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Research Article

Research on Electrical Conductivity and Mechanical Properties of Ecological Concrete Prepared from Mine Solid Waste

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Conductive concrete with nanographite–cupric nickel sulfate ore was prepared in this paper. As a new type of multifunctional multiphase conductive building material with conductive, electrothermal, electromagnetic shielding, piezoresistive properties, etc., nanographite–cupric nickel sulfate ore conductive concrete will have a wide range of applications in snow melting, electromagnetic shielding, cathodic protection and structural health monitoring, and other fields. In this paper, different dosage of nanographite and cupric nickel sulfate ore admixture that the mixture was excited by alkali excitation, ultrasonic vibration and combined alkali excitation and ultrasonic vibration, respectively were used to study the electrical conductivity and mechanical properties of conductive concrete, 36 groups of nanographite–cupric nickel sulfate ore conductive concrete specimens and seven groups of comparative specimens were cured for 28 days, and the unconfined compression test, three-point bending test, and electrical conductivity test were carried out. The results show that the electrical conductivity and mechanical properties of the specimens with 6% nanographite and 60% cupric nickel sulfate ore were the best, with the compressive strength, flexural strength and resistance reaching 40.83 MPa, 6.81 MPa, and 5,850 Ω·cm, respectively. Compared with the comparative specimens, the compressive strength and the flexural strength of the specimens are increased by 38.5% and 20.4%, respectively, and the resistivity is decreased by 55.7%. This shows that the alkali excitation-ultrasonic vibration activation method can not only improve the electrical conductivity of nanographite–cupric nickel sulfate ore conductive concrete pavement but also ensure the stability of its mechanical properties.

1. Introduction

The recent surge of urbanization in China has made the ecological environment an increasingly pressing issue at the top of the research agenda. In particular, since the 21st century, ecological environment protection and sustainable development have become worldwide concerns. The booming global industry has spawned large amounts of industrial residues and other solid wastes in the production process, and the recycling of discarded metallic minerals has become a promising new direction [1–3] in the concrete industry and one of the hotspots in the academic circle. Due to technological advances and people's increasingly higher demand for the safety and comfort of a living environment, a higher standard is set for the properties of concrete materials, and a higher degree of attention is paid to the safety of engineering structures and disaster prevention and mitigation capacity.

Dating back to the earliest development of conductive concrete [4–9], scholars of the former Soviet Union, Germany, the United States, Britain, Canada, and other countries made preliminary studies on the electric conduction of concrete, in the 1950s, scholars from the former Soviet Union classified concrete into three categories: insulating concrete, conductive concrete, and special conductive concrete. In the 1970s, Yang [10], scholars in North America and Northern Europe studied the electrification and heating performance of concrete to alleviate the corrosion caused by salt spreading on icy concrete pavements, in the 1990s, conductive concrete has been further researched and applied. Many scholars have added aggregate substitutes to concrete to enhance its conductivity, for example, Banthia et al [11] added a certain amount of carbon fiber and steel fiber into concrete to prepare composite materials to study its electricalconductivity. The experimental results show that the resistivity of 28-day concrete is 32–78 Ω·cm. Yehia et al. [12, 13] prepared conductive concrete by adding a certain amount of steel filings and steel fiber as conductive fillers, and the average resistance is 20 Ω·m at −4°C. Then, they improved the conductive filler by adding graphite and carbonaceous materials in replacement of steel filings to the concrete and carried out the engineering application of melting snow and deicing [14]. Cai [15] proposed in his invention patent that adding a certain amount of graphite to the concrete according to its formula can increase the resistivity by 221 times and the compressive strength up to 70 MPa.

Jia et al. [16] had studied the mechanical properties and influencing factors of conductive concrete, and the research showed that conductive concrete had certain resistance stability, but the working performance of concrete was greatly affected by the amount of added materials, the ambient temperature, and humidity.

Li [17] hasused carbon black, graphite, steel fiber, carbon fiber, and steel slag as conductive phase to prepare conductive concrete, and proper experimental electrode is designed and the mixing technology is optimized. Experiment results show that the concrete mixed with carbon fiber has excellent electrical conductivity and flexural strength, graphite concrete has better conductivity, and the more the graphite, the lower the resistivity and the higher the flexural strength, carbon black concrete has good conductive effect, but its strength decreases significantly, the concrete with steel fiber has an obviously decreased resistivity and significantly increased flexural strength.

Ge et al. [18] summarized the origin and classification of conductive concrete, and described the conductive mechanism of conductive concrete. The working property, conductive property, mechanical property, electric thermal effect, pressure sensitivity, temperature sensitivity, durability, and microscopic characteristics are included and the factors influencing the electrical conductivity are discussed in detail, and the microscopic characteristics are used to verify the electrical conductivity and mechanical characteristics.

Ren et al. [19] had researched on the electrical conductivity and mechanical properties of copper slag multiphase nanomodified electrically conductive cementitious composite. It has been proposed to use nanographite and copper slag as coarse aggregate instead of gravel in concrete, and different modification methods and various ratios of admixture are used to prepare new functional concrete. This can not only achieve the electrical conductivity of concrete but also recycle waste materials, thereby promoting the green development of the mining industry and the construction of ecological civilization [20–22]. Therefore, this paper explores the influence rules of mechanical properties and electrical conductivity of the new type of functional concrete through the modification and reprocessing of the proportion of cupric nickel sulfate ore and nanographite [23–25].

The preparation of conductive concrete with different kinds of metal slag has become a research hotspot in recent years [26, 27]. Metal slag has good wear resistance. A large body of literature suggests that slag powder can improve the performance of concrete and has excellent electrical conductivity [28, 29].

Chen [30] researched on electrical resistance tomography technique for conductive concrete damage detection. The resistance tomography data acquisition system and image reconstruction algorithm are established to effectively detect cracks and holes in concrete. The proposed image secondary processing method can significantly improve the image quality and accuracy.

Peng [31] studied on mechanical properties and microstructure of alkali activated recycled concrete and its mix design. The thesis proposed the idea that using recycled coarse aggregate instead of natural stone material to combined with alkaline activated cementing materials completely to create a new type of concrete. The exploration of the relationship between macroperformance and influencing factors of the concrete is conducted by the way of transition based on cementing materials.

Guo et al. [32] used graphite powder to prepare conductive concrete, and its properties and microstructure were investigated. The results show that the strength of conductive concrete reduces with the increase of graphite powder dosage. The electrically resistivity of conductive concrete reduces along with the increase of fineness and content of graphite powder.

In summary, conductive concretes are predominantly made by adding definite ratios of conductive materials such as particles and fibers into concrete, especially carbon materials such as graphite and carbon fiber. The conductive concrete prepared by this kind of material can conduct electricity, and its mechanical properties can meet the needs of practical engineering. However, how to improve the service time of conductive concrete and how to use solid waste instead of aggregate to prepare conductive concrete according to environmental protection requirements, so as to save the cost of urban construction is rarely reported and studied by scholars.

In this paper, it is proposed to use nanographite and cupric nickel sulfate ore as coarse aggregate instead of gravel in concrete, and different modification methods and various ratios of admixture are used to prepare new functional concrete. This can not only achieve the electrical conductivity of concrete but also recycle waste materials, thereby promoting the green development of the mining industry and the construction of ecological civilization. Therefore, this paper explores the influence rules of mechanical properties and electrical conductivity of the new type of functional concrete through the modification and reprocessing of the proportion ofcupric nickel sulfate ore and nanometer graphite.

2. Materials and Test Methods

2.1. Experimental Materials

2.1.1. Nanographite. As a conductive material with good performance, nanographite can significantly improve the resistance and facilitate the measurement of electrical parameters after being added to concrete and to ensure the accuracy of

Table 1: Content composition and physical properties of nanographite.

