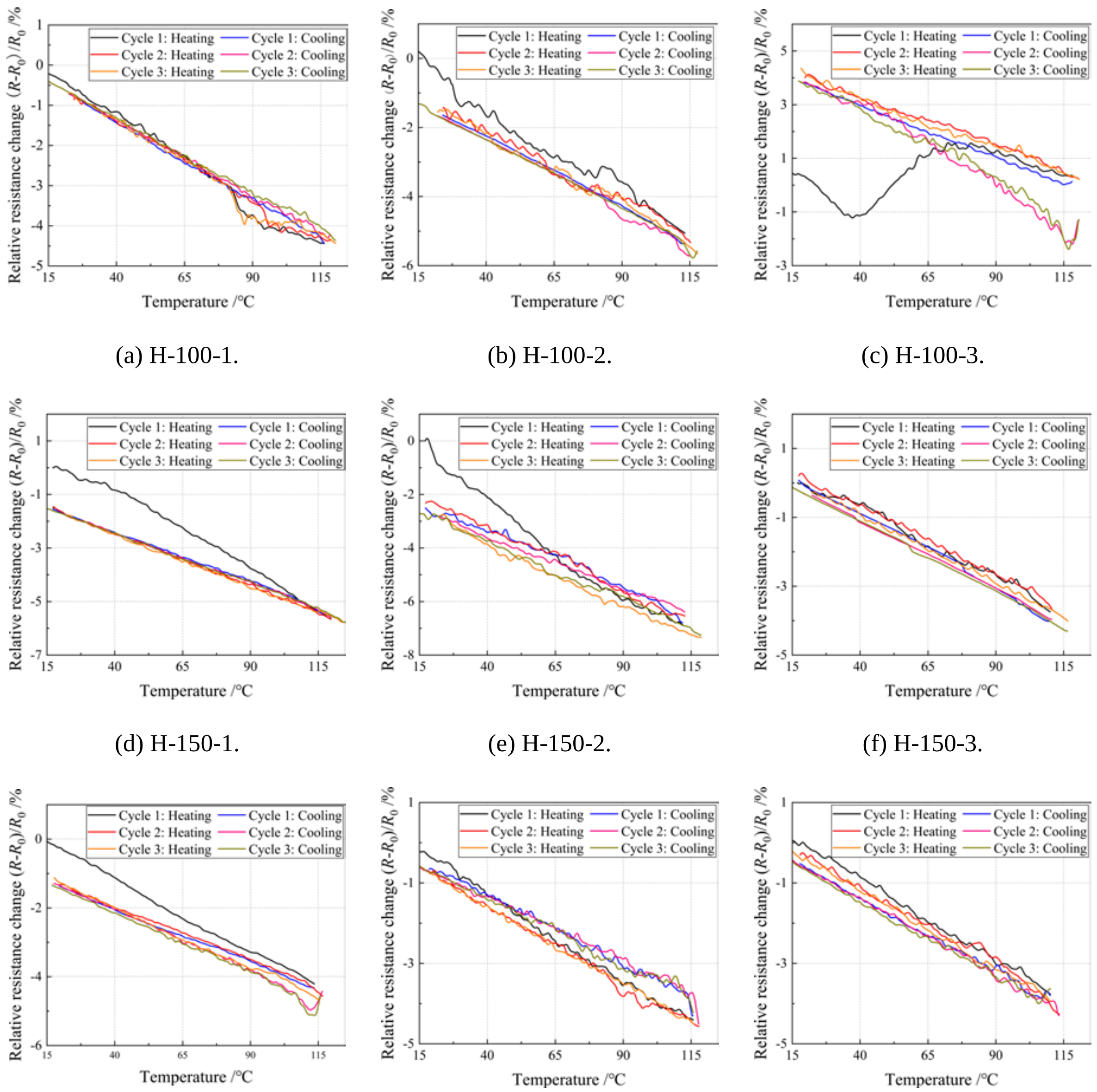
Figure 3. Heating procedure.

