

Preparation, Properties, and Microstructure of Graphite Powder-Containing Conductive Concrete

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Conductive concrete not only retains the advantages of ordinary concrete but also possesses high electrical conductivity. It can be applied to snow and ice control on the roads. In preparing the conductive concrete, sand as the conductive fine aggregate was replaced with graphite powder. Its properties and microstructure were also investigated. The conductive concrete strength is shown to decrease with a graphite powder ratio. The conductive concrete resistivity goes down with the powder fineness and content; the temperature grows after electrification, and the concrete exhibits a high heating effect. Graphite powder exerts little influence on the hydration products of the concrete. With an increase in the content and fineness of graphite powder, its filling efficiency becomes rather helpful to form the conductive path.

Keywords: conductive concrete, graphite powder, strength, conductivity, microstructure.

Introduction. Conductive concrete containing conductive medium has good conductive property whilst retaining the advantages of ordinary concrete. It has broad potential for applications in many fields [1], such as reducing metal-to-screen radio interference, melting snow and ice on the road, nondestructive inspection of concrete structures, and detection of microcracks in large structures. But, the current research of conductive concrete is difficult to meet the requirements of both mechanical and conductive properties, and the cost of conductive concrete is generally high.

Graphite powder is an inorganic material with high electrical and thermal conductivity. Therefore, it is often used as a conductive material in industrial products [2]. In 2001, a new type of conductive concrete was prepared by using graphite products and steel fiber [3]. In 2001, conductive concrete was successfully applied to the bridge deck of Roca Spur bridge in Nebraska Prefecture, and better deicing results were achieved as a result of its thermoelectric effect [4]. The electrical resistance decreases with increasing graphite content. When the content of graphite is below a certain value, the resistivity of the concrete decreases slowly. When a critical value is reached, the resistivity drops rapidly [5]. A network with good conductivity can only be formed in the concrete when a higher fraction of graphite is used [6]. When the graphite content reaches the percolation threshold, the resistivity decreases exponentially [7]. Conductive concrete has a conductivity seepage phenomenon. When the volume fraction of the conductive phase reaches the percolation threshold, the resistivity decreases sharply; and when the volume content of the conductive material exceeds the critical value, the resistivity decreases gradually [8]. However, the water demand of graphite powder is very high, and the water consumption for the concrete mixture is greatly increased. The strength of concrete decreases rapidly with increasing graphite powder dosage [9]. It means that graphite can improve the conductivity of concrete but reduce the strength. The current research mainly focuses on the conductive properties and strength of graphite powder conductive concrete. It is rarely involved in the electrothermal benefits and microscopic characteristics.

In this work, graphite powder was used to prepare conductive concrete, and the influence of the fineness and content of the graphite powder on the properties and microstructure of the conductive concrete were investigated.

1. **Experimental.** The experimental conductive concrete materials are Yadong P.O42.5 ordinary Portland cement produced in Hubei Yadong Cement Plant, silica fume, 5–15 mm coarse aggregate, river sand, graphite powder, GK-3000 polycarboxylate superplasticizer and tap water. Among them, the graphite powder is the conductive material, which is two kinds of flake graphite powder produced by Qingdao Rocksea Carbon Materials Co. Ltd. The particle size is 325 mesh (G325) and 5000 mesh (G5000). The main properties are shown in Table 1.

Table 1

Test Results of Graphite Powder

Sample	Bulk density (g/cm ³)	Particle size (μm)	Carbon content (%)	Water content (%)	Iron content (%)	Expansion degree (times)
G325	0.82	44.00	99.12	0.02	0.03	1–2
G5000	0.48	2.86	99.93	0.01	0.02	1–2

Table 2

Mix Proportion of Conductive Concrete (kg/m³)