Carbon content	Ash content	Water content	pH value	Oversize	Undersize
≥99.9%	≤0.36%	≤0.35%	6.3	10%	90%

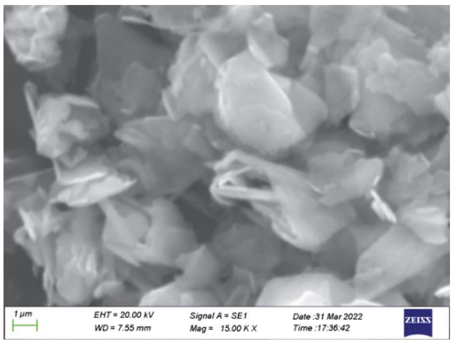


Figure 1: SEM diagram of 1.54 μm nanographite.

concrete intelligent monitoring. As nanographite powder has a higher degree of fit than cement sand, it is easier to enter the gap to wrap coarse and fine aggregate, but a small amount of nanographite cannot significantly improve the resistance of concrete and cannot form a good conductive network. Therefore, in our experiment, a proper ratio of nanographite is added to concrete to achieve the desired conductive effect, and to prepare conductive concrete materials with good performance for engineering practice.

The nanographite used is produced by Liugong Graphite Co., Ltd., with a specification of 1.54 μm and a particle size of about 1.3 μm. The detailed composition and physical properties of carbon content, ash content, water content etc are shown in Table 1, and the microstructural features of then anographite captured by scanning electron microscope (SEM) are shown in Figure 1.

2.1.2. Cupric Nickel Sulfate Ore. Metal materials are good conductors of electricity with good electrical conductivity.

In our experiment, the cupric nickel sulfate ore containing copper and nickel elements supplied by the Panzhihua-Xichang Mineral Resource Area of Sichuan Province was selected as conductive concrete material. The total 50 kg of mineral samples are coarsely crushed, medium crushed, fine crushed, roller ground, screened, and finally ground to a particle size of about 77 μm. After mixing and shrinking, a composite sample is packaged and used. The specific surface area of the slag is about 450 m^2/kg, which accords with the Chinese standard GB/T18046-2008 "granulated blast furnace slag powder used in cement and concrete." The specific surface area is more than 400 m^2/kg, the average particle size is 14.50 μm, and the density is 3.387 g/m^3. The chemical composition analysis results of the ore are shown in Table 2, the chemical phase analysis results of nickel in the ore are shown in Table 3, the physical indexes of slag powder are shown in

Table 2: Results of chemical composition analysis of ores (%).

Chemical composition	SiO_2	MgO	Fe	S	Ni	Ca	Cu	Al	Na
Content	32.96	26.89	13.2	5.14	1.43	1.1	0.85	0.83	0.12

Table 3: Results of chemical phase analysis of nickel in ores (%).

Phase	Nickel sulfide	Nickel oxide	Nickel in silicate	Total nickel content
Content	1.371	0.030	0.026	1.427
Occupancy	96.08	2.10	1.82	100.00

Table 4, and the SEM diagram of cupric nickel sulfate ore is shown in Figure 2.

2.1.3. Cement. The cement used in the test is 42.5 grade Portland cement (purchased in bags) provided by Shandong Building Materials 97 building Materials Co., Ltd. The main chemical composition of cement is shown in Table 5.

2.1.4. Gravel. (*Supplied by the manufacturer*, *natural stone*) The gravels with a particle size of 3–6 mm and an apparent density of 2,700 kg/m^3 from Shijiazhuang Hangqian Co., Ltd. are used in the experiment.

2.1.5. Quartz Sand. Quartz sand between 192.5 μm and 128 μm from Anhui Shengli Quartz Sand Factory is used in the experiment.

2.1.6. Fly Ash. High quality first-class flyash (*named by the manufacturer*) from Shanxi Yuncheng Sanyuesan Building Materials Co., Ltd. is used in the experiment.

2.1.7. Copper Screen. The 385 μm copper screen is used in this experiment.

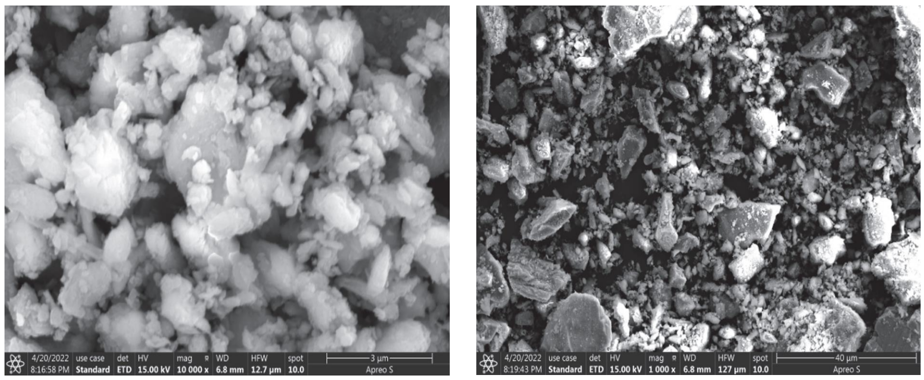
2.1.8. Other Materials. Tap water, water reducer (polycarboxylic acid concrete superplasticizer), sodium hydroxide solution, dispersant, coupling agent, fly ash, and 75% industrial alcohol are used in the experiment.

2.2. Preparation of Solid Waste Conductive Concrete

2.2.1. Experiment Scheme. The experiment was composed of 36 nanographite–cupric nickel sulfate ore conductive concrete (experimental groups, three kinds of cupric nickel sulfate ore content × 3 different graphite content × 4 production processes = 36 groups) and seven control groups (one group without graphite and slag + 3 groups without graphite but with slag content of 20%, 40%, and 60% + 3 groups without slag and with graphite content of 3%, 6%, and 9% [22]). The concrete compression test includes six specimens with the size of 50 mm × 50 mm × 50 mm, the concrete test includes six specimens with the size of 160 mm × 40 mm × 40 mm, and the concrete conductive test includes two specimens with the size of 160 mm × 40 mm × 40 mm. These specimens were prepared by the Quartering method (also called conical

Table 4: Physical indexes of slag powder.

Crush index	Apparent density/(kg/m^3)	Robustness	Bulk accumulation density/(kg/m^3)	Acicular and flaky grain in aggregate/%	Porosity/%
19.2	3,387	2	2,280	1.2	32.6



(a) (b)

Figure 2: SEM diagram of 77 μm cupric nickel sulfate ore: (a) 10,000 times and (b) 1,000 times.

Table 5: Main chemical components in cement.

Name	CaO	SiO_2	TiO_2	Al_2O_3	MgO	Fe_2O_3
Content	63.72%	17.28%	0.54%	4.44%	1.23%	3.48%

Table 6: Table of the mix design (control groups kg/m^3).

No.	Water	Cement	Coarse aggregate	Fine aggregate	Dispersing agent	Coupling agent	Nano-graphite	Graphite ratio	Copper and nickel slag	Copper nickel ore ratio
Control 1	192	450	300	1,150	0	0	0	0	0	0
Control 2	192	450	300	920	0	0	0	0	230	0.2
Control 3	192	450	300	690	0	0	0	0	460	0.4
Control 4	192	450	300	460	0	0	0	0	690	0.6
Control 5	192	450	300	1,150	2	0.6	13.5	0.03	0	0
Control 6	192	450	300	1,150	2	0.6	27	0.06	0	0
Control 7	192	450	300	1,150	2	0.6	40.5	0.09	0	0

quartering method) with a total number of 602. After curing under standard conditions for 28 days, the compressive and flexural strength were tested on the 7th, 14th, and 28th, respectively, and the electrical conductivity was tested on the 7th, 14th, 21th, and 28th day.