3 Results and discussion

3.1 Test results

The initial resistance of CFRCM has discrete distribution, which could affect the resistance significantly during heating. On the contrary, the relative resistance change is more concentrated, which is a more suitable index to evaluate its thermal-temperature characteristics (Chen 2021). The "temperature-relative resistance change" curves of CFRCM during heating are shown in Figure 4. The most specimens showed a significant NTC effect. Their resistance decreased with the increasing temperature during heating. After the center temperature reached the maximum, the specimens gradually cooled down and their resistance also recovered. The resistance varied almost linearly with the temperature, whether heating or cooling.

In different cycles, the curves of some specimens almost coincide, as shown in Figures 4a, f, h and i. Their resistance after repeated heating is close to their initial resistance. Some specimens cannot be restored to the original state, as shown in Figures 4b, d, e and g. However, except the curves during the first heating, other curves are basically consistent during the subsequent heating and cooling. There is also a special curve, as shown in Figure 4c. Its resistance showed a PTC effect first and then changed to the NTC effect in the first heating. Similar to situation mentioned above, next curves are also consistent.



(a) H-100-1. (b) H-100-2. (c) H-100-3.

(d) H-150-1. (e) H-150-2. (f) H-150-3.

(g) H-200-1. (h) H-200-2. (i) H-200-3.

Figure 4. Temperature-relative resistance change curves during heating.

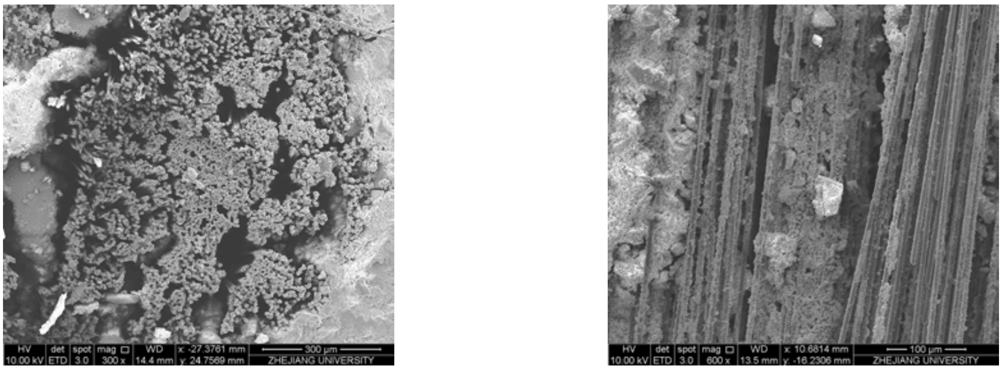
3.2 Discussion

As mentioned above, when the temperature rises, the resistivity of the carbon fiber decreases accordingly (Schulte and Baron 2002). Moreover, if the temperature is less than 300 ℃, the carbon fiber shrinks longitudinally and expands transversely (Morgan 1972). Then, its length is shorter and its cross-sectional area is larger. Therefore, the resistance of carbon fiber inside the CFRCM decreased during heating. In addition, some filaments of CFRCM are initially broken, and they may be separate due to the mortar. If a filament is close to one another, the tunneling electrons can pass through the gap and conduct electricity. According to the tunneling theory (Liu and Luo 2011), the carrier concentration can be calculated by

$$\sigma = \sigma_0 e^{-E/kT} \tag{1}$$

where σ is the carrier concentration, σ_0 is the initial carrier concentration, E is the band gap, k is the Boltzmann's constant, and T is the thermodynamic temperature. If the CFRCM is heated, more electrons will gain energy and the carrier concentration will increase. That is why the specimens showed an obvious NTC effect in most cases.