Sample	Cement	Silica fume	Sand	Gravel	Water	Water cement ratio	Graphite powder content (%)	Graphite powder	Super-plasticizer (%)
G325–0	500	100	760	1120	270.00	0.45	0	0	0
G325–5	500	100	722	1120	266.77	0.45	5	38	0.7
G325–10	500	100	684	1120	325.38	0.55	10	76	1.0
G325–15	500	100	646	1120	323.07	0.55	15	114	1.5
G325–20	500	100	608	1120	380.76	0.65	20	152	2.0
G5000–0	500	100	760	1120	270.00	0.45	0	0	0
G5000–5	500	100	722	1120	325.38	0.55	5	38	1.0
G5000–10	500	100	684	1120	324.46	0.55	10	76	1.2
G5000–15	500	100	646	1120	336.46	0.57	15	114	1.2
G5000–20	500	100	608	1120	347.07	0.59	20	152	1.5

Note. Graphite powder is used to replace sand as conductive fine aggregate, and the calculation of graphite content is based on the total mass of fine aggregate.

Two series of conductive concrete mixture ratios were designed. The G325 and G5000 graphite powders are used as the conductive materials to prepare the conductive concrete, as shown in Table 2. The preparation process is similar to the ordinary concrete. According to the mix proportion, the cementitious materials, water and superplasticizer are added and mixed 2 min to form paste; and then, sand, gravel and graphite powder are added and mixed 5 min and form the fresh concrete with good workability. After the workability of the fresh concrete is tested, the concrete specimen is formed and placed in a standard

curing room until the stipulated ages. The strength and conductivity are tested. The conductivity test in this paper uses an embedded electrode, which involves a carbon rod inserted into the concrete. The concrete is poured into a mold, the carbon rods are inserted into the concrete on two opposite sides with 10 mm between the electrodes on each side, and 15 mm of the carbon block's top surface is exposed. Wires are connected, then a multimeter is used to measure the electrical resistivity. The slump of the concrete mixtures prepared as detailed in Table 2 can be controlled between 190 and 225 mm and the workability is good, which meets the construction requirements.

2. Results and Discussion.

2.1. **Strength.** The specimen size is a 100-mm concrete cube. All the specimens are cured under standard conditions. After curing for 14, 28, 90, and 180 days, the compressive strength and splitting tensile strength are measured as shown in Fig. 1. It can be seen that, both in the G325 and G5000 groups, with increasing graphite powder content, the strength of the concrete decreases. The initial decline in strength is large, and then decreases with age. The strength increases rapidly with age, and the growth rate tends to be smooth after 90 days.