2.2.2. Experimental Mix Ratio Design. The mixed design data are shown in Tables 6, and 7. In this experiment, 1.54 μm nanographite is used to design different mix ratio to replace the fine aggregate in conductive concrete, and the replacement ratio is 3%, 6%, and 9% [19, 22], respectively. About 3% as a gradient to add nanographite to enhance the electrical conductivity and mechanical properties of concrete; about 1.54 μm of cupric nickel sulfate ore is selected to replace the coarse aggregate in conductive concrete, and the replacement amount is 20%, 40%, and 60% [19, 22].

The numbers 0, 3, 6, and 9 indicate that the amount of nanographite added is 0%, 3%, 6%, and 9% of the cement, respectively. The numbers 0, 20, 40, and 60 represent cupric nickel sulfate ore instead of 0%, 20%, 40%, and 60% of quartz sand, respectively.

2.2.3. Modification Design. In this experiment, the nanographite–cupric nickel sulfate orewas modified to prepare solid waste conductive concrete by three modification methods: alkali excitation, ultrasonic vibration, and alkali excitation-ultrasonic vibration.

(1) Alkali Activation. Alkali activation is a common modification method. In Group A, cupric nickel sulfate ore reacts

Table 7: Table of the mix design (test groups kg/m^3).

No.	Water	Cement	Coarse aggregate	Fine aggregate	Dispersing agent	Coupling agent	Nano-graphite	Graphite ratio	Copper and nickel slag	Copper nickel ore ratio
Test 1						G3C20, AG3C20, UG3C20, AUG3C20				
Mix ratio	192	450	300	920	2	0.6	13.5	0.03	230	0.2
Test 2						G3C40, AG3C40, UG3C40, AUG3C40				
Mix ratio	192	450	300	690	2	0.6	13.5	0.03	460	0.4
Test3						G3C60, AG3C60, UG3C60, AUG3C60				
Mix ratio	192	450	300	460	2	0.6	13.5	0.03	690	0.6
Test 4						G6C20, AG6C20, UG6C20, AUG6C20				
Mix ratio	192	450	300	920	2	0.6	27	0.06	230	0.2
Test 5						G6C40, AG6C40, UG6C40, AUG6C40				
Mix ratio	192	450	300	690	2	0.6	27	0.06	460	0.4
Test 6						G6C60, AG6C60, UG6C60, AUG6C60				
Mix ratio	192	450	300	460	2	0.6	27	0.06	690	0.6
Test 7						G9C20, AG9C20, UG9C20, AUG9C20				
Mix ratio	192	450	300	920	2	0.6	40.5	0.09	230	0.2
Test 8						G9C40, AG9C40, UG9C40, AUG9C40				
Mix ratio	192	450	300	690	2	0.6	40.5	0.09	460	0.4
Test 9						G9C60, AG9C60, UG9C60, AUG9C60				
Mix ratio	192	450	300	460	2	0.6	40.5	0.09	690	0.6

Description G and C represent nanographite andcupric nickel sulfate ore, A and U represent chemical alkali excitation and ultrasonic vibration, respectively, and AU represents alkali excitation-ultrasoicvibration combined preparation method.

Figure 3: Alkali-activated suspension.

with an alkali solution to form slag cementitious material, thus improving the strength of concrete. Alkali-activated suspension is shown in Figure 3.

In addition, the cupric nickel sulfate ore contains steel slag and mineral slag, which can promote the hydration of each other in the alkaline environment and compact the internal structure of the steel slag cementitious material after alkali activation. For this reason, the alkali-activated admixture processing can increase the strength and durability of concrete.

(2) Ultrasonic Vibration. In Group U, nanographite and cupric nickel sulfate ore were mixed in acetone solution for 1 hr for activation treatment, then dried in an oven at 105°C and mixed in 200 ml ethanol solution. Then, the mixed suspension was oscillated in an ultrasonic oscillator. After continuous mixing and concussion, the activation and wrapping effect of ultrasonic shock makes nanographite adsorbed uniformly and continuously in the slag surface and cracks to fully combine it with conductive particles to form a conductive network. This maximizes the electrical conductivity of the material, thereby improving the electrical conductivity of solid waste concrete.

(3) Combined Activation (Alkali Activation + Ultrasonic Aibration). The AU group test combines the advantages of alkali excitation and ultrasonic vibration. First, the graphite and slag surfaces were activated by alkali excitation, and then ultrasonic vibration processing was carried out. After processing, the particles of the two materials were uniformly dispersed to form a conductive network with good properties. Finally, the conductive concrete specimens with good mechanical properties were obtained. Compared with the SEM diagram in Figure 4, it can be seen that the nanographite does not bind tightly with cupric nickel sulfate ore before modification, and there is a large gap in the massive edge. After modification, there are many flakes $Ca(OH)_2$ crystals and flocculating C–S–H gel, indicating that the slag has undergone a hydration reaction under the action of the activator, and after ultrasonic vibration, the graphite particles have been perfectly bound with the slag and formed a good covering layer.

Figure 5 is the SEM scanning image of ordinary concrete combined with alkali excited ultrasonic vibration excited concrete. As can be seen from Figure 5(a), the pores and cracks of ordinary concrete coexist with ups and downs and looseness, the concrete structure is mainly composed of cement and quartz sand aggregate, and the hydration products are mostly C–S–H gel, followed by $Ca(OH)_2$. The content of other products such as ettringite is very low, and CS–H gel and $Ca(OH)_2$ are closely combined.

As can be seen from Figure 5(b), in the concrete material prepared from cupric nickel sulfate ore by alkali excitation and ultrasonic vibration, the cement hydration products in the concrete are mainly C–S–H gel, and the hydration products are mainly composed of some irregular flat particles tightly packed. Each hydration product cements with each other to form a dense continuous phase, and the overall structure is very complete and dense. C–S–H gel is filled with graphite material, the distribution of cupric nickel sulfate ore in colloidal material is more uniform, spread each gap, and flocculent cupric nickel sulfate ore distribution. The solid particles and pores of hydrated cement slurry have a great influence on the macroscopic mechanical properties of concrete. C–S–H gel is not a completely amorphous substance. It is generally composed of fine grains with the size of 0.1–1 μm. In comparison with Figures 5(a) and 5(b), the colloid density of the combined excited cupric nickel sulfate ore concrete is smaller than that of ordinary concrete, and its macroscopic mechanical strength is slightly reduced, while the density distribution of conductive materials determines that concrete has certain electrical conductivity.

2.3. Test Method

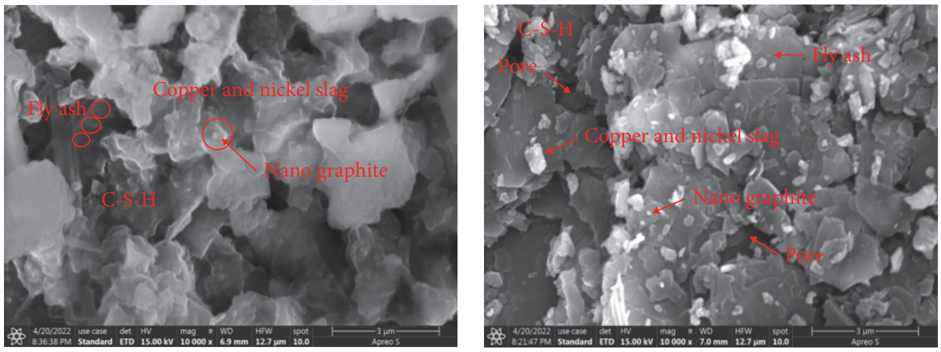
2.3.1. Mechanical Property Test. The compressive and flexural strength of the solid waste conductive concrete test specimens was tested strictly according to the national standard. The unconfined compression test and three-point bending test were carried out on the 7th, 14th, and 28th day of curing, respectively. The effects of different contents of nanographite and cupric nickel sulfate ore and four manufacturing processes on the mechanical properties of the test specimens were studied. The unconfined compression test was carried out on the YAW-200B universal press and the three-point bending test was carried out on the WBW-100 testing machine. The loading diagram is shown in Figure 6.

