Article

Electrical Characteristics of Ultra-High-Performance Concrete Containing Carbon-Based Materials

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Abstract: Recently, carbon materials with unique properties, such as high tensile strength and electrical conductivity, have been extensively investigated for the multi-functionalization of concrete. Previous studies mainly focused on improving the performance of normal-strength concrete using carbon nanomaterials, such as carbon nanotubes and graphene nanoplates. Therefore, this study analyzed the effect of carbon materials on ultra-high-performance concrete (UHPC) mixed with steel fibers, which has an outstanding mechanical performance. In addition, length effects were investigated for carbon fibers with nanometer, micrometer, and millimeter sizes. The influences of carbon materials on 120 MPa UHPC were investigated, including expanded graphite, a well-known superior conductivity material. Electrical conductivity, compressive strength, tensile strength, and electrical conductivity were analyzed experimentally. As a result, compressive strength tends to decrease as the concentrations of carbon materials increase, and chopped fiber has the best performance at 10.5 MPa in terms of tensile strength. Since the electrical conductivity of chopped fiber was observed to be significantly higher than that of other materials at 6.6 times, millimeter-sized fiber would be most suitable as a carbon material for concrete. This study could guide future research on the multi-functionalization of UHPC with carbon-based materials, including mechanical and electrical conductivity performances.

Keywords: UHPC; carbon materials; electric conductive; direct current; alternating current

1. Introduction

Reinforced concrete (RC) is an outstanding construction material that facilitates durable constructions with enhanced mechanical properties. Although reinforced concrete is durable compared to other construction materials, it is associated with the limitations of chloride penetration and reinforcing-bar corrosion [1]. This problem is particularly significant in bridge structures where the air-exposed area can be widened. Ultra-high-performance concrete (UHPC) bridges, with lower cross-sections than RC bridges, high chloride resistance, and low rebar use, have been used to overcome the abovementioned limitations. UHPC bridges are being increasingly used due to their advantageous properties; some examples are the Wild Bridge (2010) in Europe and the Jakway Forest Park bridge (2008) in the United States [2]. Performance improvement and multi-functionalization could increase the applications of UHPC in the future.

Recently, the prevention of accidents related to black ice on winter roads has gained prominence in road and bridge construction. According to the Federal Highway Administration (FHWA), a substantial annual budget of $5.9–9.7 billion has been utilized for de-icing work in bridge construction, with a continuous requirement of maintenance costs [3,4]. Furthermore, de-icing agents (which are commonly chlorides) penetrate the concrete, adversely affecting its durability. In the harsh condition of direct exposure to
chloride, it would be difficult to ensure durability from substances such as deicing agents in winter, even if UHPC shows outstanding chloride resistance performance. Thus, to ensure the service life of concrete, it is vital to develop a method for black ice removal without utilizing a de-icing agent; strategies involving embedded heating coils have been widely used, and the use of conductive concrete mixed with carbon materials has been recently reviewed.

The utilization of carbon nanomaterials (with high chemical stability and unique mechanical, electrical, and thermal properties) in various industries has been recently reviewed [5–8]. Farcas et al., (2021) have studied the exothermic properties of concrete mixed with carbon nanotubes (CNT) [9], Wang et al., (2019) have investigated the use of CNT to minimize concrete corrosion [10], while Reddy et al., (2021) have analyzed CNT mixing to develop self-sensing concrete [11]. The self-sensing technology is a method for building a structural health monitoring system (SHMS) to detect damage occurring in infrastructure in real-time. For this system, the applicate method of carbon materials to concrete has been continuously studied. This technology detects changed electrical resistance when the structural member experiences the deflections of cracks [12]. In addition, other studies have analyzed the reduction in the high electrical resistance of concrete to improve its heating performance and prevent its freezing in winter and its utilization for various purposes such as de-icing [13–15]. In particular, the de-icing research intended to improve thermal conductivity performance with improved electrical conductivity when CNTs are mixed into the concrete mixture [16,17]. The technologies have been developed and studied to prevent the road from freezing by heating concrete by supplying electrical energy to the concrete with increased electrical and thermal conductivity. In addition, winter concrete technology development using carbon nanomaterial sheets has been conducted. This technology for preventing unexpected accidents in the winter is being investigated as a method of embedding carbon nanosheets in concrete and transferring the heat generated from these sheets to the concrete pavement surface [18].

