Study on the Effects of Carbon Fibers and Carbon nanofibers on Electrical Conductivity of Concrete

Tengjiao Wang¹, Jinyu Xu¹,², Erlei Bai¹, Xin Luo³, Haowen Chen¹, Gaojie Liu¹, Sen Chang¹
¹Teaching-research Office of Airfield and Building Engineering, Air Force Engineering University, Xi’an 710038, China
²College of Mechanics and Civil Architecture, Northwest Polytechnic University, Xi’an 710072, China
³National Defense Engineering Institute, Academy of Military Sciences, Beijing, 100036, China
Corresponding author, E-mail: wtengjiao83087@163.com

Abstract. In order to study the effects of carbon fibers and carbon nanofibers on the electrical conductivity of concrete, we adopt the four-electrode method to measure the resistivity of concrete with different test voltages, different ages and different fiber content. The test results show that both carbon fibers and carbon nanofibers can significantly reduce the electrical resistivity of concrete. When carbon fiber content and carbon nanofiber content are same, the resistivity of carbon fiber reinforced concrete (CFRC) is lower than that of carbon nanofiber reinforced concrete (CNFRC). The resistivity of CFRC and CNFRC can decrease with the increase of the test voltage, increase with the development of the concrete, and decrease with the increase of the fiber content. For concrete with an age of 28 days, CFRC has the largest decrease in resistivity when the carbon fiber content is between 0.2% and 0.3%, and the resistivity of CNFRC drops biggest when the carbon nanofiber content is between 0.1% and 0.3%.

1. Introduction
Concrete is an excellent load-bearing material and is widely used in the construction of various engineering facilities. During the use of these facilities, concrete often suffers from cracks and other internal damages due to factors such as loads, causing engineering accidents which bring huge losses to the country and people. Recently, the majority of scholars have carried out research on intelligent concrete to predict and prevent internal damage of concrete [1-2]. Intelligent concrete requires concrete to be self-adapting, self-diagnosing and self-repairing, and the key to achieving these capabilities is the electrical conductivity of concrete. Therefore, it is meaningful to study and improve the electrical conductivity of concrete.

Plain concrete (PC) is a bad conductor with poor electrical conductivity. Short-cut carbon fiber is a kind of microcrystalline graphite material with high aspect ratio, low density, high elastic modulus and excellent electrical conductivity [3]. It can not only improve the mechanical properties of concrete [4-5], but also improve the electrical conductivity of concrete. At present, some scholars have begun to study the conductive properties of CFRC [6-8]. Chen, B. [9] and other researchers have shown that CFRC will cause changes in the carbon fiber network when it is damaged, resulting in an increase in...
the electrical resistance of the concrete. The degree of damage of the concrete can be monitored by
detecting the change in resistance; Reza, F. [10] etc. have extended the resistance technology from
metal fracture mechanics analysis to the internal damage analysis of concrete. It is found that the
resistance change of CFRC is closely related to the deformation. Carbon nanofiber is a new type of
nanomaterial that combines the excellent properties of nanomaterials and carbon fiber materials [11].
At present, scholars have researched the conductivity of CNFRC [12-14]. For example, Yanlei, W. [15]
and others studied the piezoresistive properties of CNFRC. The results show that the sensor can be
made according to the change of piezoresistance of concrete to detect the health of concrete structures.
Roberts, RH [16] and other researchers found that the incorporation of carbon nanofibers into concrete
allowed monitoring of the compressive strain and tensile strain of the concrete, and the relationship
between electrical resistance and strain could be determined for the detection of possible damage to
the concrete structure.

At present, the research on the electrical conductivity of CFRC and CNFRC is mostly independent,
and there are few reports on the comparative study of the electrical properties of the two composite
materials. In this paper, the resistance and resistivity of two composites were compared from the
perspective of test voltage, age and fiber content. The effects of carbon fibers and carbon nanofibers
on the electrical conductivity of concrete under different conditions were analyzed, and it was of
certain significance to propose methods to improve the electrical conductivity of concrete.

2. Experimental research

2.1 Experiment materials
The experiment has used ordinary Portland cement, laboratory clean tap water, river sand with
fineness modulus of 2.6 and mud content of 1.3%, tributyl phosphate defoamer, polycarboxylic acid
high performance water reducing agent, dispersion, carbon fibers and carbon nanofibers. The physical
map of carbon fibers is shown in Figure 1 and the main performance indicators are shown in Table 1.
The physical map of carbon nanofibers are shown in Figure 2 and the main performance indicators are
shown in Table 2.