For testing the mechanical properties of concrete specimens, the loading speed of the unconfined compression test is 0.5 MPa/s, the distance between loading points is 140 mm, and the loading speed of the three-point bending test is 0.03 MPa/s. The instrument records the load–displacement curve automatically. The unconfined compression test can be calculated according to Equation (1) and the three-point bending test can be calculated according to Equation (2):

$$F_C = \frac{F}{A}, \tag{1}$$

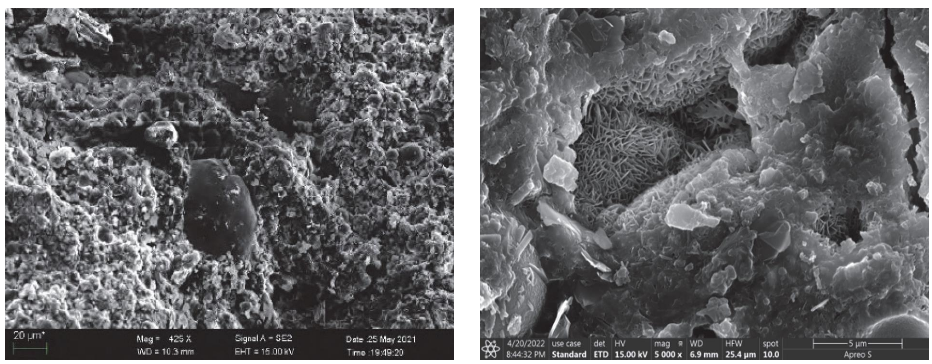
$$f_t = \frac{2\,Fl}{3\,bh^2}, \tag{2}$$

where F_C is the compressive strength of concrete test block (MPa); F is the failure load of the specimen (N); A is the bearing area of the specimen (mm^2). f_t is the flexural strength of concrete test block (MPa), the calculation result should be accurate to 0.1 MPa; F is the failure load of the specimen (N);



(a) (b)

Figure 4: SEM images after processing with different methods: (a) graphite slag mixture after physical stirring and (b) graphite slag mixture by the combined preparation method.



(a) (b)

Figure 5: SEM comparison between ordinary concrete and combined excited concrete: (a) ordinary concreteand (b) combined excitation of copper-nickel concrete.

(a) (b)

Figure 6: Test loading diagram of mechanical properties of solid waste conductive concrete: (a) unconfined compression test and (b) three-point bending test.

l is the span between supports (mm); b is the specimen section width (mm); h is the specimen section height (mm).

The span l is 100 mm, and the cross-section width and height of the specimen are 40 mm.

2.3.2. Electrical Conductivity Test. In this experiment, the four-electrode method was used to test the electrical conductivity of the test specimens on the 7th, 14th, 21th, and 28th day, as shown in Figure 7.

The test specimens of solid and waste conductive concrete are all 160 mm × 40 mm × 40 mm. At the same time, the metal mesh of 30 mm × 70 mm is parallel inserted into the test specimens according to the 40 mm spacing, and the digital multimeter records the resistivity by connecting the

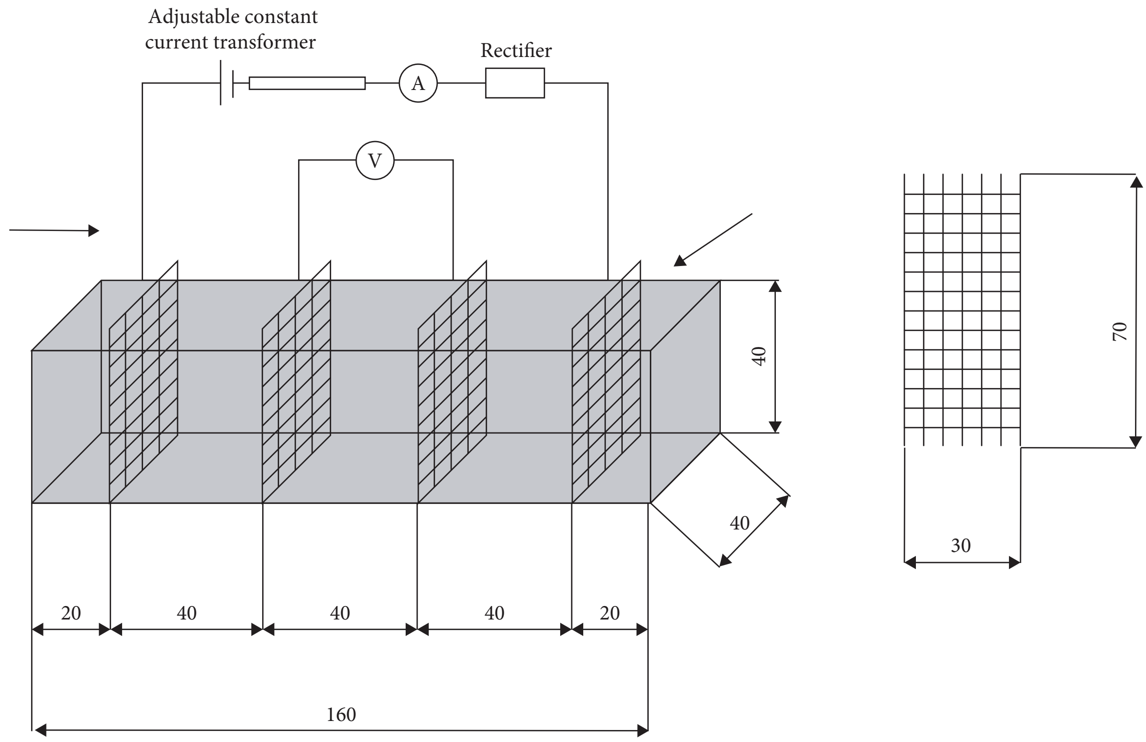


Figure 7: Schematic diagram of testing conductive concrete by the four-electrode method.

metal mesh electrode with copper wire. The resistivity can be calculated by the Equation (3):

$$\rho = \frac{UA}{I \times L}, \quad (3)$$

where P is the resistivity (Ω·cm); A is the cross-sectional area of the concrete specimen (m^2); L is the distance between electrodes (m); U is voltage; I is current (A).

3. Experimental Results and Analysis

3.1. Effect of the Amount of Nanographite Admixture on Concrete Strength. The use of nanographite in concrete can improve the resistance and achieve the desired conductive effect. In this experiment, 3%, 6%, and 9% nanographite powder were selected as the content instead of fine aggregate into concrete. In the course of the experiment, it is found that after adding a certain ratio of nanographite, the workability of cement mortar becomes better, the color changes from light to dark, and no obvious sedimentation occurred. The smooth microinterface of nanographite crystal can reduce the friction between microscopic aggregate and hydration products, but excessive nanographite can produce molecular agglomeration and decrease the compressive strength of concrete, so the amount of nanographite admixture determines the strength of concrete. Figure 8 shows the effect of different amounts of nanographite admixture on the compressive and flexural properties of the test specimens. As can be seen from Figures 8 and 9, when the amount of nanographite admixture is 6%, the compressive strength is above 30 MPa after curing for 28 days, whereas when the amount of nanographite admixture is 9%, the compressive strength decreases obviously after curing for 28 days. When the amount of nanographite admixture is 6% and the amount ofcupric nickel sulfate ore admixture is 60%, the concrete achieves the optimal compressive strength of exceeding 40 MPa, and the resistivity is 5,850 Ω·cm. When the amount of nanographite admixture is 6% and the amount of cupric nickel sulfate ore admixture is 40%, the concrete achieves the optimal flexural strength, reaching 7.26 MPa, and the resistivity is 4,500 Ω·cm. Therefore, adding a proper ratio of nanographite powder can effectively improve not only the electrical conductivity but also the compressive and flexural properties of concrete.