Carbon materials exhibit high mechanical performance and conductivity. Research has been conducted to enhance concrete performance based on carbon material characteristics [19,20]. Various research focused on the increase in compressive and tensile strength, expecting that the CNT contributes to the bridging across the crack in the interfacial transition zone (ITZ). As a result, those studies could have found an increased compressive strength when the CNTs were used [21–23]. However, the opposite trends were observed in the research, and the compressive strength was decreased when the concentration of CNTs was increased. These decreased results were analyzed and it was found that the CNTs were in the shape of tangled lumps caused by van der Waals forces during the mixing process, and this established voids, which caused the strength to decrease [24–26]. Since the performance of concrete is exposed to various variables such as materials, material conditions, environmental conditions, and mechanical mixing methods, it is difficult to predict the performance without detailed controlled experiments. For UHPC, performance evaluation is more difficult because UHPC contains more mineral admixture and complicated mixing conditions than NSC. Therefore, it would be difficult to evaluate that UHPC technology mixed with carbon materials shows a consistent trend, and more research should be accumulated.

This study was conducted to find the electrical conductivity of UHPC, and the main objectives were as follows: (1) increase the curing efficiency by improving the conductivity of concrete; (2) develop conductive concrete to solve problems such as a bridge pavement freeze in winter. In general, UHPC requires high temperature curing at an early age to ensure high quality. When the thermal conductivity of concrete is improved, it could be expected to develop an efficient curing technology with optimization energy. Therefore, the performance 3 days after concrete casting was evaluated. The electrical conductivity was evaluated at 3 days of age to find the highest conductivity carbon material at the initial age. The compressive strength and tensile strength were assessed at the initial age, which was assumed to be the point at which demolding from the formwork occurred. In addition,
to evaluate suitability as a conductive concrete at a long-term age, these performance evaluations were also conducted at 28 days of age. For these reasons, this study attempted to evaluate the performance of UHPC mixed with carbon materials. In order to select the most suitable material among carbon materials for improving electrical conductivity for UHPC, performance was evaluated according to the mixing of carbon materials of various lengths. The influence of carbon materials in a UHPC matrix with a very dense microstructure was analyzed experimentally. Additionally, direct and alternating current methods for measuring conductivity were used to identify the optimum strategy for measuring the conductivity of concrete. This study could guide the development of a technology to impart electrical conductivity to UHPC.

2. Materials and Methods

2.1. Mix Proportions and Materials

The main components used in 120 MPa UHPC are listed in Table 1. The premixed binder included ordinary portland cement (OPC), silica fume, blast furnace slag, and filler. Filler with a size of less than 30 µm was used for beneficial purposes such as filling in the voids between cement particles, enhancing strength by contributing to the pozzolanic reaction during hydration, and increasing the fluidity of cement paste. Fine aggregate with a density of 2.62 g/cm³ and an average particle size of 0.5 mm was used. Steel fibers with a length of 13 mm and a diameter of 0.2 mm were added to improve the tensile performance of UHPC.

Table 1. The mix proportions of UHPC.

| W/B | Unit Weight (kg/m³) |
|-----|---------------------|
|     | Water | Premixed Binder | Fine Aggregate | Steel Fiber |
| 0.23| 210   | 1180            | 847            | 78         |

The experimental parameters are listed in Table 2. CNT dispersions were used in specimens 1 to 4, carbon fibers of millimeter and micrometer length were used in specimens 5 to 12, and graphite (GP) was used in specimens 13 to 15. Those carbon materials were mixed with the UHPC in mixing contents of 0.5, 1, 1.5, and 2%.

