Experimental study on electrical conductivity of carbon nanofiber reinforced concrete

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Abstract. To study the effect of carbon nanofibers (CNFs) on the electrical conductivity of concrete, we used the four-electrode method to measure the resistance and resistivity of carbon nanofiber reinforced concrete (CNFRC) under different ages, different fiber content and different test voltages. The results show that the incorporation of CNFs into concrete can improve the electrical conductivity of concrete. The electrical resistance and electrical resistivity of CNFRC increase with the increase of concrete age, but the growth rate decreases gradually. The resistance and electrical resistivity of CNFRC decrease with the increase of carbon nanofiber content and the optimum dosage range is 0.1%-0.3%. The resistance and electrical resistivity of CNFRC decrease with the increase of test voltage, and when the test voltage is 1V~5V, the resistance and electrical resistivity decrease significantly.

1. Introduction
Concrete is a common building material and is widely used in engineering construction [1]. As the project develops in large quantities, the safety of the project is receiving more and more attention. In recent years, many scholars have carried out extensive research on intelligent concrete [2] based on how to detect the internal crack damage of concrete and predict the development trend of cracks [3]. Intelligent concrete refers to the incorporation of certain conductive materials into the concrete to improve the electrical conductivity of the concrete. The use of electronic instruments to detect and diagnose the concrete structure can reduce personnel and property losses caused by accidental damage [4, 5]. Therefore, it is important to improve the electrical conductivity of concrete.

Carbon nanofiber is a new type of material with many excellent physical properties. Some scholars have found that the incorporation CNFs into concrete can significantly improve the mechanical and electrical properties of concrete [6, 7]. Meng et al. [8] found that the incorporation of nano-graphite sheets and CNFs into concrete could improve the mechanical properties of concrete. When the content of nano-graphite sheets and carbon nanofibers increased from 0 to 0.3%, the tensile strength and energy absorption capacity of concrete grew by 56% and 187% respectively, the bending strength and toughness increased by 59% and 276% respectively. Savas Erdem et al. [9] researched on the self-inductance damage evaluation and crack quantification of CNFRC. The results showed that carbon nanofiber could effectively reduce the development of microcracks, however, it could slow down the development of macroscopic cracks and improve the compactness of concrete. Gao Di et al. [10] studied the static resistance of CNFRC and found the appropriate density of carbon nanofiber self-compacting concrete.
was a kind of semiconductor, and the resistance change rate had a good linear relationship with stress and strain when the concrete was pulled or pressed. It is a new type of smart concrete material with great potential.

At present, the research on CNFRC is still at a preliminary stage [11, 12], especially in the research on the electrical properties of CNFRC. Based on it showing excellent electrical properties, this paper has carried out in-depth research on CNFRC. By investigating the variation of resistance and electrical resistivity of CNFRC with age, fiber content and test voltage, it is possible to use concrete itself as a sensor for safety diagnosis inside the structure, which is of great significance for preventing engineering safety accidents.

2. Experiment

2.1. Experimental materials and mix ratio

Ordinary Portland cement in 42.5 grade produced by Xi'an was used in test, with a fineness modulus of 2.7, silt content of 1.4% and a well-graded limestone gravel. Tributyl phosphate defoamer was used to eliminate the bubbles generated by the incorporation of CNFs into the concrete. The use of polycarboxylic acid high-performance water reducing agent can reduce the viscosity of concrete and enhance the dispersion effect of CNFs. The physical map of CNFs used in the experiment is shown in Figure 1 and the main performance indexes are shown in Table 1. Laboratory clean tap water was used.

The electrical resistivities of the concrete with five different mix ratios were tested. The concrete mix ratio is shown in Table 2, and the volume of CNFs in the CNFRC test specimens is 0.1%, 0.2%, 0.3% and 0.5% respectively.

![Carbon nanofibers (CNFs)](image)

Table 1. Main performance indicators of CNFs

| Monofilament diameter (nm) | Density (g·cm⁻³) | Purity (%) | Length-diameter ratio | Specific surface area (m²·g⁻¹) | Resistivity (Ω·cm) | Thermal Conductivity (W·(m·°C⁻¹)) | Thermal expansion coefficient (°C⁻¹) |
|---------------------------|------------------|------------|-----------------------|-------------------------------|-------------------|-----------------------------------|-----------------------------------|
| 160–200                   | 0.17             | 99.7       | 68                    | 310                           | <0.013            | 2000                              | 0.99                              |