3.2. Effect of the Amount of Cupric Nickel Sulfate Ore Admixture on Strength. The slag is added to the concrete in replacement of the coarse aggregate, which is a crucial factor affecting the concrete strength. cupric nickel sulfate ore is used as a substitute for coarse aggregate in concrete, with a substitution ratio of 20%, 40%, and 60%. As can be seen from Figures 8 and 9, different amounts ofcupric nickel sulfate ore admixture have different effects on the compressive and flexural properties of the specimens. When the amount of slag admixture is 60%, the average compressive strength of 28 days is about 30 MPa, and the average flexural strength is more than 6 MPa. Therefore, cupric nickel sulfate ore as a replacement for gravel coarse aggregate can effectively improve the compressive strength of conductive

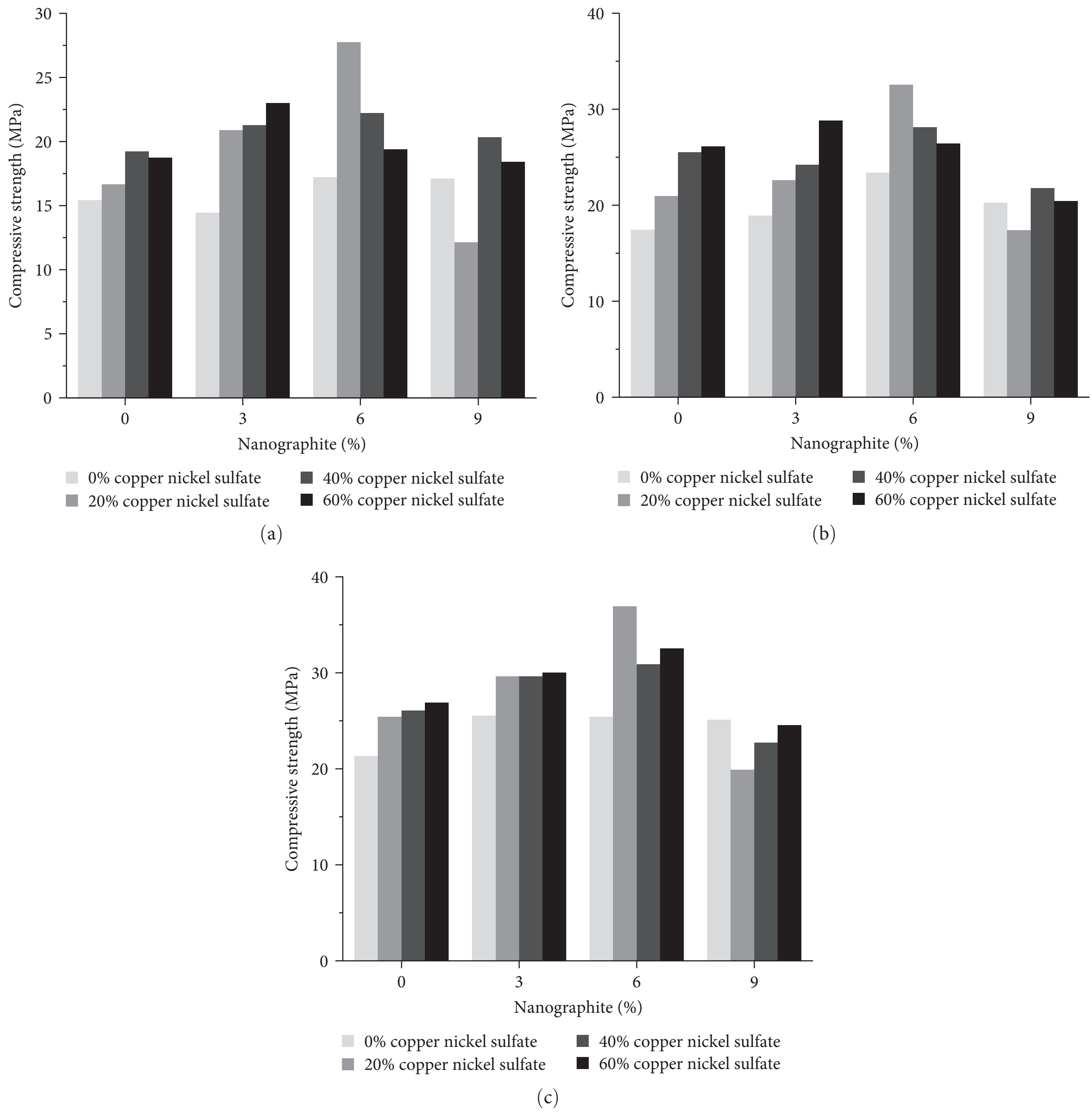


Figure 8: Compressive strength of different amounts of graphite and slag admixture after curing for 7 days, 14 days, and 28 days: (a) 7 days, (b) 14 days, and (c) 28 days.

concrete and meet the requirements of mechanical properties, and it has good wear resistance, durability, and metal conductivity.

3.3. Effect of Modification of Admixture Amount on Strength. Adding different ratios of nanographite or slag can either improve the electrical conductivity or mechanical properties of concrete, but cannot improve the properties of both. Therefore, it is necessary to modify the material and prepare a new type of multiphase conductive concrete, which can maximize the mechanical properties and electrical conductivity of concrete, and effectively reduce the cost of practical engineering.

The strength of concrete after alkali-activated modification of admixture develops rapidly in the early stage, and the strength of concrete can be close to 85% of that of 28 days at 14 days. The effect of alkali activation can increase the strength of 4 MPa when the amount of nanographite admixture is 6% and the amount of cupric nickel sulfate ore admixture is 60%. The reason is that the slag admixture activated by alkali will have higher strength and durability than ordinary cement. After the admixture is modified by the ultrasonic