Table 2. Carbon-based materials and their contents.

| Specimens | Carbon Materials       | Volume Contents (%) | Specimens | Carbon Materials | Volume Contents (%) |
|-----------|------------------------|---------------------|-----------|------------------|---------------------|
| 1         | CNT                     | 0.5                 | 9         | Milled fiber     | 0.5                 |
| 2         | Carbon nanotube         | 1                   | 10        |                  | 1                   |
| 3         | dispersion              | 1.5                 | 11        | Expanded graphite| 1.5                 |
| 4         |                        | 2                   | 12        |                  | 2                   |
| 5         | Chopped fiber           | 0.5                 | 13        |                  | 0.5                 |
| 6         |                        | 1                   | 14        |                  | 1                   |
| 7         |                        | 1.5                 | 15        |                  | 1.5                 |
| 8         |                        | 2                   |           |                  |                     |

CNTs with 4–9 nm diameter and 10–200 µm length were used in a dispersion form with a solid fraction of 1%. Chopped fibers (CF) with 12 mm length and milled fibers (MF) with 7.2 µm diameter and 100 µm length were used. Expanded graphite with a particle size of d90 < 75 µm was used. Since expanded graphite contains numerous pores due to its production by the expansion of graphite on heating, it is well known that the material has outstanding conductivity [27,28]. However, when using expanded graphite, it was difficult to ensure concrete fluidity because of porosities, therefore, a specimen of 2.0%, which showed significantly poor fluidity performance, was excepted.

Compressive strength was measured at the ages of 3 and 28 days; three Ø100 specimens were cast for specimens of each age. The direct tensile strength was measured
The test specimens for direct current (DC) conductivity measurement were prepared using 15 variables, as shown in Figure 1. The specimen size was 60 mm × 60 mm × 160 mm, and four copper plates were installed at intervals of 20 mm. As shown in Figure 2, a digital multimeter was used to record the current and voltage while supplying DC power to both ends of the apparatus using a power supply; 15.0 V and 2.0 A were applied to each specimen. The DC power was supplied from both ends of the copper plates, and the voltage and current of the test specimen were measured from the two copper plates in the middle. The resistance of the test specimen was calculated by the ratio of voltage and current. Measurements were carried out thrice at the ages of 3 and 28 days and averaged.

![Figure 1. Specimens for the conductivity measurements.](image1)

**Figure 1.** Specimens for the conductivity measurements.

![Figure 2. The setups for conductivity measurements (Left: direct current, Right: alternating current).](image2)

**Figure 2.** The setups for conductivity measurements (Left: direct current, Right: alternating current).

### 2.3. Alternating Current Measurements

In the alternating current (AC) experiments, the impedance was measured by connecting an AC measuring device to a copper plate, as shown in Figure 2. The resistance of each specimen was determined by measuring the impedance (Z) in the frequency range of 20 Hz to 1 MHz.

Impedance is a value that interferes with the current flow when a voltage is applied to a circuit. The impedance is expressed as a complex number and as a ratio of the voltage and current of an AC circuit. In a DC circuit, the impedance and the resistance are the same, which is a case where the phase angle of the impedance is zero. The impedance in AC experiments can be expressed as the sum of the impedance values of the resistor (R), inductor (L), and capacitor (C), as shown in Equation (1). If the inductor and capacitor impedances are expressed in the unit of resistance (Ω), they can be correlated by Equation (2). These equations indicate that the resistance (R) is not affected by the frequency, the inductor (L) has a proportional relationship with the frequency, and the capacitor (C) has a fractional function, as shown in Figure 3. Consequently, the inductor impedance increases as the frequency increases, while the value of the capacitor impedance tends to decrease. The
impedance response of the concrete is represented by a semicircle. The point at which $\omega$ becomes zero indicates the resistance of the entire conductor model [29]. Therefore, for AC measurements, the point where the arc converges with the real part (or the imaginary part becomes zero) indicates the resistance ($R$) of concrete [30]. This point indicates the resistance of the entire conductor model during the AC measurement.

$$Z = R + L - C$$  \(1\)

$$Z = R + \omega L - \frac{1}{\omega C}$$  \(2\)

Figure 3. The complex impedance plane plot.

3. Results and Discussions

3.1. Compressive Strength

Figure 4 shows the compressive strengths at the age of 3 days. The specimens with 0.5% carbon content exhibited negligible differences in compressive strength; thus, 0.5% carbon material content did not affect the strength of concrete. The CNT dispersion did not influence the compressive strength of concrete; however, the compressive strength of the specimens containing chopped, milled fibers, and graphite decreased on increasing their content. The compressive strength difference between the 0.5% and 2.0% CF specimens was 17.1 MPa, between MF specimens it was 15.5 MPa, and between the 0.5% and 1.5% GP specimens it was 40.8 MPa. The 1.5% GP specimen exhibited the lowest compressive strength (32.7 MPa).