![Figure 1. Carbon fibers (CFs)](image1)

![Figure 2. Carbon nanofibers (CNFs)](image2)

| Carbon content (%) | Young's modulus (GPa) | Tensile strength (MPa) | Resistivity (Ω cm) | Density (kg m⁻³) | Monofilament diameter (μm) | Elongation at break (%) |
|--------------------|-----------------------|------------------------|--------------------|------------------|---------------------------|------------------------|
| 95                 | 228                   | >3500                  | 1.0~1.6            | 1780             | 7                         | 1.5                    |

| Purity (%) | Monofilament diameter (μm) | Length-diameter ratio | Thermal Conductivity (W (m·C)⁻¹) | Resistivity (Ω cm) | Thermal expansion coefficient | Specific surface area | Density (g·cm⁻³) |
|------------|----------------------------|-----------------------|---------------------------------|--------------------|----------------------------|----------------------|-----------------|

Table 2. Main performance indicators of CNFs
2.2 Test piece preparation

2.2.1 Fiber dispersion
Due to the large van der Waals force between the fibers, the fibers often agglomerate and are not easily dispersed. Therefore, the fibers are first dispersed before being incorporated into the concrete. For the dispersion of carbon fibers, hydroxyethyl cellulose was used as the chemical dispersant of the fibers [17]. The hydroxyethyl cellulose, water reducing agent and water were uniformly stirred to prepare a dispersion solution. Then the carbon fibers was added to the dispersion solution and stirred in a high speed to achieve uniform dispersion. For the dispersion of carbon nanofibers, the FDN superplasticizer was used as a dispersing agent, the water reducing agent and water are uniformly mixed to form a dispersion solution, and then the carbon nanofibers are poured into the configured dispersion solution. Then high speed agitation to achieve uniform dispersion of carbon nanofibers.

2.2.2 Test piece pouring
PC, CFRC, and CNFRC test pieces were all poured based on the “sanding stone method”. When preparing the PC group test piece, firstly, mixed some water with the sand. After thorough stirring, added the crushed stone, cement and the other water in turn. Then stirred the mixture thoroughly. Finally, a mixture of uniformly stirred was obtained. When preparing the CFRC and CNFRC test pieces, the prepared CFs dispersion and the CNFs dispersion were separately mixed with the antifoaming agent, stirred to form a mixed solution, and then the mixed liquid was divided into two parts, and the subsequent preparation process is the same as PC test piece. After the casting of each group of specimens was completed, the corresponding mold was placed in the room for 1 d, and then the mold was removed. Then specimens were quickly moved into the curing box for standard maintenance (temperature was maintained at 20±2°C, relative humidity (RH)>95%). The matching of the concrete specimens of each group was shown in Table 3. The volume change of CFs in the CFRC group specimens and CNFs in the CNFRC group specimens were 0.1%, 0.2%, 0.3%, 0.4%, and 0.5%.

Table 3. Concrete mix ratio (kg·m⁻³)

| Number   | Water | Cement | Sand | Stone | Water reducing agent | Defoamer | CFs | CNFs |
|----------|-------|--------|------|-------|----------------------|----------|-----|------|
| PC       | 180   | 495    | 672  | 1008  | 0                    | 0        | 0   | 0    |
| CFRC01   | 180   | 495    | 672  | 1008  | 5.0                  | 0.30     | 0   | 0.18 |
| CFRC02   | 180   | 495    | 672  | 1008  | 7.5                  | 0.45     | 0   | 0.36 |
| CFRC03   | 180   | 495    | 672  | 1008  | 10.0                 | 0.60     | 0   | 0.54 |
| CFRC05   | 180   | 495    | 672  | 1008  | 15.0                 | 0.90     | 0   | 0.90 |
| CNFRC01  | 180   | 495    | 672  | 1008  | 5.0                  | 0.30     | 1.78| 0    |
| CNFRC02  | 180   | 495    | 672  | 1008  | 7.5                  | 0.45     | 3.56| 0    |
| CNFRC03  | 180   | 495    | 672  | 1008  | 10.0                 | 0.60     | 5.34| 0    |
| CNFRC05  | 180   | 495    | 672  | 1008  | 15.0                 | 0.90     | 8.90| 0    |

2.3 Experiment method
The test piece is a rectangular measuring 100mm×100mm×400mm. Since the resistance is required to test, the test piece needs to be pre-embedded before the pouring. The electrode is made of copper wire with a diameter of 1 mm, which can be seen clear in Figure 3. The test piece is shown in Figure 4.
four-electrode method has been adopted in the experiment. The test equipment is shown in Figure 5 and the schematic diagram is shown in Figure 6.

