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# A study on mechanical and pressure-sensitive properties of cement mortar with nanophase materials

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**Abstract**

The mechanical properties and self-monitoring capability of cement mortar containing nano-$SiO_2$ or nano-$Fe_2O_3$ were experimentally studied and compared with that of plain cement paste. The results showed that the compressive and flexural strengths measured at the 28th day of cement mortar containing nano-$SiO_2$ or nano-$Fe_2O_3$ were both higher than that of plain cement mortar with the same water–binder ratio (w/b). Furthermore, the self-monitoring capability of cement mortar with nano-$Fe_2O_3$ is also presented in this paper.


*Keywords:* Composite; Mortar; Electrical properties; Mechanical properties

## 1. Introduction

Health monitoring of structures by embedded or attached sensors has been gaining increasing interest and is more effective to guarantee structural safety in service. However, smart concrete, which can sense its own strain and damage, is more attractive due to its strong mechanical properties and self-monitoring characteristics. Smart concrete with short carbon fiber has been systematically developed [1,2]. The advantages of intrinsically smart concrete in contrast to smart sensing materials such as optical fibers, piezoelectric sensors, etc. are low cost, great durability, absence of mechanical property degradation due to the embedding of sensors, etc. [1].

In consideration of nanoparticles with many novel properties and significant improvement on some properties of materials mixed with nanoparticles such as nanophase ceramic, etc. [3,4], cement mortars mixed with nano-$SiO_2$ or nano-$Fe_2O_3$ were proposed and fabricated, and their mechanical properties and self-sensing of strain were experimentally studied in this paper. The results indicated that cement mortar with nano-$Fe_2O_3$ could sense its own compressive stress in the elastic and inelastic regimes because the volume electric resistance of cement mortar with nano-$Fe_2O_3$ could change with the applied loading. This property is valuable for structure health monitoring in real time. Furthermore, the compressive strength of cement mortar with nanoparticles was also simultaneously improved.

## 2. Experimental methods

### 2.1. Materials and specimens

Cement mortar is composed of small grains of hydrated calcium silicate gels and large crystals of hydrated products, with nanosized individual pores and capillary pores (structural defects) distributed among them. There should be room for nanoparticles to improve the properties of plain cement mortar. $Fe_2O_3$ nanoparticles in the amounts of 3%, 5% and 10% by weight of binder (the sum of cement and nanoparticles) were used, and the same amount for $SiO_2$ nanoparticles. Nano-$SiO_2$ was obtained from Zhoushan Mingri Nanophase Material Co. (Zhejiang, China); its properties are shown in Table 1. The mean grain diameter of the nano-$Fe_2O_3$ is 30 nm; nano-$Fe_2O_3$ was obtained from Fangyuan Nanophase Material Institute (Anhui, China).

The cement used was Portland cement (P.O32.5). NF water-reducing agent (a sulfonate surfactant, China) and UNF water-reducing agent (one kind of β-naphthalene sulfonic acid and formaldehyde condensates) were used to

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Table 1
The properties of nano-$SiO_2$

| Item | Diameter (nm) | Surface–volume ratio ($m^2/g$) | Density ($g/cm^3$) | Purity (%) |
|---|---|---|---|---|
| Target | $15 \pm 5$ | $160 \pm 20$ | < 0.15 | >99.9 |

aid the nanoparticles' dispersion, with 0.25 wt.% nano-$Fe_2O_3$ and 0.5 wt.% nano-$SiO_2$, respectively (Table 2). The defoamer, tributyl phosphate (made in China), was used to decrease the amount of air bubbles. Fine aggregate (natural sand) only was used.

The water–binder (w/b) ratio was 0.5, and the binder content was taken as the sum of cement and nanoparticles. Ten compositions, as listed in Table 2, were studied. The compositions A-8 to A-10 were used to study the self-stress sensing properties. The amount of the cement was larger than the mixtures A-1–A-7 to obtain good sensing ability by increasing the absolute amount of the $Fe_2O_3$ nanoparticles and keeping the same ratio of the cement and nanoparticles.

### 2.2. Testing procedure

Defoamer and NF water-reducing agent (if applicable) were dissolved in water, and then the nanoparticles were added and stirred at high speed for 2 min. This mixture and the cement were mixed in a mortar mixer at a low speed for 1 min, then the mixture and sand were mixed in the same mixer at a low speed for 1.5 min. Finally, the mortar was poured into oiled molds to form cubes of size $40 \times 40 \times 40$ mm for all mix proportions, in which compositions A-1–A-7 were used for compressive testing and A-8–A-10 for self-monitoring testing, and prisms of size $40 \times 40 \times 160$ mm, in which compositions A-1–A-3, A5–A6 and A-8 were used for flexural testing. Note that flexural strength test was not conducted for mixtures A-4 and A-7 because it was found that nanoparticles were more difficult to uniformly disperse when the contents were large. After pouring, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were demolded after 24 h and then cured in air at room temperature for 7 and 28 days, respectively.

