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Three-phase composite conductive concrete for pavement deicing

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HIGHLIGHTS

- A three-phase composite conductive concrete is proposed.
- The conductive phase materials contains steel fiber, carbon fiber, and graphite.
- Electrical resistivity of 322 Ω cm is proven to meet the requirements of deicing.
- This pavement presents satisfactory potential for snow-melting or deicing.

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ABSTRACT

The use of electrically conductive concrete for pavement deicing is an emerging material technology. Three kinds of electrically conductive concrete composites, namely, steel fiber, carbon fiber, and steel fiber-graphite, are measured, and the factors that affect conductivity are analyzed. A three-phase composite conductive concrete containing steel fiber, carbon fiber, and graphite is developed for pavement deicing. The conductive property test and the compressive strength of this concrete in the laboratory show that the dispersion uniformity of the carbon fiber, as well as the concrete voids, significantly affects conductivity. The composition ratio, preparation techniques and electrode layout mode of the three-phase composite conductive concrete are introduced and studied. A specimen consisting of a three-phase composite conductive concrete with an electrical resistivity of 322 Ω cm is used in the heating experiment and is proven to render satisfactory heat effects that meet the requirements of pavement deicing.

1. Introduction

Statistics indicate that nearly 10–15% of traffic accidents are caused by ice and snow on the road, which reduce road safety and traffic capacity [1]. Several methods are used to deal with ice in pavements through winter maintenance, such as plowing, natural melting, traffic movement, and chemical treatment. Most highway winter maintenance techniques depend on the use of chemicals and fine aggregates as the primary means of deicing and anti-icing. Although sodium chloride is considered the most cost-effective product, the use of chloride can reinforce bar corrosion, pavement erosion, and environmental pollution.

The use of electrically conductive concrete for deicing is a relatively new material technology. Conductive concrete is a heterogeneous material [2] that is composited by binding and conductive materials, dielectric aggregates, and water. Conductive materials replace ordinary concrete aggregates formulated for the concrete provided high electrical conductivity and high mechanical strength.

Xie et al. [3] applied for a patent on cement-based conductive concrete recipe after his studies determined conductive fibers as excellent conductive phases with high mechanical properties. The effectiveness of conductive concrete for pavement deicing was studied as well [4,5]. Kang et al. [6] used carbon fiber with a diameter of 105–715 μm and length of 2–40 mm as conductive material. The conductive concrete is primarily used for heat, anti-static, and anti-corrosion purposes, as well as for shielding radio frequency waves.

Sherif and Tuan summarized various road deicing methods employed in the past 30 years and proposed steel fiber and shaving were added to the concrete as conductive materials, and heating power to melt road snow and ice and to conduct conductive concrete slab snowmelt trials [1,7,8]. Through continuous research, carbon products were used to replace the steel shaving in the

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conductive concrete mixture design, and had been implemented for deicing on the Roca Spur Bridge of the United States in November 2002 [9,10].

Tang et al. [11] studied the heated layer layout of the carbon fiber conductive concrete affecting road deicing and determined conductive concrete arrangement. More detailed studies have been conducted on carbon fiber conductive concrete, including its resistivity [12], resistance change characteristics [13], electric heating and cooling law [14], snow melting power [15], and an electric element [16]. Shen and Dong [17] discussed the changes in the resistance and 28 day-compressive strength with graphite contents, as well as confirmed the percolation threshold of graphite. Zhu et al. [18] employed a carbon fiber mat as a conductive material for concrete. Wu et al. [19] studied the conductivity and road performance of graphite-modified asphalt concrete for road-deicing.

Based on a study on the conductive properties of steel fiber, carbon fiber, and steel fiber-graphite conductive concrete, a three-phase composite conductive concrete with the carbon and steel fibers, as well as graphite, is proposed. To achieve low resistivity and sufficient strength, the mix proportions and preparation techniques of the three-phase composite conductive concrete are studied. The heat effects of this concrete are verified through a heating experiment in a freezer.

2. Raw materials and the conductive mechanism

Xie et al. [3,4,20] summarized the efforts of numerous researchers in investigating conductive concrete compositions. Conductive concrete can be classified into two: (1) conductive fiber-reinforced concrete and (2) concrete containing conductive aggregates. Conductive fiber-reinforced concrete exhibits increased mechanical strength with diminished conductivity because of the small fiber-to-fiber contact areas that fail to overlap to form a conductive path between conductive materials, such as carbon and steel fibers. The concrete containing conductive aggregates possesses increased conductivity with a resistivity value of 10–30 Ω cm, but relatively low compressive strength (less than 25 MPa). The high water content required during mixing to offset water absorption by conductive aggregates, such as graphite, carbon black, and coke, lead to low compressive strength. The reason for the increased conductivity is that when conductive particle content increased to a certain extent, some of the particles come in contact with one another to form a chain of conductive particles.