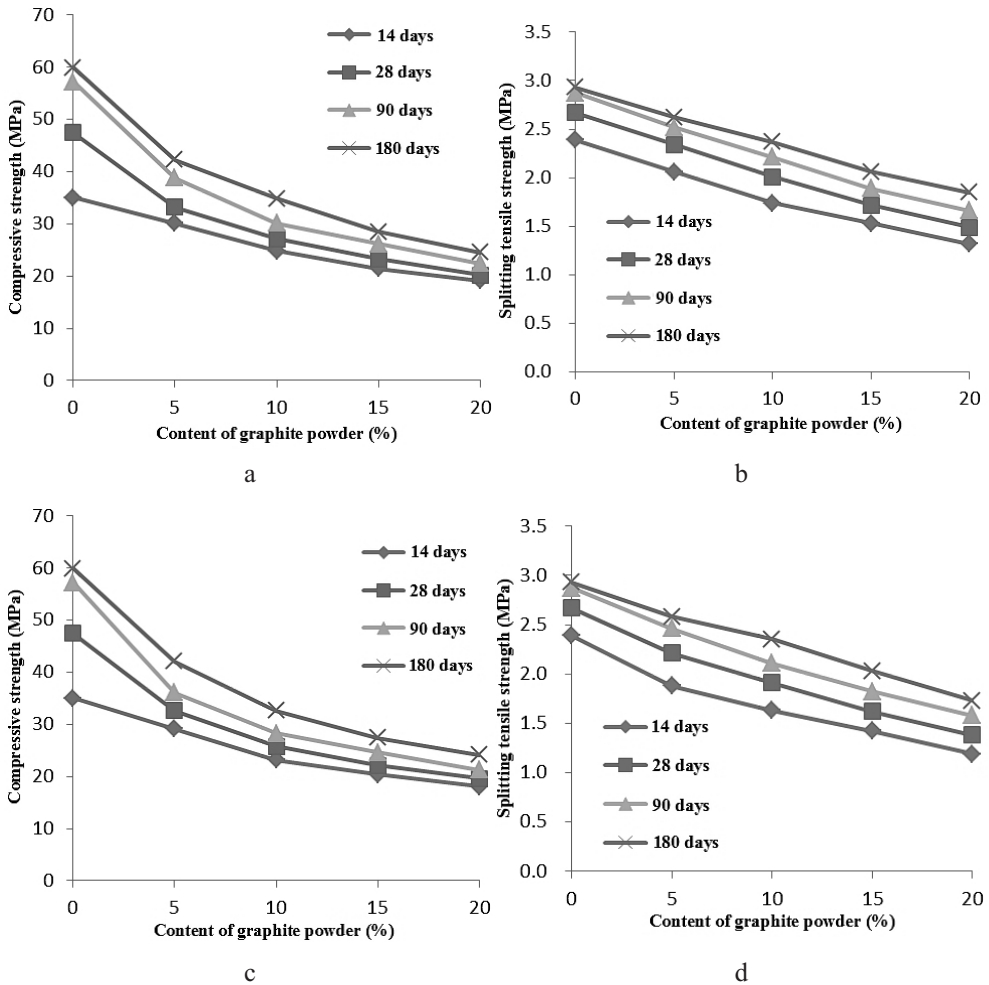


Fig. 1. Compressive strength and splitting tensile strength of conductive concrete: compressive (a) and splitting tensile (b) strengths for G325 group; compressive (c) and splitting tensile (d) strengths for G5000 group.

There are three main reasons to explain why the strength of concrete decreases with increasing graphite content. First, because the friction coefficient of graphite is less than 0.1, it has good lubricity. When the graphite content is high, the contact area between the graphite particles increases and the friction resistance is reduced, so the concrete strength decreases [10]. Second, due to the different hydrophilicity of graphite and cement, the interface bonding force produced during the mixing process is low, and decreases with the increase of graphite content, thus reducing the strength [11]. Third, owing to the large water demand of graphite, the mixing water consumption of concrete increases with increasing graphite content, and the water to cement ratio increases accordingly, which leads to the strength reduction [12]. Graphite powder has a great adverse effect on the strength. Therefore, it can be used in the concrete structure only after special treatment.

2.2. **Electric Conductivity.** Figures 2 and 3 show the relationship between the resistivity and graphite powder content of specimens in the G325 and G5000 groups. The resistivity of the conductive concrete decreases remarkably with increasing graphite powder content. The resistivity of the G5000 group is smaller than that of the G325 group, thus the conductivity increases remarkably with increasing the fineness of graphite powder.

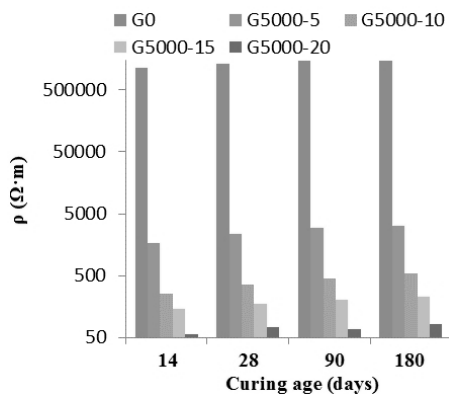
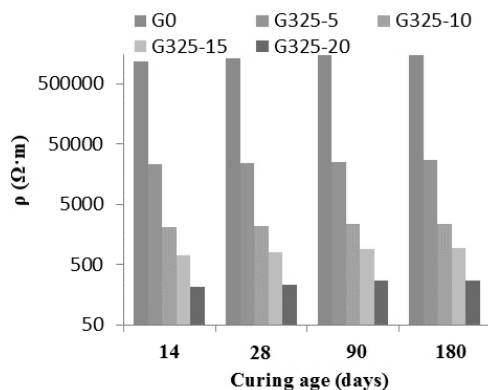


Fig. 2. The electric resistivity of G325 group. Fig. 3. The electric resistivity of G5000 group.