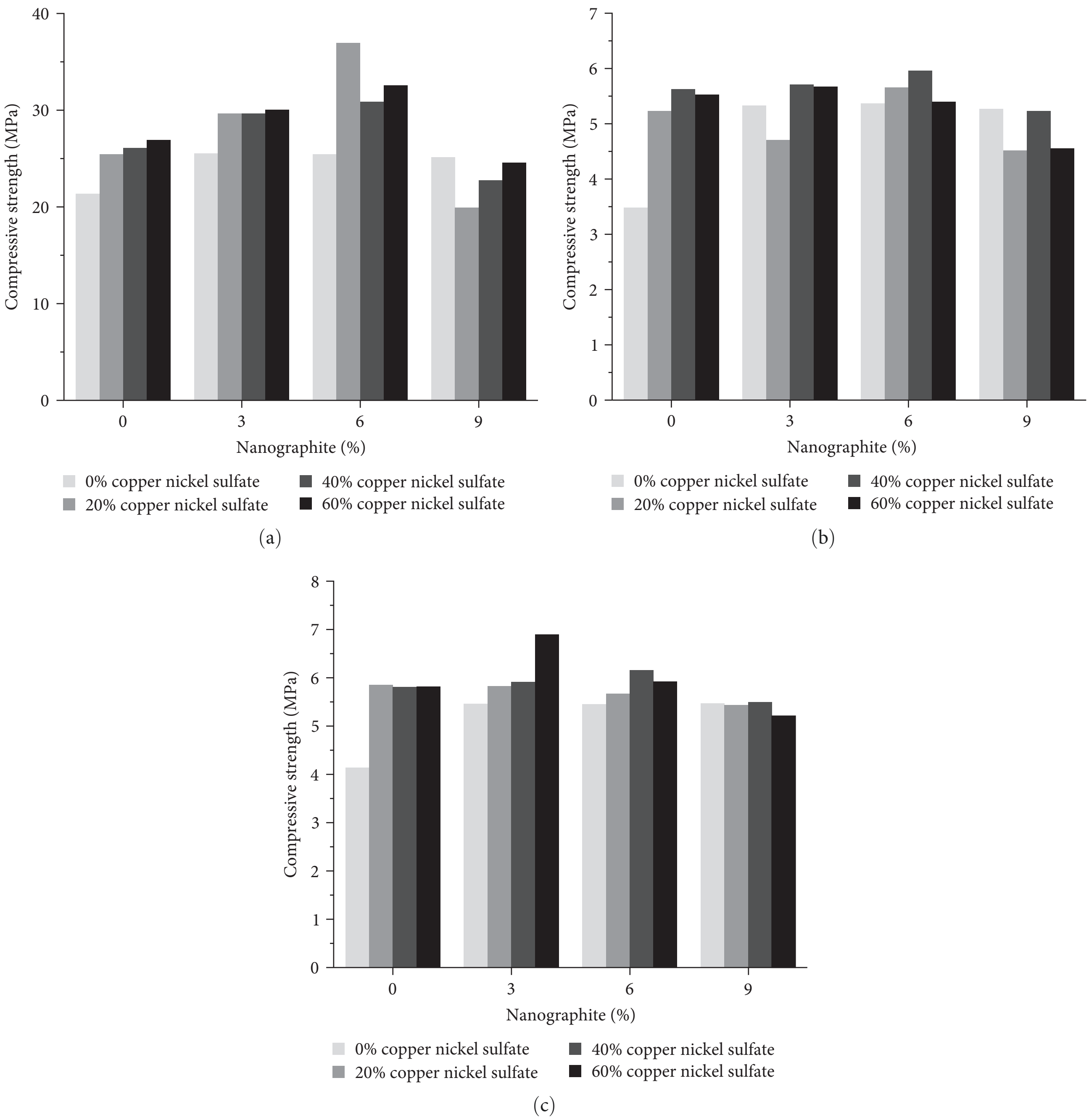


Figure 9: Flexural strength of different amounts of graphite and slag admixture after curing for 7 days, 14 days, and 28 days: (a) 7 days, (b) 14 days, and (c) 28 days.

vibration method, the nanographite can be filled into the pores of cupric nickel sulfate ore to enable the concrete to develop conductive properties while maintaining its mechanical properties.

The combined preparation method of alkali activation and ultrasonic vibration has both advantages and can greatly improve the mechanical properties and electrical conductivity of conductive concrete. Figures 10–12 and Tables 8–11 show that the mechanical properties and electrical conductivity of the specimens processed by the three modified methods are higher than those of the unmodified control group, and the compressive strength, flexural strength, and electrical conductivity are increased by 29.3%, 15.7%, and 48.9%, respectively, compared with the average value of control group. Compared with the average value of the control group, the compressive strength, flexural stress, and electrical conductivity of the test groups increased by 38.5%, 20.3%, and 55.7%, respectively. Compared with the average value of the control group, the compressive strength, flexural stress, and electrical conductivity of the test groups increased by 18.0%, 19.9%, and 72.0%, respectively. To sum up, after the modification by the combined preparation method, the

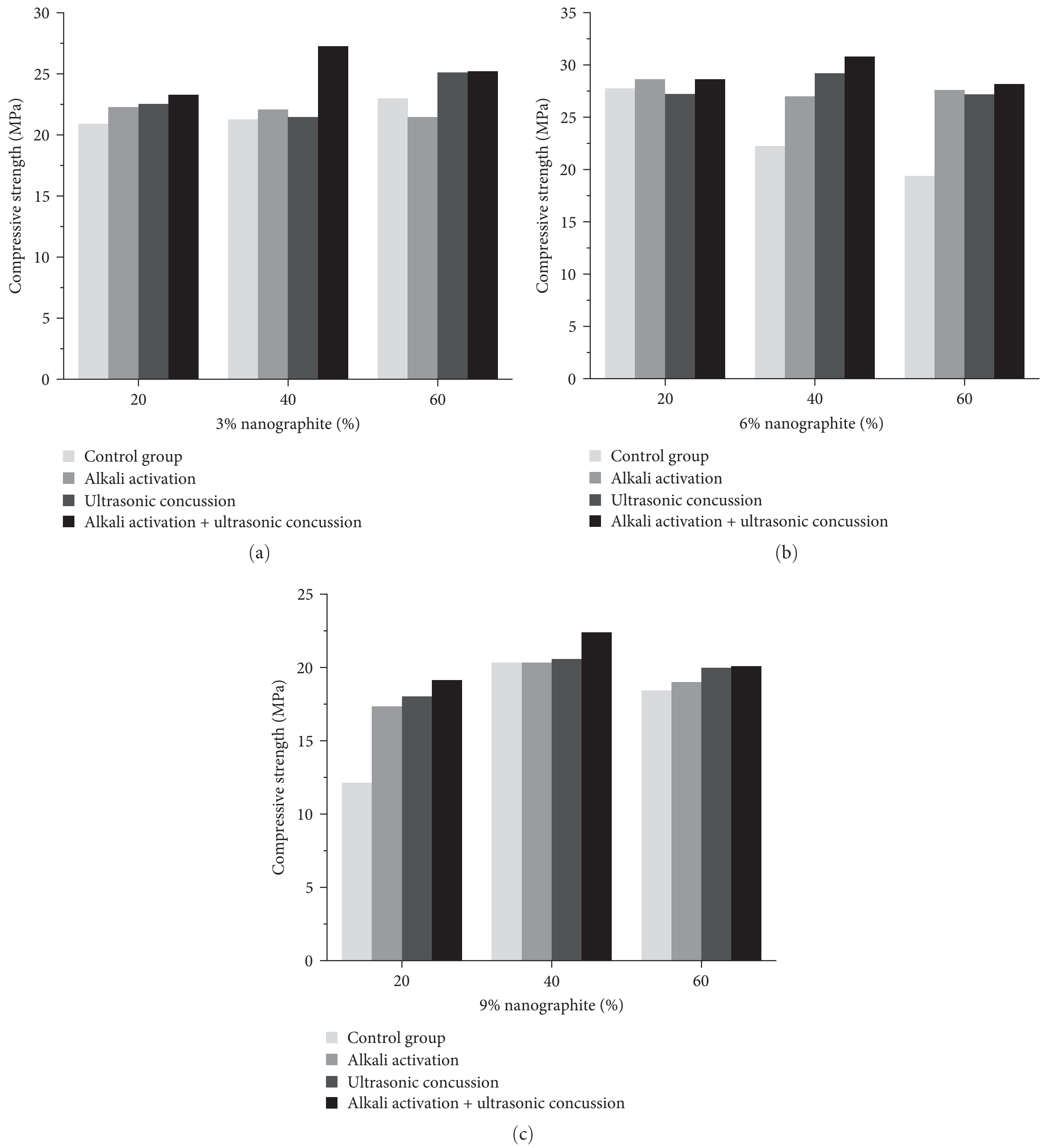


Figure 10: 7-day compressive strength of concrete after modified processing with different amounts of admixture: (a) 3%, (b) 6%, and (c) 9%.

higher the ratio of nanographite and cupric nickel sulfate ore, the greater the increase of electrical conductivity, which is 2.43 times. The mechanical properties also increase synchronously, in which the mechanical properties of the concrete samples with 6% nanographite and 60% cupric nickel sulfate ore are the best. It indicates that the admixture needs to be kept in a proper ratio, and it can also be observed from above data that the strength and electrical conductivity of the combined preparation method are more obvious than that of the single modified processing method.