When the curing age of each group reaches 1d, 3d, 7d, and 28d, the current values passing through the test pieces of each group are tested at test voltages of 1V, 3V, 5V, 7V, 10V, 15V, and 30V. The current value measured by the peripheral electrodes at both ends of the test piece is recorded as $I_0$, and the voltage value measured by the internal two electrodes is recorded as $U_0$. According to Ohm's law, the resistance $R_0$ of the test piece can be calculated as follow.

$$ R_0 = \frac{U_0}{I_0} \quad (2.1) $$

The resistivity of the test piece can be calculated from the following formula.

$$ \rho = \frac{R_0 A}{L} \quad (2.2) $$

In the above formula, $A$ is the cross-sectional area of the current passing through the test piece, and $L$ is the length of the test piece of the measured section.

Power supply with a function of regulating voltage is adopted to provide the test voltage, and the two universal meters are used to test the voltage and current between the electrodes.

3. Analysis and discussion

3.1 Effects of test voltage on concrete resistivity
Figure 7 to 10 show the variation of the resistivity with the increase of test voltage for PC, CFRC03, and CNFRC03 concrete specimens which respectively have an age of 1, 3, 7, and 28 days. It can be seen from the figure that the resistivity of the three sets of concrete specimens at different ages all decrease with the increase of the test voltage. When the test voltage is between 0 to 15V, the resistivity decreases rapidly, and when between 15 to 30V, the resistivity decreases slowly. Taking the concrete specimen with 28 days old as an example, when the test voltage is 1V, the concrete specimens of PC, CFRC03, and CNFRC03 group have the highest resistivity, which are 131.46 Ω·m, 103.02 Ω·m, 107.81 Ω·m respectively. When the test voltage is 30V, the concrete specimens of PC, CFRC03, and CNFRC03 group have the lowest resistivity, which are 113.83 Ω·m, 90.13 Ω·m, and 94.15 Ω·m respectively. With the increase of test voltage, the resistivity of plain concrete is always the largest and that of CFRC is always the smallest. However, the resistivity of CNFRC is slightly larger than that of CFRC, which is between the above two. And it can be seen that the incorporation of carbon fibers and carbon nanofibers in concrete can significantly reduce the resistivity of concrete. Compared with PC, the resistivity of CFRC has decreased by 20.63%-21.63%, and the resistivity of CNFRC has decreased by 17.05%-17.99%.

3.2 Effects of age on concrete resistivity
Figure 11 to 14 show the variation of the resistivity of PC, CFRC03, and CNFRC03 concrete specimens with concrete age at different test voltages. Although the test voltages are different, the change trend in the resistivity of each group of concrete specimens is consistent with the change of age. All the resistivity of PC, CFRC, and CNFRC increase with the increase of age. When the age is between 0 to 7 days, the resistivity of concrete increases rapidly, and the resistivity of concrete grows slower when the age is between 7 to 28 days. For example, when the test voltage is 10V, the resistivity of the PC, CFRC03, and CNFRC03 concrete specimens are all the smallest at the age of 1 day, and the resistivities are 34.15 Ω·m, 20.36 Ω·m, 23.60 Ω·m respectively. The concrete specimens of PC, CFRC03, and CNFRC03 have the highest resistivity, when they have developed for 28 days, which are 120.40 Ω·m, 94.83 Ω·m and 98.92 Ω·m respectively. Compared with the age of 1 day, it can be seen that the resistivity of PC increases by 252.57%, the resistivity of CFRC increases by 365.87%, and the resistivity of CNFRC increases by 319.24%. With the increase of age, the resistivity of PC has always been the largest, the resistivity of CFRC and CNFRC are significantly lower than that of plain concrete. The resistivity of CNFRC is slightly larger than that of CFRC.

3.3 Effects of carbon fiber and carbon nanofiber content on concrete resistivity
Figure 15 depicts the relationship between the resistivity and fiber content of CFRC and CNFRC. From the overall trend, the resistivity of both CFRC and CNFRC decrease with the increase of fiber content. With the same fiber content, the resistivity of CFRC is always smaller than that of CNFRC. For concrete with an age of 3 days, as shown in Figure 15(a) and (c), when the carbon fiber content is between 0.1% and 0.3%, CFRC has the largest decrease in resistivity; when the carbon nanofiber content is between 0.2 and 0.3%, CNFRC has the largest decrease in resistivity. For concrete with a 28-day age, as shown in Figure 15(b) and (d), CFRC has the largest decrease in resistivity when the carbon fiber content is between 0 and 0.1% or between 0.2% and 0.3%, when the dosage of carbon nanofiber is between 0.1% and 0.3%, the resistivity of CNFRC decreases the most.