Table 2. Concrete mix ratio (kg/m³)

| Number | CNFs | Gravel | Sand | Water | Cement | Water reducing agent | Defoamer |
|--------|------|--------|------|-------|--------|----------------------|----------|
| PC     | 0    | 1008   | 672  | 180   | 495    | 0                    | 0        |
| CNFRC01| 0.18 | 1008   | 672  | 180   | 495    | 5.0                  | 0.30     |
| CNFRC02| 0.36 | 1008   | 672  | 180   | 495    | 7.5                  | 0.45     |
| CNFRC03| 0.54 | 1008   | 672  | 180   | 495    | 10.0                 | 0.60     |
| CNFRC05| 0.90 | 1008   | 672  | 180   | 495    | 15.0                 | 0.90     |
2.2. Specimen preparation
Concrete specimens are poured using the “sanding method”. Due to the large van der Waals force between CNFs, CNFs are not easily dispersed. The FDN water reducing agent was uniformly mixed with water to prepare a CNFs dispersion solution, and the CNFs and the prepared dispersion solution were poured into a stirrer for high-speed stirring to obtain a suspension in which CNFs were uniformly dispersed. The suspension was uniformly mixed with the antifoaming agent and then divided into two parts to obtain two identical mixed solutions. One mixture was first mixed with sand, stirred uniformly, and then gravel, cement and another mixture were added in sequence, stirred while being added, and then the uniform concrete was poured into the mold. When preparing the PC group test piece, replaced the mixture with water and the other processes were same. After all the specimens were poured, they were demolished for 1 day in the room for standard maintenance.

The specimen is a standard rectangular test piece of 100 mm × 100 mm × 400 mm. As shown in Fig. 2, the electrode is a copper mesh with a diameter of 1 mm (see in Figure 3). They were embedded in the concrete when it was poured.

2.3. Experiment method
Four-electrode method is used in the experiment. The two middle electrodes are connected to a universal meter by wires to measure the voltage. The two outer electrodes are connected to a regulated power supply and a universal meter to measure the current passing through the concrete. The test is powered by a regulated power supply with regulated voltage. The test equipment and test schematic are shown in Figure 4 and Figure 5.

After each group specimen is standardly maintained to 1d, 3d, 7d, and 28d, we adjusted the test voltages to 1V, 3V, 5V, 7V, 10V, 15V, and 30V respectively and tested the current values passing through the concrete. The voltage value read by the voltmeter is recorded as \( U_0 \), and the current value read by the ammeter is recorded as \( I_0 \). According to Ohm's law, the resistance \( R_0 \) under the measured length of the specimen is calculated as:

\[
R_0 = \frac{U_0}{I_0}
\]
Then the resistivity of the concrete specimen is figured out as:

\[ \rho = \frac{R \cdot A}{L} \] (2.2)

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

3. Result Analysis and discussion

3.1. Concrete resistance and resistivity change with age

Figure 6 and Figure 7 respectively show the variation of resistance and resistivity of PC and CNFRC01 with the concrete age when test voltage is 5V. It can be seen from the two figures that the resistance and resistivity of the two different concretes increase with age. As for the two different concretes with same age, the resistance and resistivity of CNFRC are always smaller than PC. When the age is less than 7 days, the resistance and resistivity of PC and CNFRC01 increase rapidly. When the age is more than 7 days, the resistance and resistivity of PC and CNFRC01 increase slowly. When the age is 7 days, the resistance and resistivity of CNFRC01 are 672.49 Ω and 84.06 Ω•m respectively, which grow by 125.91% compared with the age is 1 day. When the age is 28 days, the resistance and resistivity of CNFRC01 are 976.21 Ω and 122.03 Ω•m respectively, which show an increase of 227.94% compared with 1 day age. The above results show that the electrical conductivity of CNFR C is better than that of PC. As the age increases, the resistance and resistivity of CNFRC increase continuously while the effects of age on CNFR C’s resistance and resistivity are continuously attenuated.

3.2. Concrete resistance and resistivity change with fiber content

Figure 8 shows the relationship between the resistance of CNFRC and the amount of CNFs, and Figures 9 denotes the relationship between the resistivity of CNFRC and the amount of CNFs. It can be seen from the figures that the resistance and resistivity of CNFRC decrease stepwise with the increase of CNFs. When the amount of CNFs is 0-0.1% and 0.3%-0.5%, the resistance and resistivity decrease slowly. When the amount of CNFs is 0.1%-0.3%, the resistance and resistivity decrease rapidly. When
the amount of CNFs is 0.1% and the age is 7 days, the resistance and resistivity of CNFRC are 629.91 Ω and 78.74 Ω•m respectively, which are 3.90% lower than that of PC; when the age is 28 days, the resistance and resistivity of CNFRC are 921.07 Ω and 115.13 Ω•m respectively, which is 1.96% lower than PC. When the amount of CNFs is 0.3% and the age is 7 days, the resistance and resistivity of CNFRC are 452.07 Ω and 56.51 Ω•m, which is 31.03% lower than PC; when the age is 28 days, the resistance and resistivity of CNFRC are 779.26 Ω and 97.41 Ω•m, which is 17.05% lower than PC. The above results show that when the dosage of CNFs is less than 0.1% or more than 0.3%, the amount of CNFs has little effect on the resistance and resistivity of concrete; when the amount of CNFs increases from 0.1% to 0.3%, the resistance and resistivity of concrete are significantly affected by the amount of CNFs and the corporation of CNFs can significantly reduce the resistance and resistivity of concrete.

