Experimental study on smart concrete based on resistivity and damage monitoring

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Abstract. This paper investigates the correlation between strain and the electrical resistivity of smart concrete. During applying an axial compression load to the smart concrete, the electrical resistivity and the ultrasonic velocity penetrating the samples are collected. According to the piezoresistive characteristic, the damage index of the smart concrete can be determined with the electrical resistivity and the ultrasonic velocity. Eventually, it concludes that the smart concrete is more suitable to measure the damage of a concrete structure

1. Introduction
Concrete has become the most widely used building materials due to its excellent properties of high compressive strength and figurability. However, there are various defects, such as micro-voids and micro-cracks in the concrete, which seriously affect the durability of concrete. Because of this, structural health monitoring (SHM) for essential concrete structures is showing an increasing attraction [1, 2]. Nowadays, the common methods of SHM, including resistance strain gauges, fiber optic sensors and piezoresistive sensors, have a disadvantage of incompatibility with concrete [3]. Intrinsic self-sensing concrete (ISSC) [4] can avoid this drawback. Therefore, it is promising to develop smart concrete as a new method of SHM.

The self-sensing properties of concrete, also known as pressure-sensitive properties or piezoresistive, were originally investigated by adding carbon fibers into concrete [5]. The functional fillers that can improve the piezoresistive properties of concrete also include steel fiber [6], iron powder, carbon black, carbon nanotube [7], graphene [8], etc. Among them, graphene has attracted an increasing attention of scholars because it is a newly found material with an extremely great electric conductivity.

Sedaghat et al. [9] studied the effect of graphene content on the electrical resistivity of hydrated graphene-cement samples. It was found that the resistivity dramatically dropped with the increasing graphene content from 1%, 5% to 10% (w/w). Liu et al.’s [10] research showed that when the amount of graphene was 6.4% (weight ratio between graphene and cement), the percolation threshold was reached and the material exhibited relatively stable force-sensitive properties. It was also reported that Chu et al. [11] used smart concrete (containing carbon fibers) as the monitoring component to detect damage and the research achieved meaningful results that the damage monitoring with the piezoresistance of smart concrete was more informative than the traditional method of ultrasonic.
Although, researches on the piezoresistance properties of smart concrete have attracted increasing interests of scientists, few reports on smart concrete containing graphene was found. In this paper, the damage evolution of concrete containing graphene based on electrical resistivity is measured and compared with traditional method with ultrasonic.

2. Test materials and design

2.1. Materials Preparation

In this study, standard Type-42.5 cement (following Chinese code [12]) was used for preparing the concrete. The fine aggregate is standard river sand. The coarse aggregate is natural stone with a particle size between 5mm and 10mm. To facilitate the dispersion of graphene in an aqueous suspension and prevent them from agglomerating again, a polycarboxylate superplasticizer was selected as the surfactant in the mix design. The graphene produced by Sixth Element Inc. (Changzhou, China) was used. The main physical properties of graphene are listed in Table 1. The electrode used is a copper mesh with a diameter of 1mm.

| Factory Number  | In-plane diameter(μm) | Thickness (nm) | Specific surface area (m²/g) | Morphology       |
|-----------------|-----------------------|----------------|-------------------------------|------------------|
| Jcpg-99-1-105   | 5-15                  | 2-3            | 190                           | Black powder     |

For grasping the micro internal morphology of the graphene, a scanning electron microscopy (SEM) was employed in this study. Fig. 1 shows the topographical diagram. It can be seen that the surface of the graphene is pleated, and the size is basically consistent with the factory report.

![Graphene SEM diagram](image)

Figure 1. Graphene SEM diagram.

2.2. Mix proportion

In this experimental study, the mix proportion of the concrete is shown in Table 2. Due to that graphene are powder material having a high specific surface area, a hybrid treatment combining ultra-sonication and surfactant is a proper method to aid the dispersion of graphene in water. Prior to mixing concrete, graphene aqueous suspension was ultra-sonicated with the assistant of polycarboxylate superplasticizer for half an hour. The weighed cement, sand and coarse aggregate were mixed for 1 minute, then, the
graphene suspension was poured into the mixer and the stirring was kept for another 1 minute. According to the mixing proportion, the ratio of graphene to cement is 4.5%.

### Table 2. Mix proportion.

| Cement (g)       | Aggregate (g) | Sand (g)  | Water (g) | Graphene (g) | Polycarboxylate superplasticizer (g) |
|------------------|---------------|-----------|-----------|--------------|-------------------------------------|
| 459.8            | 1669.2        | 896.7     | 340.3     | 20.693       | 20.693                              |

2.3. Preparation for specimens

After mixing, the concrete was placed in a mold with dimensions $50 \times 50 \times 150 \text{mm}^3$. Four copper mesh electrodes were embedded at a distance of 25mm. The concrete samples were vibrated after filled the molds fully. The specimens were demolded 24 hours after air curing, and then placed in a curing room with a constant temperature of $25^\circ \text{C}$ and a constant humidity of 95% for 28 days. The resistance was measured in an absolutely dry condition after dried in an oven at $105 \pm 2 ^\circ \text{C}$ for 48 hours. After cooled to room temperature in a drying tank, the specimens were coated with epoxy resin to prevent the impact of moisture on the electrical properties.