The conduction is attributed to the large number of graphite particles connected in the matrix and forms a conductive path for the ions and electrons in the base material. When the graphite powder content is low, the number of conductive particles is too low to form a conductive chain, and the conductivity is poor. With a higher content of graphite powder, the conductive particles form an interconnected conductive network in the matrix, which decreases the resistivity of the specimen and improves the conductive effect. The smaller particle size provides more conductive particles with the same amount, so the conductive network and conductive effect are improved.

Considering the safety of the test, the heating effect and uniformity of the sample are optimum when using 24 V AC. Test blocks are prepared under standard conditions and cured for 28 days. The top, bottom, and four sides were covered with high-density foam board and then in plastic wrap, which has an insulating effect. The central temperature at the surface of the test block is measured every 30 min for 6 hours by using a GM320 infrared thermometer. The results are shown in Fig. 4. The control sample shows almost no change for the temperature. But, the temperature of all the samples containing graphite powder increases with increasing electrifying time. The temperature of the energized specimen increases linearly and quickly, but then the temperature increase rate tends to be slow and has very small fluctuation. The greater the content and fineness of graphite powder, the faster the temperature increases. With the same graphite content, the heating effect for the G5000 group is higher than that for the G325 group.

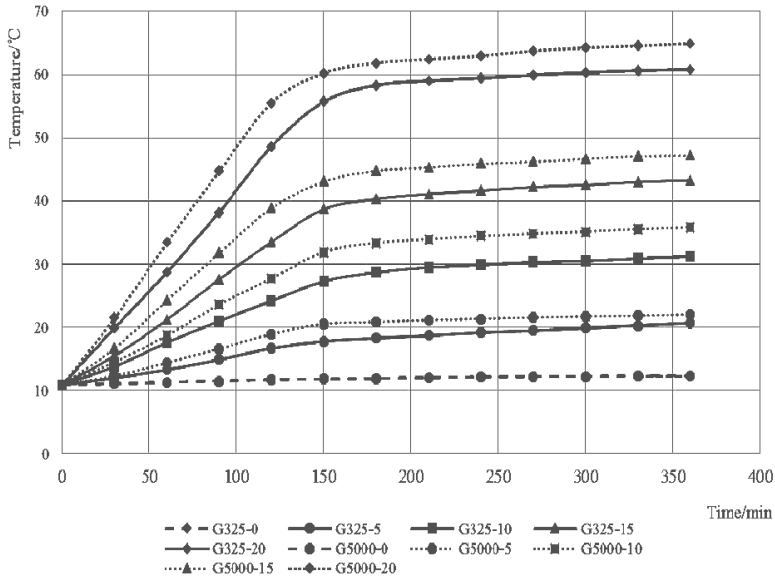
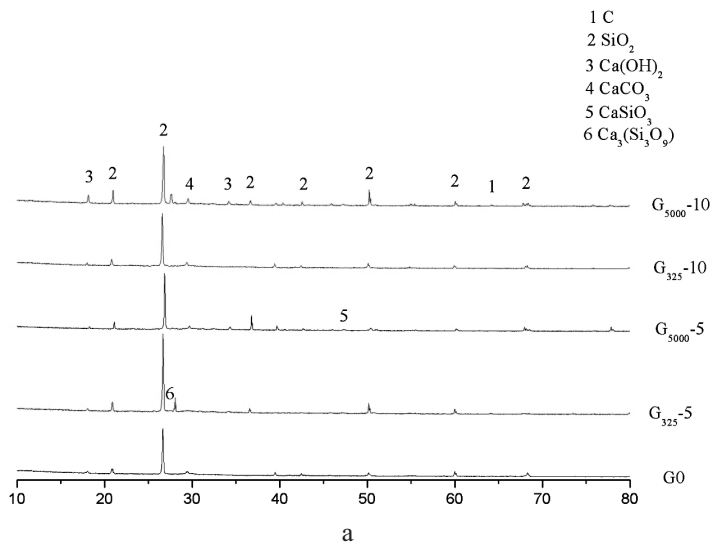


Fig. 4. The temperature development curve of concrete specimen with the electric time.