Compressive testing was performed on a side of each cubic specimen to obtain the compressive strength. Compressive testing under force control was performed using a hydraulic mechanical testing system (MTS) with 120-kN maximum loading capacity. Flexural testing was conducted in accordance with GB/T 17671-1999 (standard test method for strength of hydraulic cement mortar of China).

Another compressive testing to measure the electric resistance of the specimens was performed on a side of each cubic specimen. As an initial study, the scheme of monotonically static loading up to specimen failure was arranged. DC electric resistance measurement was made in the stress axis, using a two-probe method, in which aluminum foil bonded on the parallel opposite surface with conductive gel (a compound of black carbon and epoxy resin) served as electric contacts. A FLUKE 8842A multimeter was used to measure the volume resistance of these specimens.

Table 2
Mix proportions of the specimens

| Mixture no. | W/b | Mix proportions ($kg/m^3$) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Water | Cement | Sand | Nano-$SiO_2$ | Nano-$Fe_2O_3$ | NF | Defoamer |
| A-1 | 0.5 | 230 | 460 | 1380 | – | – | – | – |
| A-2 | 0.5 | 230 | 446.2 | 1380 | – | 13.8 | 3.5 | 0.5 |
| A-3 | 0.5 | 230 | 437 | 1380 | – | 23 | 5.8 | 0.5 |
| A-4 | 0.5 | 230 | 414 | 1380 | – | 46 | 11.5 | 0.5 |
| A-5 | 0.5 | 230 | 446.2 | 1380 | 13.8 | – | 6.9 | 0.5 |
| A-6 | 0.5 | 230 | 437 | 1380 | 23 | – | 11.2 | 0.5 |
| A-7 | 0.5 | 230 | 414 | 1380 | 46 | – | 23 | 0.5 |
| **Mixture no.** | **W/b** | **Mix proportion ($kg/m^3$)** | | | | | | |
| | | Water | Cement | Sand | Nano-$SiO_2$ | Nano-$Fe_2O_3$ | UNF | Defoamer |
| A-8 | 0.5 | 255 | 510 | 1275 | – | – | – | – |
| A-9 | 0.5 | 255 | 494.7 | 1275 | – | 15.3 | 3.8 | 0.5 |
| A-10 | 0.5 | 255 | 484.5 | 1275 | – | 25.5 | 6.4 | 0.5 |

## 3. Results and discussion

### 3.1. Compressive and flexural strengths

Table 3 shows the compressive strengths of all specimens. It can be seen that the compressive strengths of the specimens with mixtures A-2, A-3 and A-4 (cement mortar with nano-$Fe_2O_3$) at the 7th and 28th day were all higher than that of a plain cement mortar with the same w/b. As for the strength at the 28th day, the effectiveness of the nano-$Fe_2O_3$ in increasing strength increased in the order A-4 < A-3 < A-2 (with the decreases on the nano-$Fe_2O_3$ volume fraction). Furthermore, the strength enhancement for A-4 at the 7th day is evidently higher than that at the 28th day. These results indicated that the appropriate content of nano-$Fe_2O_3$ for reinforcing cement mortar purposes should be less

Table 3
Compressive strengths of specimens

| Mixture no. | Compressive strength at the 7th day | | Compressive strength at the 28th day | |
|---|---|---|---|---|
| | Target (MPa) | Enhanced extent (%) | Target (MPa) | Enhanced extent (%) |
| A-1 | 17.6 | 0 | 28.9 | 0 |
| A-2 | 21.4 | 22.7 | 36.4 | 26.0 |
| A-3 | 20.6 | 16.7 | 33.1 | 14.5 |
| A-4 | 21.1 | 20.0 | 30.0 | 3.7 |
| A-5 | 18.6 | 5.7 | 32.9 | 13.8 |
| A-6 | 21.3 | 20.1 | 33.8 | 17.0 |
| A-7 | 21.3 | 20.1 | 36.4 | 26.0 |

Table 4
Flexural strengths of specimens at the 28th day

| Mixture no. | A-1 | A-2 | A-3 | A-5 | A-6 |
|---|---|---|---|---|---|
| Flexural strength (MPa) | 4.90 | 5.77 | 6.04 | 5.84 | 6.23 |
| Enhanced extent (%) | 0 | 17.76 | 23.26 | 19.18 | 27.14 |

than 10% (by weight of cement) under the present dispersion condition.