3. Test method

The compressive test was carried out on a SANS-60T hydraulic testing machine, which is equipped with two extensometers that have an accuracy of 0.001 mm. The strain of the specimens can be calculated with the displacement of the extensometers.

The resistance was measured using a four-electrode method to eliminate the effects of contact resistances, including the contact resistance between the mesh electrode and the cement matrix and that between the meter and the mesh electrodes. The two outer electrodes were applied a constant current of 10mA and the inner two electrodes were used for measuring the voltage with a multi-meter (Victor 86E). The resistivity is calculated with equation (1):

$$\rho = \frac{RA}{L}$$  \hspace{1cm} (1)

where $R$ is the electrical resistance, $A$ is the cross-section of the samples, and $L$ is the length between two inner probes.

![Figure 2. Testing system.](image-url)
4. Results and discussion

4.1. Damage analysis
The classical damage theory defines the damage degree coefficient $D$ as shown in equation (2).

$$ D = 1 - \frac{A}{A_0} \quad (2) $$

where $A$ is the effective area and $A_0$ is the initial area.

Komlos [13] suggested equation (3) to express concrete damage by using the ultrasonic velocity penetrating concrete specimens perpendicularly to the loading direction.

$$ D = 1 - \left( \frac{V}{V_0} \right)^2 \quad (3) $$

where $V$ represents the effective ultrasonic velocity of the damaged concrete and $V_0$ is the ultrasonic velocity of the initial non-destructive concrete.

According to equation (1) and equation (2), the damage degree $D$ can be expressed by resistance, and the equation is shown as follows:

$$ D = 1 - \frac{R_0}{R} \quad (4) $$

where $R$ represents the resistance of the initial state and $R_0$ is the resistance of the damaged concrete.

4.2. Analysis of damage evolution process

(a) Sample -1
On the basis of the classical theory of damage, the damage indexes with different methods are calculated. In this paper, the damage evolution curves obtain by ultrasonic velocity and resistivity of concrete are plotted in Fig. 3, in which the strain-stress is also provided for comparison.

As shown in Fig. 3, the damage calculated with resistivity is negative in the elastic phase. This indicates that the micro-cracks become finer and the distance between conductive fillers becomes closer due to the external force. Therefore, there is no damage in the concrete. When the stress is close to the peak, the internal cracks of the concrete gradually develop, and the damage begins to accumulate.

**Figure 3.** Damage evolution process (a) (b) (c).
gradually. The overall damage degree is still small, so the bearing capacity of the test piece is still very high.

According to Fig. 3(a) and Fig. 3(b), the damage calculated with ultrasonic velocity increased to 1.0, which means the specimen is damaged completely. However, it still has the ability to carry a considerable external loading. This indicates that when a crack appears on the path of ultrasonic transmission, it can totally hinder the transmitting of ultrasonic pulse. Due to the above reason, the ultrasonic velocity drops to 0 and the damage calculated with ultrasonic velocity becomes 1.0.

The damage evolution obtained with resistivity still works comprehensively when the stress-strain curve develops at the drop section. Obviously, the value of damage calculated with resistivity is smaller than that of ultrasonic velocity. Additionally, the damage calculated with resistivity lags behind the real damage which may be due to the fact that cracks regarded as damage losing the ability to bear external loading can still pass electric current.

In Fig. 3(c), the damage calculated with ultrasonic velocity and that calculated with resistivity are all as small as around 0.2. For Sample-3, the results are quite different from Sample-1 and Sample-2. The reason is that the damage of Sample-3 occurred at one end of the sample, however, Sample-1 and Sample-2 breaks at the middle section. Conversely, Sample-3 crushed in the end portion of the specimen. Therefore, it is important to analyze the failure region while doing damage monitoring in concrete.

5. Conclusion
The ultrasonic velocity can reflect the damage evolution of the smart concrete. However, the ultrasonic velocity will vanish when cracks hinder the path along which the ultrasonic velocity transmit. Therefore, the damage calculated with ultrasonic velocity quickly becomes 1.0.

The damage calculated with resistivity can describe the evolution of damage completely which includes an elastic phase without any damage, a moderate damage developing stage, an expedition after the force peak and a relaxed stage when the main cracks occurs. The value of damage calculated with resistivity only increases to 0.8 approximately. Additionally, the damage calculated with resistivity lags behind the real damage which may be due to the fact that cracks regarded as damage losing the ability to bear external loading can still pass current by indistinct contact.

For the specimen whose failure region is not in the area where the resistivity is measured, the value of damage calculated with resistivity is small, which can only rise to approximate 0.2 owing to only small damage occurred at this region.

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