2.3. Microstructure. Figure 5 shows the XRD results of the concrete paste. The XRD spectra of the G325 group is similar to that of G5000 group with the same graphite powder dosage because they differ in terms of graphite particle size but have the same composition. The main crystalline phase is calcium hydroxide, and there are little the other crystalline phases. The SiO_2 diffraction peak of the sand is very strong, so the diffraction peak of the hydration products is relatively weak. The calcium hydroxide diffraction peak of the sample cured at 90 days is slightly lower than that for cured at 28 days because the hydrated calcium hydroxide and silica fume generate a pozzolanic reaction, and the calcium hydroxide consumption exceeds the amount of hydration of the later clinker. The chemical properties of graphite are stable, so the particle size and content of the graphite powder have little influence on the type and amount of hydration products.



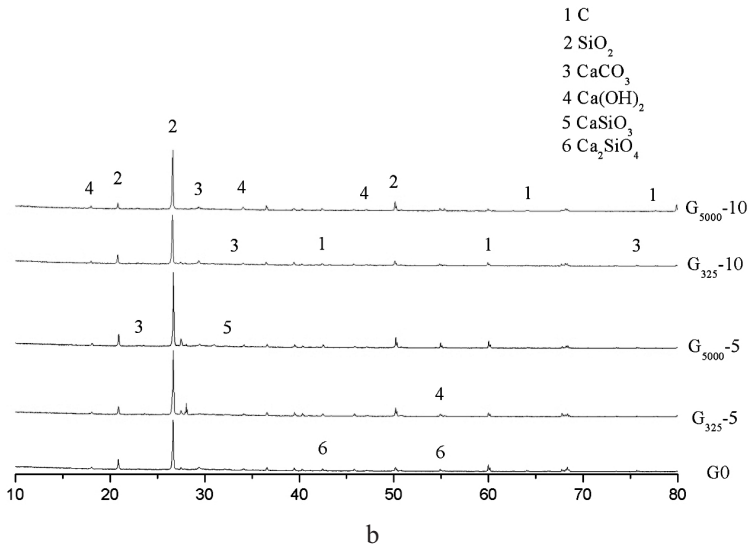
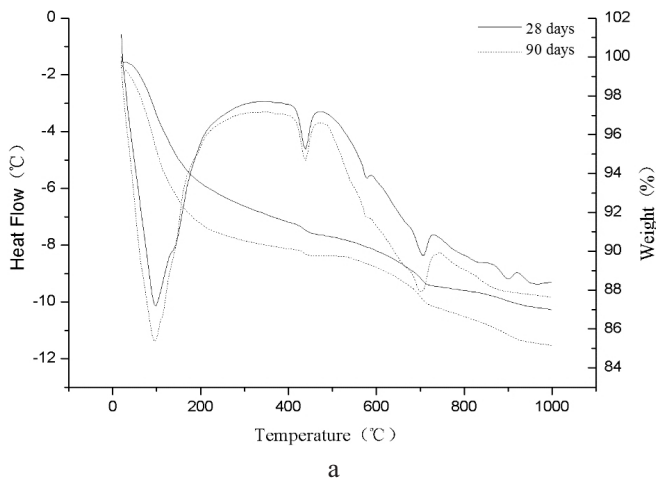
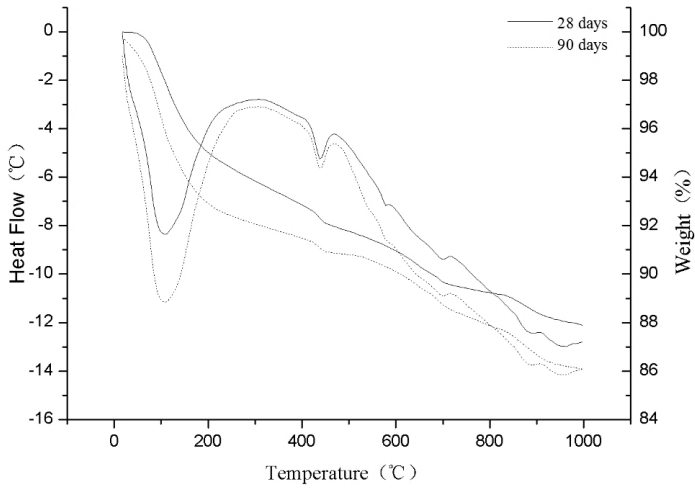