The conductive materials used in this research are graphite powder, steel fiber, and carbon fiber. Graphite powder is used for its high carbon content, which can significantly improve the conductivity of cement concrete. Steel fiber can improve the compressive and flexural strengths of concrete to offset the low strength caused by graphite. But when steel fiber is used as a conductive material alone, its conductivity decreases obviously after a period of time because of rust. Carbon fiber can act as a conductive bridge to induce the shorting effect, which can significantly improve concrete conductivity.

2.1. Raw materials

Cement: Portland cement, P·I 42.5;

Coarse aggregate: The normal maximum size of aggregate is 16 mm. Large particles block the conductive path, and carbon fiber is more easily worn in the mixing process;

Fine aggregate: Medium sand;

Superplasticizer (Water Reducer): Naphthalene superplasticizer can reduce 20% of water by a 1% dosage of the cement mass;

Rust inhibitor: Prevents the corrosion of the steel fiber, which is 1% of the cement mass;

Dispersive agent: Hydroxy-propyl-methylcellulose with a dosage of 0.4% of the cement mass, which is used to disperse the carbon fiber;

The specifications of graphite, steel fiber, and carbon fiber are introduced in the following sections.

2.2. Main equipment

Contact type voltage regulator: Rated capacity is 1 kW. This voltage regulator supplies AC power with a frequency of 50 Hz;

Regulated AC stabilized power supply: Provides a stable AC or current voltage;

Freezer: For frozen specimens and negative temperature conditions;

Digital multimeter: Measures voltage, electric current, and resistance;

Infrared thermometer: Measures the temperature of the concrete surface with a built-in emissivity of 0.95, whereas the surface emissivity of the concrete or cement ranges from 0.94 to 0.96 (emissivity refers to the radiation capacity of the object and the ratio of the blackbody radiation capability at the same temperature).

Other instruments include the compression-testing machine and the cement concrete mixer.

3. Selecting conductive materials

3.1. Graphite

Graphite possesses good electrical conductivity can be easily obtained in powder form. Studies indicate that the resistivity of the conductivity of concrete ranges from 10^{-1} Ω cm to 10^{5} Ω cm [21] with graphite dosage changes, and good concrete conductivity is achieved only with high graphite dosage. The use of graphite powder requires a large amount of water, so the strength of concrete will reduce rapidly with increasing graphite powder dosage. When the graphite dosage is greater than 15%, the increasing of its conductivity is not obviously, but the compressive strength decreases remarkable. When the dosage of graphite is greater than 20%, the compressive strength is less than 2 MPa [22].

Three different sizes of graphite powder are used, and its carbon content is greater than 98%. The particle sizes of graphite are 200, 425, and 600 mesh, with a density range from 2.1 g/cm^3 to 2.3 g/cm^3.

3.2. Steel fiber

Steel fiber can improve the concrete in terms of tensile, bending, shear, and other mechanical strengths. Steel fiber also serves a metal conductive function, which is why it is often used as a conductive concrete material. In 1998, Yehia et al. [1] proposed that the addition of steel fiber to concrete can improve the conductivity of the latter. The resistivity of steel fiber concrete was found to increase significantly. This condition can be attributed to the fact that the alkaline environment in the concrete causes the steel fiber to produce a layer of passive film, which leads the resistivity increasing. After one year, the resistivity of steel fiber conductive concrete increases by nearly 60 times. Thus, steel fiber alone is unsuitable for use as conductive material.

A large amount of steel fiber easily agglomerates, thus reducing the workability of concrete and increasing cost. However, a small amount of steel fiber is insufficient to enhance the strength of concrete and hinders it from forming a conductive network. Steel fiber volume ratio should generally range from 0.6% to 1.0% [23]. The largest volume content is 1.2% in the test (see Table 1).

3.3. Carbon fiber

Carbon fiber is among the microcrystalline graphite materials that consist of organic fiber through carbonization and graphitization. The advantages of carbon fiber include high specific strength, high modulus, fatigue resistance, good conductivity, heat transfer, and small thermal expansion coefficient. The conductivity of carbon fiber is stable at high and low temperatures. In addition, carbon fiber possesses a satisfactory corrosion resistance.

Carbon fiber is divided into two types: one is based on polyacrylonitrile (PAN) fiber as raw material to produce PAN-based carbon fiber and the other is pitch-based carbon fiber, which is

Table 1
Properties of steel fiber.

Density (g/cm^3)	Length (mm)	Diameter (mm)	Aspect ratio	Electrical resistivity (20 °C)/(Ω cm)
7.8	35–40	0.6	50–70	1.3×10^{-4}