The compressive strengths of the specimens with mixtures A-5, A-6 and A-7 (cement mortar with nano-$SiO_2$) were all higher than that of plain cement mortar. The effectiveness of the nano-$SiO_2$ in increasing strength increased in the order A-5 < A-6 < A-7 (with the increases on the nano-$SiO_2$ volume fraction).

The origin of the ability to increase the compressive strength can be interpreted as follows. When a small amount of the nanoparticles is uniformly dispersed in the cement paste, the nanoparticles act as a nucleus to tightly bond with cement hydrate and further promote cement hydration due to their high activity, which is favorable for the strength of cement mortar. The second reason is that the nanoparticles among the hydrate products will prevent crystals from growing, such as $Ca(OH)_2$ and AFm, and such fine crystals are also favorable for the strength of cement paste [5,6]. The third reason is that the nanoparticles fill the cement pores, thus increasing the strength, as silica fume does. However, when the contents of nano-$Fe_2O_3$ are too large, nano-$Fe_2O_3$ cannot be well dispersed to form weak zones by the aggregating nano-$Fe_2O_3$ and the homogenous hydrate microstructure cannot be formed. Nano-$SiO_2$ can participate in the hydration process to generate C-S-H through reaction with $Ca(OH)_2$. The small amount of aggregating nano-$SiO_2$ is not a weak zone, so the strength of cement mortar increases with increasing content of nano-$SiO_2$ even when the small amount of nano-$SiO_2$ is not well dispersed.

As shown in Table 4, the flexural strengths of specimens A-2, A-3, A-5 and A-6 were all higher than that of plain cement mortar, which indicated that nanoparticles were also efficient for improving the toughness of cement mortar.

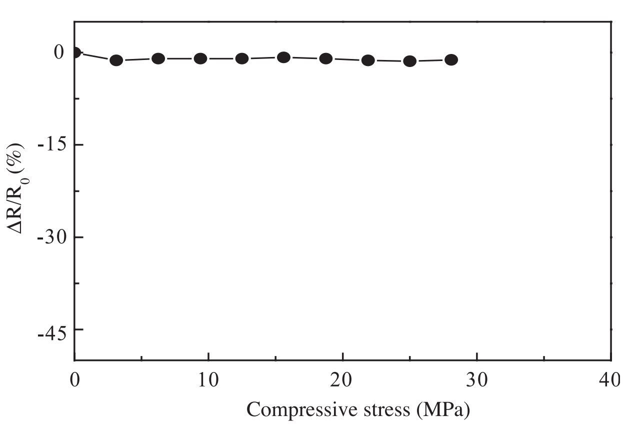


Fig. 1. Stress-sensing property of composition A-8.

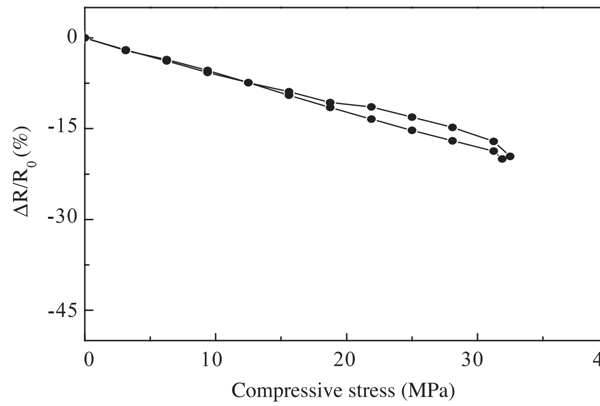


Fig. 2. Stress-sensing property of composition A-9.

### 3.2. Stress-sensing properties

The stress-sensing properties of A-8–A-10 compositions are also investigated in this study. The results show that their initial resistivities change slightly from $144 \times 10^3$ to $180 \times 10^3$ Ω cm, which indicate that nano-$Fe_2O_3$ particles do not decrease the resistivity of cement mortar. Such property is beneficial to the durability of reinforced concrete structures. Furthermore, the fractional change in resistance is the self-diagnostic criterion, not the resistivity itself.

Fig. 1 shows the fractional change of resistance ($\Delta R/R_0$) along the stress direction versus stress with compressive loading of a plain cement mortar. It shows that the $\Delta R/R_0$ of the plain cement mortar slightly changed with different compressive loadings. The plain mortar is poor in monitoring its stress.