4. Conclusions

In this paper, the effects of different amounts of materials such asnanographite, cupric nickel sulfate ore to the electrical conductivity and mechanical properties of conductive

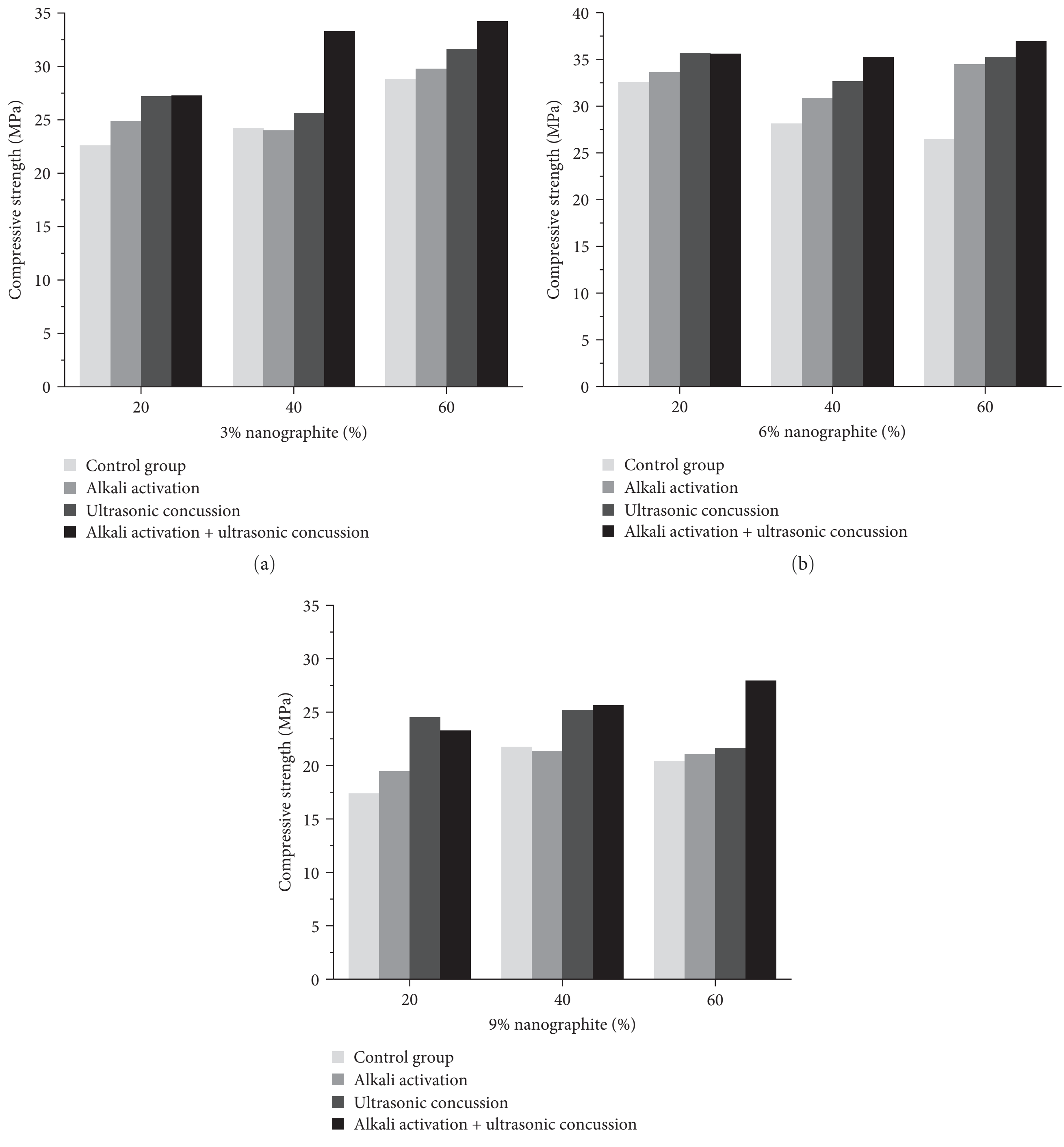


Figure 11: 14-day compressive strength of concrete after modification with different amounts of admixture: (a) 3%, (b) 6%, and (c) 9%.

concrete are explored, and the optimal design mix ratio is determined. The following conclusions can be drawn based on the above test and the microstructure analysis:

(1) The test results show that the 28-day compressive strength and flexural strength of the conductive concrete equal or even exceed those of the ordinary concrete, indicating that this new type of conductive concrete can meet the requirements of concrete mechanical properties.

(2) The resistance of the optimal conductive concrete is 5,850 Ω·cm, and the resistivity of the concrete decreases by 55.7% compared with that of the control specimen. The addition of nanographite to concrete can greatly enhance the electrical conductivity of concrete, effectively reduce the resistance of concrete,

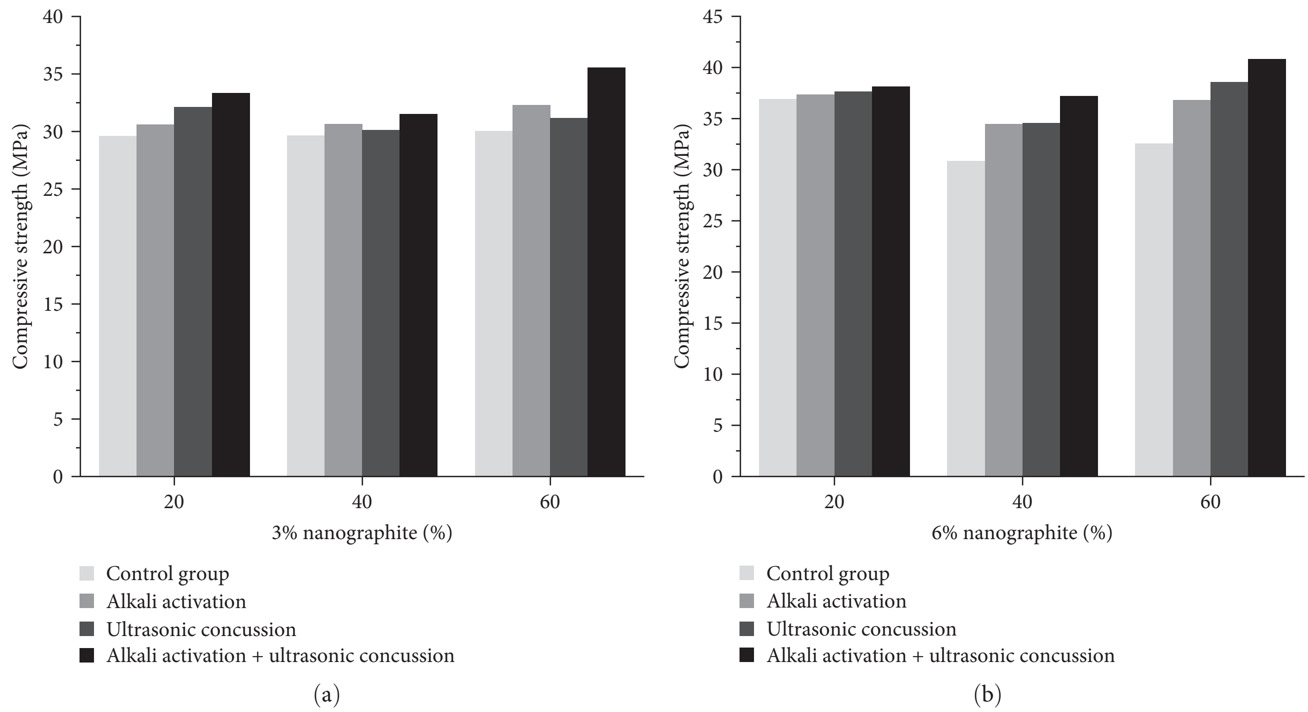


FIGURE 12: 28-day compressive strength of concrete after modification with different amounts of admixture: (a) 3%, (b)6%, and (c) 9%.

significantly improve the sensitivity of concrete piezoresistive effect. It is convenient for automatic detection and acquisition of force-electric signal, thereby achieving the purpose of intelligent detection. However, an excessive amount of admixture can lead to little increase or even decrease in concrete strength. This paper concludes that the amount of 6% nanographite admixture is optimal.