3.4 Mechanism analysis
The incorporation of carbon fiber or carbon nanofiber into concrete can reduce the resistivity of concrete because there are only two forms of ion conduction and electronic conduction in PC, and hole conduction in CFRC and CNFRC [18]. Ion conduction is based on the presence of ions of Ca$^+$, SO$_4^{2-}$, OH$^-$, K$^+$, Na$^+$ etc in the concrete, which have been generated through the hydration reaction of cement. When these ions move under the action of external voltage, the concrete will be conductive. Electron conduction is based on the presence of products of hydration reaction in the concrete and unreacted cement particles, whose main components are compounds such as calcium, aluminum, iron, etc. And the electrons in these compounds are directionally moved under the external voltage, resulting in forming a current. Hole conduction is a new form of electrical conductivity that occurs when carbon fibers or carbon nanofibers are incorporated into concrete. It means that under the action of external voltage, electrons on one fiber can break through the barrier to another fiber, so as to realize the directional movement of electrons.

The resistivity of both CFRC and CNFRC decrease with the increase of test voltage, because the
greater the test voltage, the greater driving force of ions and electrons in concrete, and more electrons can break through the potential. When the directional movement of more ions and electrons, there is the greater current value can be measured, which shows the smaller resistivity of the concrete. When the test voltage is less than 15V, the resistivity of CFRC and CNFRC decreases rapidly as the test voltage increases, because the barrier between fibers is the main factor affecting the resistivity. When the test voltage is larger, the energy required to break through the barrier is saturated, and the barrier is no longer the main factor. Therefore, the resistivity decreases slowly as the test voltage increases.

The resistivity of both CFRC and CNFRC increase with the development of concrete, because the hydration reaction of cement in concrete becomes more and more complete with the increase of concrete age and some water has been evaporated, which make fewer and fewer ions present in the unreacted water. When the age is less than 7 days, the hydration reaction in the concrete proceeds faster and there is the continuous evaporation of water, both of which make the resistivity of CFRC and CNFRC increase rapidly. When the age is more than 7 days, the hydration reaction in the concrete is slower and the reduction of ions is slower, so the resistivity of CFRC and CNFRC grow slowly.

Both CFRC and CNFRC have a certain fiber content range. In this range, the concrete resistivity decreases the fastest because of the conductive seepage in CFRC and CNFRC. When the dosage of carbon fibers or carbon nanofibers is between two thresholds, the carbon fibers or the carbon nanofibers can overlap each other to form a conductive network [19] that penetrates each other, which can greatly improve the conductivity of the concrete. If the fiber content exceeds this range, the conductive network overlapped by the fibers is only more perfect without significant changes, and thus the resistivity of CFRC and CNFRC decrease, but tend to be slower. When the other conditions are the same, the resistivity of CFRC is smaller than that of CNFRC if they have same fiber content. Because carbon fibers are more dispersible than carbon nanofibers and has a larger length-diameter ratio. In addition, the effect of carbon fibers overlapping each other is better and carbon fibers can form a more complete conductive network.

4. Conclusions
In this paper, the four-electrode method is adopted to measure the resistivity of CFRC and CNFRC that have different fiber contents, under different test voltages and have different ages. The following conclusions are drawn from the test results.

(1) The resistivity of both CFRC and CNFRC decrease with the increase of test voltage. When the test voltage is smaller, the resistivity decreases faster, and when the test voltage is larger, the resistivity decreases at a slower speed and gradually becomes stable;

(2) The resistivity of both CFRC and CNFRC increase with the increase of concrete age. When the age of the concrete is less than 7 days, the rate of increase of resistivity is faster. When the age of concrete is more than 7 days, the rate of increase of resistivity is slower;

(3) The resistivity of both CFRC and CNFRC decrease with the increase of fiber content. When the fiber content is within two threshold ranges, the concrete resistivity decreases at the fastest rate;

(4) Both carbon fibers and carbon nanofibers can significantly reduce the resistivity of concrete. When the same content of carbon fibers and carbon nanofibers are incorporated into the concrete, the resistivity of CFRC is smaller than that of CNFRC.

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