Figs. 2 and 3 also depict the variations of the resistance $\Delta R/R_0$ versus stress for A-9 and A-10 compositions with 3% and 5% nano-$Fe_2O_3$, respectively, in the monotonically compressive loading test (up to failure). The measured direction of the resistance is also along the stress direction. The figures show that the resistance $\Delta R/R_0$ linearly decreased with the increase of the compressive loading and the

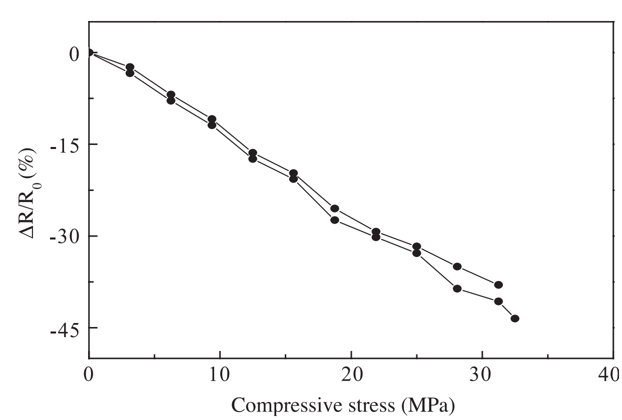


Fig. 3. Sress-sensing property of composition A-10.

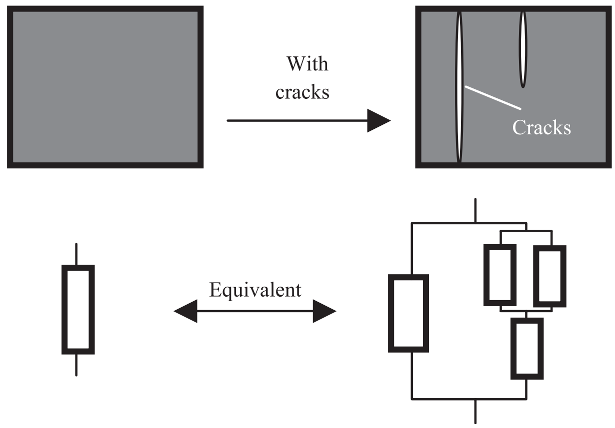


Fig. 4. Equivalent DC circuit model of the specimen with and without cracks.

resistance $\Delta R/R_0$ of specimen A-10 decreased more sharply than A-9. The results show that the more nano-$Fe_2O_3$ the mortar contained, the more sensitive the mortar is to monitor stress. Compared with that of the plain cement mortar, the volume resistance of cement with 3% and 5% nano-$Fe_2O_3$ decreases about 20% and 45%, respectively.

It is also shown from the figures that the fractional change of electric resistance gradually decreased even when the applied loading increased enough to expand the cracks of the specimens, which is different from that of the carbon fiber concrete. This is because the cracks of the specimens mainly grow along the compressive loading axis, and the transverse cracks perpendicular to the stress axis are very few. A simple equivalent DC circuit with a series–parallel array of electrical resistors, as depicted in Fig. 4, is used to model the electrical characteristics of the specimen with cracks parallel to the loading direction to analyze the influence on the fractional change of electric resistance due to cracks. Assuming the resistance of the specimen without cracks is $R_0$, we can easily infer that the electric resistance of the specimen with parallel cracks is also $R_0$, which shows that the longitudinal cracks of the specimen have no influence on the electric resistance.

Nano-$Fe_2O_3$ is a type of semiconducting material that absorbs energy, and the energy gap of nanoparticles is narrowed down when compressive force is applied to the mortar specimen, which makes the electrons of nanoparticles transit easily to enhance the electrical conductivity of nanoparticles. Another reason is that with the application of the compressive force, the nanoparticles are also compelled to approach each other, which makes the tunneling current flows become more intense. Therefore, the electrical resistivity of the cement mortar decreases gradually [7].

## 4. Conclusions

The compressive and flexural strengths of cement mortar with nano-$SiO_2$ or nano-$Fe_2O_3$ were both higher than that of plain cement mortar with the same w/b, indicating that nanoparticles are valuable for reinforcing cement mortar.

Besides the enhancement on the strengths, the fractional change in resistance $\Delta R/R_0$ linearly decreases with increasing compressive loading and the change is more sharply with increasing the content of nano-$Fe_2O_3$, indicating that the cement mortar with nano-$Fe_2O_3$ is better in the ability to monitor stress itself and the self-diagnostic ability increases with increasing content of nano-$Fe_2O_3$ by mass of binder, so the cement mortar with nano-$Fe_2O_3$ is a smart structural material that can sense its own stress.

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