Due to the large particle size, the mortar usually only infiltrates the outer filaments of CFRCM, as show in Figure 5a. The volume of the mortar increases during heating, and the filaments are tightly wrapped. The more filaments contact with each other, including those which have broken and do not conduct electricity. Then, the resistance of CFRCM decreased. However, some mortars may still penetrate into the interior, as shown in Figure 5b. These mortars expand during heating and the original conductive paths are cut off, which bring out increasing resistance. The joint effect of the two phenomena causes to the fluctuation of the curves.



(a) Filaments wrapped by mortar. (b) Filaments infiltrated by mortar.

Figure 5. Microscopic images of CFRCM.

It is worth mentioning that even if the CFRCM was cooled, some carriers which have been excited remained in the conduction band (Yao et al. 2006). Therefore, some specimens cannot be restored to the original state after one cycle. If these specimens are heated again, the carrier concentration will have a fewer decrement. In the second and third cycle, the carrier remaining in the conduction band did not increase much, so the curves have good consistency. As shown in Figure 4c, a specimen had a high water content before heating, which decreased with increasing temperature. The lower the water content, the greater the resistance (Wang 2017). Therefore, this specimen had a PTC effect first. When the water content was close to 0, it showed an NTC effect. The water content did not change too much during subsequent repeated heating, and these curves are more consistent.

In general, the thermal-resistivity curves of CFRCM after a heating cycle have a good repeatability. According to this characteristic, CFRCM can be employed to monitor the temperature of structures. The thermal-resistivity coefficient can be used to describe the relationship between the relative resistance change and the temperature, which is expressed by

$$\alpha = (R_m - R_0)/(T_m - T_0) \times R_0 \quad (2)$$

where α is the thermal-resistivity coefficient, R_0 is the initial resistance, R_m is the resistance at the maximum temperature, T_0 is the initial temperature and T_m is the highest temperature. Then, the thermal-resistivity coefficient α of different specimens after first heating were calculated, as shown in Table 4. The thermal-resistivity coefficients are about -0.04% and independent of length. Therefore, the resistance decreases by about -0.4% for every 10 ℃ increase in temperature.

Table 4. Thermal-resistivity coefficients of specimens.

Specimen	Thermal-resistivity coefficient					
	Cycle 1 Cooling	Cycle 2 Heating	Cycle 2 Cooling	Cycle 3 Heating	Cycle 3 Cooling	Average
H-100-1	-0.040%	-0.041%	-0.037%	-0.040%	-0.038%	-0.039%
H-100-2	-0.042%	-0.043%	-0.044%	-0.043%	-0.042%	-0.043%
H-100-3	-0.039%	-0.037%	-0.060%	-0.040%	-0.055%	-0.046%
H-150-1	-0.040%	-0.041%	-0.039%	-0.039%	-0.039%	-0.040%
H-150-2	-0.045%	-0.048%	-0.040%	-0.047%	-0.043%	-0.045%
H-150-3	-0.044%	-0.040%	-0.041%	-0.040%	-0.041%	-0.041%
H-200-1	-0.034%	-0.035%	-0.039%	-0.038%	-0.038%	-0.037%
H-200-2	-0.036%	-0.036%	-0.043%	-0.037%	-0.037%	-0.038%
H-200-3	-0.037%	-0.043%	-0.041%	-0.040%	-0.038%	-0.040%

4 Conclusion

In this paper, nine specimens were repeatedly heated to study the thermal-resistivity characteristics of CFRCM. Based on the existing researches and test results, the mechanism of the resistance change was analyzed. The main conclusions are as follows:

- The resistance of the carbon fiber decreases and the carrier concentration of CFRCM increases during heating, resulting the NTC effect of CFRCM. The thermal-resistivity coefficients are about 0.04% and independent of length.
- Some excited carriers remain in the conduction band. When the cooling is completed, the resistance of the specimens cannot return to the original value. However, the curves of subsequent heating process have a good repeatability.
- Due to the nonuniform infiltration of the mortar, filaments may be wrapped or squeezed apart, which causes to the fluctuation of the curves. Moreover, a high water content can cause the specimen to show a PTC effect initially.

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