The CNT particles (nanometer size) did not significantly influence the cement, which has micrometer-sized particles, because of their comparatively smaller size. However, CF and MF, with micrometer and millimeter sizes, respectively, could affect the microstructure of UHPC. Furthermore, carbon fibers influence the UHPC process, forming a dense structure with a high compressive strength [31,32]. In UHPC, therefore, mixing a carbon material of a size greater than a micrometer could adversely affect its compressive strength.

Despite the nanometer size of expanded graphite, a significant decrease was observed in the compressive strength of the GP specimens. Expanded graphite contains numerous pores and generates a loosely formed concrete microstructure [33,34]. Moreover, the expanded graphite absorbed water through its pores, reducing the water available for concrete hydration, thereby decreasing its compressive strength. Therefore, increasing the mixing content of graphite significantly lowered the compressive strength of concrete.
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Figure 5 shows the compressive strengths for each variable at the age of 28 days; the compressive strengths exhibited similar trends at the ages of 3 and 28 days. For each variable, the compressive strength decreased as the mixing content of the carbon material increased; additionally, the strength decreased significantly when using expanded graphite.

According to the literature, the compressive strength of concrete increases by increasing the amount of carbon material [35,36]. However, normal strength concrete has a relatively loose structure compared to UHPC, and the presence of nanomaterials could increase the microstructure density. The 120 MPa UHPC exhibited negative effects on compressive strength enhancement due to its density characteristics. Furthermore, carbon nanomaterials absorb a significant amount of water over time [37]; therefore, the water availability for concrete hydration decreases with increasing carbon content, finally becoming insufficient. Consequently, despite the high performance of carbon materials, their addition compromises the mechanical performance of concrete. These phenomena could significantly affect UHPC due to its low W/B ratio.
3.2. Tensile Strength

Figure 6 shows the results of the tensile strength experiments. High tensile strengths were exhibited by the CNT, CF, and MF specimens at a 2% mixing content and the GP specimen at a mixing content of 1.5%. The tensile strength of fiber-reinforced concrete typically tends to increase during early age. This phenomenon could also be observed in the previous literature. When the age of concrete increased, since the bond strength between the concrete matrix and the fibers was more substantial, the increase in tensile strength occurred [38,39]. In this study, the tensile strength increased by at least 26.9% and up to 46.3% on aging in comparison with the results after 3 days, which was insufficiently hardened, and 28 days, when strength development was complete.

![Figure 6. Tensile strengths of the different specimens.](image)

Generally, the tensile strength of concrete is affected by the fiber type, mixing ratio, and dispersibility [40,41]. At the age of 3 days, the different types of carbon materials (except CF) exhibited similar tensile strengths. The compressive strengths of the MF and GP specimens were 77% and 45% of that of the CNT specimen, respectively, with negligible differences in their tensile strengths; this could be attributed to the predominant influence of steel fibers on the tensile performance of concrete [42]. At the age of 28 days, the specimen with graphite exhibited the lowest tensile strength. The CNT and MF specimens were significantly hardened as the concrete aged and exhibited similar specific tensile strengths as steel-fiber-reinforced concrete [38,43]; the GP specimen exhibited low tensile and compressive strength.

The specimen containing chopped fibers (with 12 mm length) exhibited approximately 1.5 to 1.6 times higher tensile strength than that of the other specimens. Thus, in agreement with previous reports, millimeter-sized carbon fibers contributed to the tensile strength of concrete [44,45]. Furthermore, fiber bridging after cracking in concrete increases its flexibility [46]. Here, steel and carbon fibers increased the tensile strength of the CF specimen, confirming an enhancement of the tensile performance of concrete by millimeter-sized carbon fibers.

3.3. Direct Current Measurements

The DC measurements are summarized in Table 3, with the measurements at the ages of 3 and 28 days shown in Figures 7 and 8, respectively. All the specimens exhibited significantly higher conductivity than that of commonly known concrete ($10^{-5}$ to $10^{-12}$ S/m) [47];
this could be due to the formation of a conductive path inside the concrete matrix by incorporating steel fibers into the UHPC formulation. The concrete conductivity on day 28 was significantly lower than that on day 3. Initially, the concrete showed relatively high conductivity due to the presence of residual water that did not contribute to hydration [48,49]; on aging, this moisture was gradually removed by residual hydration and drying shrinkage. Here, the electrical conductivity was reduced according to the difference in the internal water content, even if there were no changes in the material properties of the concrete.