(3) Cupric nickel sulfate ore can replace the gravels of coarse aggregate in concrete and effectively improve the compressive strength of conductive concrete. This paper concludes that 60% cupric nickel sulfate ore is optimal, and the compressive strength can reach 40.83 MPa.

(4) Among the three modification methods for preparing new functional conductive concrete in this research,

Table 8: Mechanical properties and electrical conductivity of nanographite–cupric nickel sulfate ore (control groups).

No.	Compressive strength (unit MPa)			Flexural strength (unit MPa)			Electrical conductivity (unit Ω·cm)			
	7d	14d	28d	7d	14d	28d	7d	14d	21d	28d
Control 1	15.41	17.46	21.33	3.11	3.48	4.14	50,200	45,600	38,700	27,600
Control 2	16.66	20.96	25.43	4.65	5.23	5.85	4,180	4,640	13,820	14,250
Control 3	19.23	25.53	26.09	4.45	5.63	5.81	4,000	4,240	12,100	14,330
Control 4	18.74	26.12	26.9	4.59	5.53	5.82	4,320	4,610	14,330	14,650
Control 5	14.43	18.92	25.53	4.83	5.33	5.46	3,560	4,810	9,100	9,680
Control 6	17.2	23.41	25.44	4.86	5.37	5.45	3,780	4,800	5,100	5,210
Control 7	17.12	20.28	25.12	4.66	5.27	5.47	3,870	4,860	5,100	6,670

Table 9: Mechanical properties and electrical conductivity of nanographite–cupric nickel sulfate ore (G3 groups).

No.	Compressive strength (unit MPa)			Flexural strength (unit MPa)			Electrical conductivity (unit Ω·cm)			
	7d	14d	28d	7d	14d	28d	7d	14d	21d	28d
G3C20	20.89	22.59	29.63	4.24	4.71	5.83	2,520	2,580	5,670	6,050
AG3C20	22.27	24.87	30.61	5.16	6.05	6.14	2,720	2,880	4,430	5,050
UG3C20	22.52	27.19	32.14	4.94	5.28	6.52	2,620	4,090	7,200	8,920
AUG3C20	23.29	27.27	33.36	4.76	5.83	6.68	2,640	2,920	3,890	6,450
G3C40	21.27	24.22	29.64	4.75	5.71	5.91	2,790	3,390	3,790	9,010
AG3C40	22.06	24.02	30.67	4.75	5.72	6.44	3,480	3,810	4,520	9,030
UG3C40	21.46	25.63	30.15	5.6	6.65	6.95	2,210	2,660	3,390	8,990
AUG3C40	27.25	33.3	31.5	6.55	6.85	7.23	2,150	2,380	3,720	7,090
G3C60	23	28.82	30.02	4.69	5.67	6.9	2,360	3,130	6,400	9,660
AG3C60	21.44	29.78	32.28	4.76	5.67	6.7	3,050	3,710	4,500	5,100
UG3C60	25.1	31.66	31.19	5.2	5.1	6.2	4,500	6,450	6,830	8,850
AUG3C60	25.21	34.33	35.55	5.95	5.98	6.44	4,720	5,960	6,180	6,740

Table 10: Mechanical properties and electrical conductivity of nanographite-cupric nickel sulfate ore (G6 groups).

No.	Compressive strength (unit MPa)			Flexural strength (unit MPa)			Electrical conductivity (unit Ω·cm)			
	7d	14d	28d	7d	14d	28d	7d	14d	21d	28d
G6C20	27.75	32.54	36.92	5.12	5.66	5.67	4,420	5,800	5,830	8,220
AG6C20	28.63	33.6	37.37	5.66	5.62	5.92	2,710	3,000	6,770	8,420
UG6C20	27.21	35.68	37.64	5.66	5.69	5.98	2,210	3,090	3,530	4,890
AUG6C20	28.63	35.59	38.12	5.44	5.66	6.26	2,160	3,340	3,670	4,410
G6C40	22.22	28.15	30.88	5.85	5.96	6.16	1,770	1,890	2,420	6,400
AG6C40	26.98	30.86	34.45	5.75	5.93	6.83	1,520	1,660	2,380	5,660
UG6C40	29.2	32.67	34.56	5.71	6.4	7.15	2,370	5,310	5,370	5,610
AUG6C40	30.78	35.26	37.23	6.58	6.74	7.26	1,450	2,120	2,330	4,500
G6C60	19.4	26.43	32.56	5.2	5.4	5.92	2,530	3,930	5,430	5,730
AG6C60	27.6	34.49	36.83	5.63	5.96	6.21	1,790	1,890	5,300	5,950
UG6C60	27.18	35.26	38.56	5.73	5.84	6.45	1,630	3,020	3,780	5,710
AUG6C60	28.18	36.94	40.83	5.66	5.75	6.81	2,450	3,240	4,970	5,850

the optimal modification method is the alkali excitation-ultrasonic vibration combined preparation method. The optimal mix ratio is 6% nanographite and 60% cupric nickel sulfate ore to replace the gravels of coarse aggregate in concrete. The new type conductive concrete can not only achieve a good balance between mechanical properties and electrical conductivity of concrete but also can reduce the use of Portland cement and recycle solid wastes, thereby achieving the green development of the mining industry.

(5) Conductive filler particles can be uniformly distributed between aggregate and hydrated calcium silicate interface, which accelerates the formation of crystal structure and hydrated calcium silicate gel, and the filler particles processed by the combined preparation method can be uniformly distributed in the

Table 11: Mechanical properties and electrical conductivity of nanographite–cupric nickel sulfate ore (G9 groups).

No.	Compressive strength (unit MPa)			Flexural strength (unit MPa)			Electrical conductivity (unit Ω·cm)			
	7d	14d	28d	7d	14d	28d	7d	14d	21d	28d
G9C20	12.13	17.4	19.9	4.45	4.52	5.44	1,260	4,240	4,980	5,590
AG9C20	17.34	19.47	20.23	5.61	5.63	5.69	1,900	2,320	2,740	5,160
UG9C20	18.02	24.55	26.94	4.65	4.75	5.74	1,240	2,440	5,620	5,840
AUG9C20	19.14	23.28	27.02	4.73	4.69	4.79	2,010	2,490	2,700	4,700
G9C40	20.33	21.76	22.75	4.42	5.23	5.5	1,200	2,370	2,480	4,900
AG9C40	20.34	21.37	25.63	4.52	5.38	5.65	1,700	1,910	2,670	3,570
UG9C40	20.56	25.23	28.56	4.75	5.27	5.79	1,840	3,280	3,690	4,650
AUG9C40	22.38	25.63	28.74	5.18	5.76	6.18	1,510	1,700	3,270	4,420
G9C60	18.42	20.43	24.57	4.47	4.56	5.21	1,320	2,120	2,620	3,370
AG9C60	18.99	21.08	25.84	4.64	4.71	5.68	1,450	1,550	2,190	3,850
UG9C60	19.98	21.66	28.87	4.64	4.72	5.73	1,210	1,450	2,150	3,250
AUG9C60	20.08	27.97	30.64	5.61	5.77	6.78	1,260	2,350	2,850	3,690

concrete to form a good conductive network. The cupric nickel sulfate ore acts as a rigid skeleton when it is loaded, and the micropores inside the gel are filled, thus ensuring the mechanical properties of the new type of functional conductive concrete.

Data Availability

All data used to support the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Z.R. contributed in methodology, guidance, review, revision, funding acquisition,project administration, writing–original draft, and writing–review and editing; Y.P. contributed in data curation and software; X.Z. contributed in analysis, conceptualization, translation, formal analysis, funding acquisition, and writing–review and editing; X.C. and H.Z. contributed in supervision and interpretation of data; H.Z. contributed in data curation and validation; X.C. contributed in investigation and visualization. All authors have read and agreed to the published version of the manuscript.

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