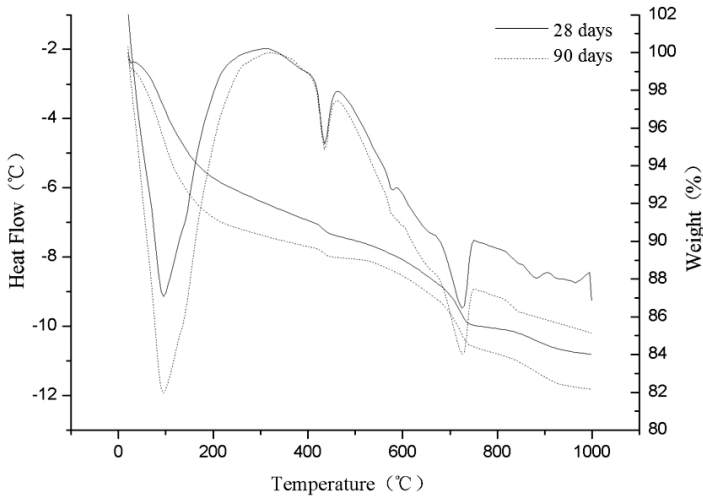
Fig. 5. XRD test results of graphite powder concrete: (a) 28 days; (b) 90 days.

Figure 6 shows the TG-DTA curves of the conductive concrete samples. All the samples exhibit an endothermic peak and weight change around 95°C, which may be caused by the crystallization water removed from ettringite and calcium silicate hydrate, and evaporation of free water. The curve shows an endothermic peak at about 445°C, which is mainly caused by dehydration and decomposition of calcium hydroxide and calcium silicate hydrate. The endothermic peak around 577°C is mainly owing to the endothermic conversion of silica from β quartz to α quartz, and there is also a weightless phenomenon in the system. The endothermic peak around 714°C is mainly caused by the decomposition of calcium carbonate, accompanied by the dehydration of hydrated silicate. The hydration products of the conductive concrete paste are similar to the ordinary concrete, which are mainly calcium silicate hydrate and calcium hydroxide. From the thermogravimetric curve, it can be seen that the calcium hydroxide content decreases slightly with age, which is consistent with the XRD result. Although more calcium hydroxide produces during the later hydration stage, most of the calcium hydroxide is consumed in the second hydration reaction, so the sample strength increases with the curing age.