3.3. Concrete resistance and resistivity change with test voltage

![Figure 10. Resistance changes with test voltage](image1)

![Figure 11. Resistivity changes with test voltage](image2)

Figure 10 and Figure 11 respectively show the variation of the resistance and resistivity of CNFRC at the age of 28 days with the increase of test voltage. It can be seen from the figure that as the test voltage increases, the resistance and resistivity of CNFRC with different fiber content decrease continuously, and the effects of the test voltage on the resistance and resistivity of CNFRC are also weakened. When the test voltage is 5V, the resistance and resistivity of PC, CNFRC01, CNFRC02, CNFRC03, and CNFRC05 are 992.14 Ω, 976.21 Ω, 894.07 Ω, 816.23 Ω, 778.34 Ω, and 124.02 Ω•m, 122.03 Ω•m, 111.76 Ω•m, 102.03 Ω•m, 97.29 Ω•m respectively. Compared with the test voltage is 1V, the resistance and resistivity are reduced by 5.66%, 4.33%, 4.12%, 5.36%, and 4.29% respectively. When the test voltage is 30V, the resistance and resistivity of PC, CNFRC01, CNFRC02, CNFRC03 and CNFRC05 are 910.62 Ω, 900.18 Ω, 833.27 Ω, 753.17 Ω, 712.75 Ω, 112.52 Ω•m, 104.16 Ω•m, 89.09 Ω•m. Compared with the test voltage is 1V, the resistance and resistivity are reduced by 13.41%, 11.78%, 10.64%, 12.67%, and 12.35% respectively. It shows that, as same as that of PC, the resistance and resistivity of CNFRC decrease with the increase of test voltage. When the test voltage increases from 1V to 5V, the resistance and resistivity of CNFRC decrease significantly.

3.4. Mechanism analysis

The variation that resistance and resistivity of CNFRC change with age are consistent with that of PC. Since the hydration reaction of the cement inside the concrete soil consumes a large amount of ions, the resistance and resistivity of the concrete continuously increase, and the electrical conductivity deteriorates. Moreover, the hydration reaction of the cement reacted violently in the first seven days after the specimens are prepared, therefore, the resistance and resistivity of CNFRC increased rapidly. The resistance and resistivity of CNFRC vary with the test voltage, which is similar to PC. As the test voltage increases, the driving force of the electrons and ions inside the concrete is increased and the speed of the directional movement is accelerated, therefore, the resistance of the CNFRC becomes smaller. When the voltage is less than 5V, the driving force generated by the voltage is more effective; when the voltage is greater than 5V, the driving force of electrons and ions is gradually saturated and the effect is continuously reduced and stabilized.

The incorporation of CFs into concrete can reduce both resistance and resistivity of concrete and
improve the electrical conductivity of concrete. When the amount of CNFs is less than 0.1%, the CNFs are dispersed in the concrete and cannot be effectively overlapped, then, the electron’s directional migration in the concrete is not accelerated. Therefore, the current is small, the resistance and resistivity are large and they decrease slowly with the increase of CNFs. When the amount of CNFs is from 0.1% to 0.3%, the fibers are uniformly dispersed inside the concrete and overlap each other effectively to form a conductive network, so that the resistance and resistivity of the concrete are rapidly reduced. When the amount of CNFs is more than 0.3%, for one thing, CNFs are attracted to each other due to van der Waals’ force and tend to agglomerate inside the concrete; for another thing, the conductive network formed by excessive fibers tends to be saturated, therefore, the resistance and resistivity of concrete decreases slowly with the increasing amount of CNFs.

4. Conclusions
The four-electrode method was used to measure the resistance and resistivity of CNFRC at different ages, different carbon nanofiber content and different test voltages. Through the result analysis, the following conclusions are drawn:

1) The resistance and resistivity of CNFRC increase with the concrete age. When the age is less than 7 days, the resistance and resistivity of CNFRC grow faster. When the age is more than 7 days, the resistance and resistivity of CNFRC grow slowly and tend to be stabilized. When the age increases from 1 day to 7 days, the resistance and resistivity of CNFRC increased by 125.91%.

2) The resistance and resistivity of CNFRC decrease with the increase of carbon nanofiber content. When the content of CNFs is less than 0.1% or more than 0.3%, the resistance and resistivity of CNFRC decrease slowly with the increase of fiber content. When the amount of CNFs increases from 0.1% to 0.3%, CNFRC has a faster reduction in resistance and resistivity and the optimum content of CNFs is between 0.1% and 0.3%.

3) The resistance and resistivity of CNFRC decrease with the increase of test voltage. As the test voltage increases, the effects of the test voltage on the resistance and resistivity of CNFRC are also gradually reduced. When the test voltage increases from 1V to 5V, the resistance and resistivity of CNFRC decrease significantly.

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