Table 3. Direct current measurements with reduction rates according to the age of concrete.

| Carbon Materials | Concentration (%) | At the Age of 3 Days | At the Age of 28 Days | Reduction Rate (%) |
|------------------|-------------------|----------------------|----------------------|--------------------|
|                  | Resistance (Ω) | Conductivity (S/m × 10^{-3}) | Resistance (Ω) | Conductivity (S/m × 10^{-3}) | (A-B)/A |
| [CNT]            | 0.5              | 27,429 | 2.92 | 415,625 | 0.19 | 93.4% |
|                  | 1.0              | 15,985 | 5.00 | 213,636 | 0.37 | 92.5% |
|                  | 1.5              | 9242  | 8.66 | 133,000 | 0.60 | 93.1% |
|                  | 2.0              | 11,561 | 6.92 | 123,182 | 0.65 | 90.6% |
| [CF]             | 0.5              | 21,522 | 3.72 | 232,877 | 0.34 | 90.8% |
|                  | 1.0              | 21,613 | 3.70 | 233,333 | 0.34 | 90.7% |
|                  | 1.5              | 1788  | 44.75 | 14,297 | 5.60 | 87.5% |
|                  | 2.0              | 1947  | 41.08 | 7644  | 10.47 | 74.5% |
| [MF]             | 0.5              | 28,955 | 2.76 | 325,926 | 0.25 | 91.1% |
|                  | 1.0              | 24,792 | 3.23 | 298,551 | 0.27 | 91.7% |
|                  | 1.5              | 8880  | 9.01 | 77,857  | 1.03 | 88.6% |
|                  | 2.0              | 5681  | 14.08 | 87,500 | 0.91 | 93.5% |
| [GP]             | 0.5              | 8986  | 8.90 | 45,323  | 1.77 | 80.2% |
|                  | 1.0              | 4870  | 16.43 | 76,674 | 1.04 | 93.6% |
|                  | 1.5              | 15,423 | 5.19 | 116,889 | 0.68 | 86.8% |

Figure 7. Direct current measurements at the age of 3 days.

The CNT specimen with a mixing content of 1.5% exhibited the highest conductivity at 3 days. The conductivity increased up to a mixing content of 1.5% at 28 days, with a slight decrease in conductivity observed for the specimen with 2.0% mixing content. Although the optimal CNT dispersion content was 1.5%, the conductivity of this specimen was not significantly higher than that of the 0.5% specimen. The CNT dispersion contained a small amount of mixed CNTs; thus, the CNT specimen exhibited low conductivity.
The 12-mm-carbon-fiber specimen exhibited a high electrical conductivity; therefore, chopped fibers efficiently enhance the electrical conductivity of UHPC. Furthermore, the conductivity increased at mixing contents exceeding 1%; the millimeter-sized carbon fibers formed a conductive network in the concrete matrix. Additionally, a percolation zone was observed in the 1.5% specimen. This study could guide further research to develop a technology for imparting conductivity to UHPC, including the design of an optimized mix incorporating chopped fibers.

The MF specimen containing 100 µm carbon fibers exhibited lower conductivity than the specimen containing CF; therefore, micrometer-sized fibers formed a conductive network less efficiently than chopped fibers. However, a percolation zone was formed within the 1.5% mixing content specimen. Thus, micrometer-sized carbon materials could improve the conductivity of concrete with the assistance of other materials.

On mixing graphite, the concrete exhibited a higher conductivity than that of the other carbon materials at 0.5% and 1.0% mixing contents; however, the conductivity was low at a mixing content of 1.5% due to inadequate fluidity. The compressive and tensile strengths indicated that graphite absorbed a large amount of moisture in the concrete, forming voids; on increasing the incorporation rate of GP, the porosity increased, adversely affecting its mechanical performance and conductivity. However, since the GP specimen exhibited the highest conductivity at the lowest mixing content among all the materials analyzed, it should not be rejected without further investigation.