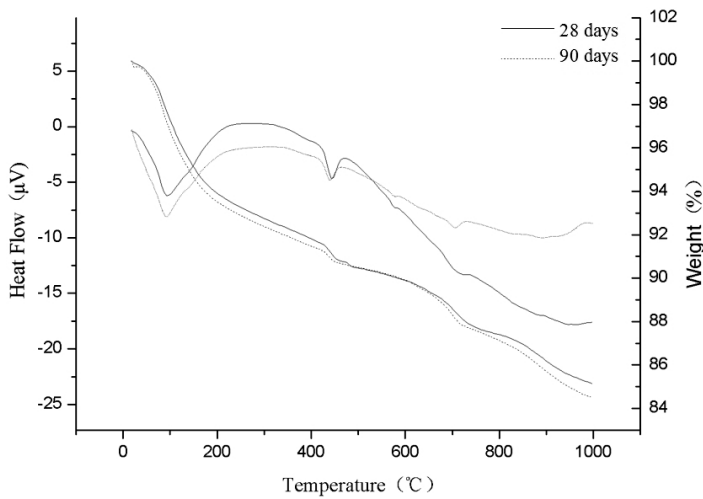




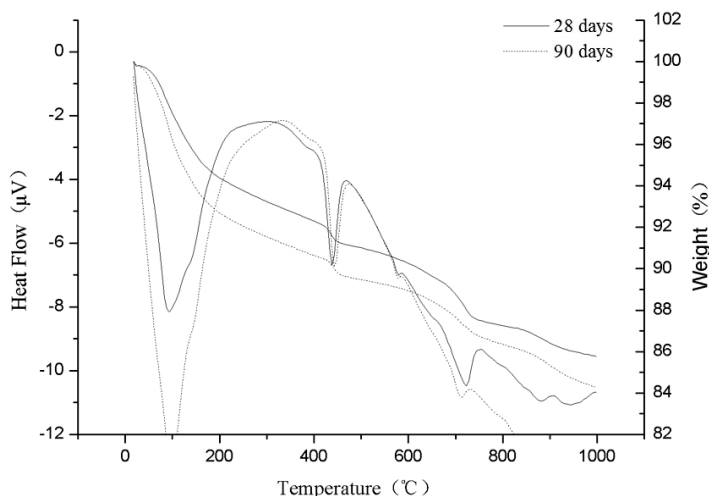
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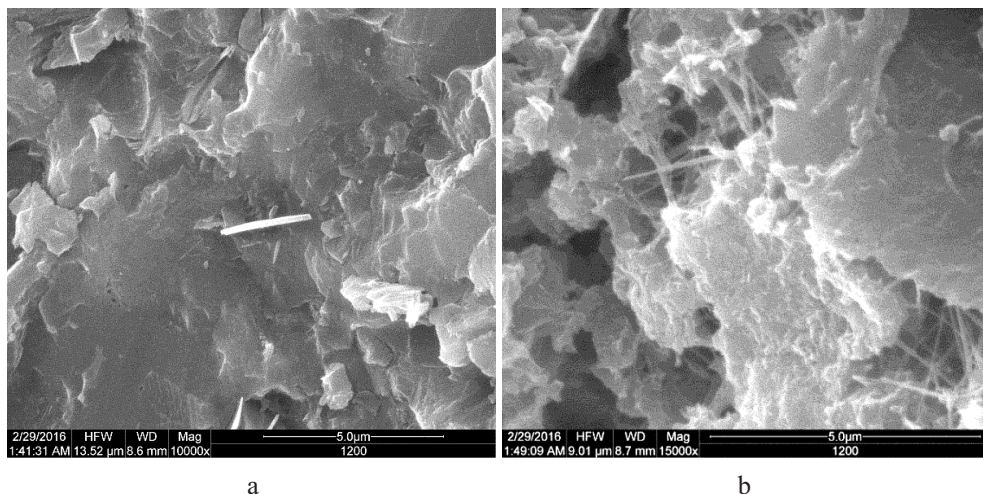
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Fig. 6. TG-DTA curves of conductive concrete pastes: (a) G0; (b) G325-5; (c) G325-10; (d) G5000-5; (e) G5000-10.

Figure 7 shows the microscopic morphology of the control sample G0 at different curing ages. At 28 days, relatively dense hydrated calcium silicate and flake calcium hydroxide crystals can be seen in the system. At 90 days, more hydration products are generated, the structure becomes denser, and more fibrous hydrated calcium silicate is used to fill the gaps and improves the overall strength of the specimens.



a

b

Fig. 7. Microscopic morphology of G0 sample. Here and Figs. 8 and 9: (a) 28 days; (b) 90 days.

Figure 8 shows the microscopic morphology of the sample G325-10. The dispersion of graphite powder is good and it fills the gaps in the cement material. A large number of graphite particles accumulate to form a conductive chain and the electrical conductivity of the sample is enhanced by tunneling effect. At 28 days, calcium silicate hydrate with needle-shaped ettringite is observed, within which there are many graphite particles. The fibrous calcium silicate hydrate plays a role in connecting the dispersed conductive graphite