3.4. Alternating Current Measurements

As shown in Table 4, and Figures 9 and 10, the AC measurements exhibited a similar overall trend to the DC measurements. The conductivity of the CNT specimens increased on increasing the mixing content; however, it was difficult to increase the conductivity of concrete significantly. The CF specimen with a mixing content of 1.5% showed the highest conductivity, while the MF and CNT specimens exhibited similar conductivity. Furthermore, as the mixing content increased, the conductivities of the GP specimens decreased.

DC resistances are lower than AC resistances. Here, the AC conductivities were higher than the DC conductivities; the AC and DC results exhibited conductivity differences of up to 4.6 times. AC measurements are more reliable than DC measurements; the measured electrical resistance increases gradually in DC measurement methods due to polarization.

![Graph showing conductivity vs. concentration]
that occurs when the electrode moves to both ends of the apparatus [50,51]. Therefore, the measurement value changes over time, making it difficult to define a single resistance value. Contrarily, in the AC measurement method, the resistance of the specimen is defined from the impedance measured at a specific frequency, making it more reliable than the DC measurement method. Here, the DC and AC measurement methods showed a similar tendency, while the latter exhibited higher reliability; thus, the AC method is more suitable for measuring the electrical conductivity of concrete.

Table 4. Alternating current measurements with reduction rates according to the age of concrete.

| Carbon Materials | Concentration (%) | At the Age of 3 Days | At the Age of 28 Days | Reduction Rate (%) |
|------------------|-------------------|----------------------|----------------------|--------------------|
|                  | Impedance, Z      | Conductivity         | Impedance, Z         | Conductivity       | (ⓐ-ⓑ)/ⓐ          |
|                  | (S/m × 10⁻³)      | (S/m × 10⁻³)         | (S/m × 10⁻³)         | (S/m × 10⁻³)       |                    |
| [CNT]            | 0.5               | 10,818               | 7.4                  | 260,823            | 0.3                | 95.9%              |
|                  | 1.0               | 6884                 | 11.6                 | 129,849            | 0.6                | 94.7%              |
|                  | 1.5               | 4577                 | 17.5                 | 81,727             | 1.0                | 94.4%              |
|                  | 2.0               | 6278                 | 12.7                 | 80,992             | 1.0                | 92.2%              |
| [CF]             | 0.5               | 4668                 | 17.1                 | 74,373             | 1.1                | 93.7%              |
|                  | 1.0               | 5535                 | 14.5                 | 97,736             | 0.8                | 94.3%              |
|                  | 1.5               | 387                  | 20.9                 | 4005               | 20.0               | 90.3%              |
|                  | 2.0               | 453                  | 176.7                | 3376               | 23.7               | 86.6%              |
| [MF]             | 0.5               | 11,066               | 7.2                  | 196,317            | 0.4                | 94.4%              |
|                  | 1.0               | 10,967               | 7.3                  | 170,319            | 0.5                | 93.6%              |
|                  | 1.5               | 3224                 | 24.8                 | 38,819             | 2.1                | 91.7%              |
|                  | 2.0               | 2038                 | 39.3                 | 36,788             | 2.2                | 94.5%              |
| [GP]             | 0.5               | 4438                 | 18.0                 | 49,640             | 1.6                | 91.1%              |
|                  | 1.0               | 1673                 | 47.8                 | 27,999             | 2.9                | 94.0%              |
|                  | 1.5               | 3504                 | 22.8                 | 34,432             | 2.3                | 89.8%              |

Figure 9. Alternating current measurements at the age of 3 days.
Although the conductivity of the CNT and MF specimens was similar, while the specimen containing graphite exhibited the lowest conductivity. The specimen containing CF exhibited high conductivity owing to the bridging effects of steel fibers; this confirmed that millimeter-sized carbon fibers significantly influence the tensile strength of UHPC.

In summary, this study confirmed that the conductivity of UHPC can be enhanced by the mixing of millimeter-sized carbon fibers with steel fibers. Furthermore, chopped fibers exhibited a positive effect on the tensile strength of concrete. This study could guide future research on the conductivity enhancement and multi-functionalization of UHPC. Moreover, further research optimizing the length/shape of carbon fibers used and mixing contents could facilitate vast improvements in concrete technology.
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