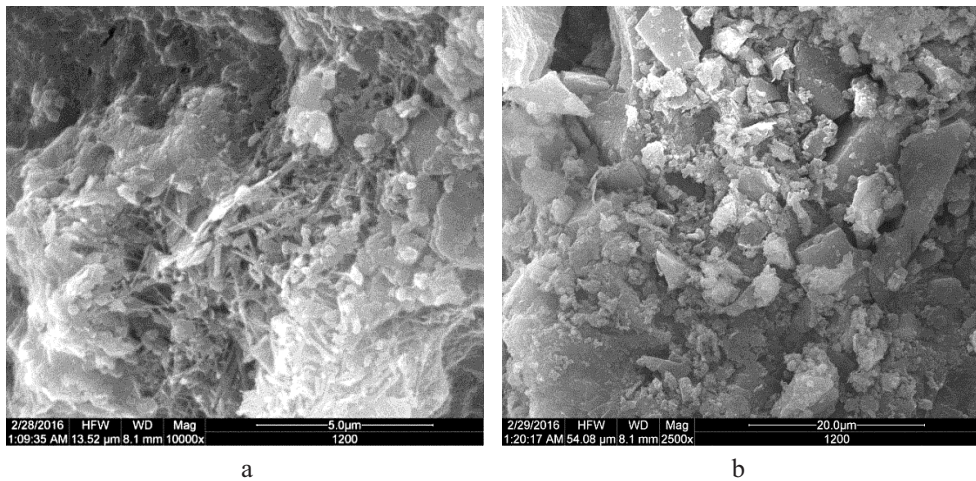


Fig. 8. Microscopic morphology of G325–10 sample.

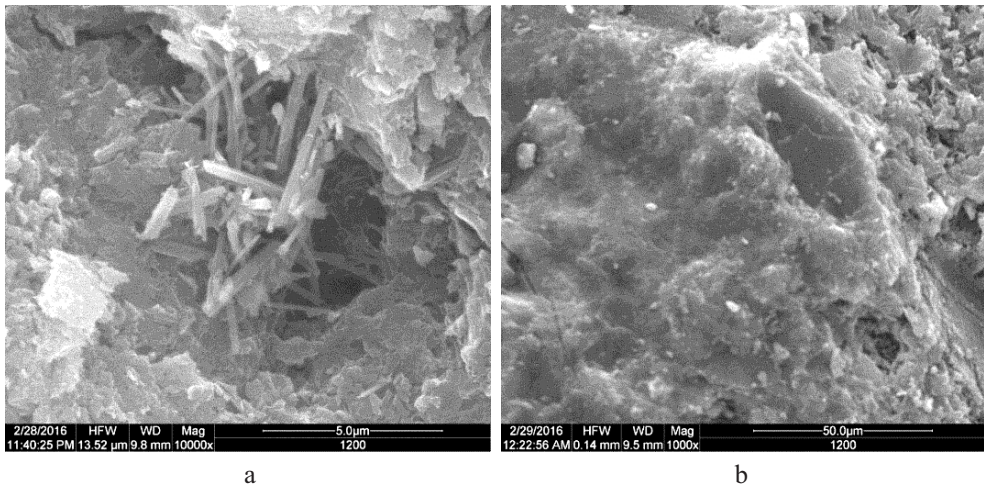


Fig. 9. Microscopic morphology of G5000–10 sample.

particles. The structure is loose and the strength is low. At 90 days, the hydration products are denser and have higher strength.

As shown in Fig. 9, the size of the 5000 mesh graphite particles is much smaller than that of the 325 mesh particles; thus, with the same amount of doping the samples in the G5000 group are more compact than those in the G325 group. There are more conductive particles in the G5000 group samples and it is easier to form a conductive path, so the conductivity is better. At 28 days, hydrated calcium silicate gel-wrapped graphite particles are connected into a whole. Other pores that are not filled with graphite-filled ettringite hydration products lap repair. At 90 days, the hydration becomes more complete and the products become more homogeneous and dense.

Conclusions

1. With the addition of graphite powder, the strength of the conductive concrete decreases. The fineness of the graphite powder has a small influence on the strength of the conductive concrete.

2. The resistivity of the conductive concrete decreases with increasing fineness and content of graphite powder, and the temperature of the specimen increases after continuous electrification, demonstrating the high electric heating effect.

3. The graphite powder has little influence on the hydration products of conductive concrete. The conductive path can be easily formed with increasing the content and fineness of graphite powder.

4. According to the experimental results, the optimal graphite powder content is recommended to be 5–10%, and the specific dosage is determined according to the actual project and its environmental conditions.

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