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Investigation of carbon fillers modified electrically conductive concrete as grounding electrodes for transmission towers: Computational model and case study

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HIGHLIGHTS

- A novel grounding grid for transmission towers using carbon fillers modified conductive concrete was proposed.
- A computational model of the grounding grid was established.
- The stereo grounding grid of conductive concrete reduced the grounding resistance effectively.

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ABSTRACT

The carbon fiber-carbon black composite electrically conductive concrete was employed as new grounding material, which has good grounding performance. As the mixing amounts of carbon fiber and carbon black were both 0.1%, the resistivity of concrete tended to be stable around 530 Ω·cm with the age growth. The resistivity fluctuation of the conductive concrete at different temperature from −40 °C to 50 °C was less than 5%. The compressive strength and flexural strength of the conductive concrete were 35.8 MPa and 6.3 MPa at 28 days, respectively. The rod grounding electrodes were made of the electrically conductive concrete and were laid in parallel on the bottom and side walls of the foundation ditch of transmission towers to build new type of stereo grounding grid. Considering parallel grounding effect, the computational model of grounding resistance of conductive concrete stereo grounding was established based on the calculation of grounding resistance of the metal electrodes. The ranges of grounding resistance amplification factor ψ and the utilization factor η were confirmed through experimental investigation. The laying scheme of electrically conductive concrete rod grounding electrodes in different soil types could be designed according to the model. Eventually, the validity of the model was verified through testing the grounding effect of the stereo grounding grid in practical grounding engineering of transmission towers.

1. Introduction

Electrically conductive concrete (ECC) is a category of concrete containing electrically conductive components to attain stable and high electrical conductivity [1–3]. Conductive concrete has the characteristics of both structural materials and conductive materials, which attracts more and more attentions from researchers and engineers due to its latent applications. Many factors affecting the electrical conductivity and performance of the conductive concrete were studied [4–10]. Nowadays, conductive concrete has been applied to the practical engineering gradually [11–15]. The electrically conductive concrete was used in snow melting project and had obtained good application effects [16,17]. The carbon fiber electrically conductive concrete materials using steel bars with good electrical conductivity as electrodes were used for heating [18,19]. The conductive concrete overlay was cast on the top of a bridge deck as an anode for cathodic protection [20]. Conductive concrete was designed to perform as an electromagnetic shield [21]. Additionally, conductive concrete was applied to improve electromagnetic characteristics on grounding grid and could effectively reduce equipment damage and body damage caused by switching surges [22].

In the grounding engineering of the power network, metallic materials, such as copper or stainless steel, were the main ground-

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ing materials at present [23–25]. Unfortunately, the metallic grounding materials had poor corrosion resistance and fell into disrepair easily due to the stray current in transmission towers [26–31]. Conductive concrete became a focus of the study of grounding materials as it had good mechanical properties, electrical conductivity and corrosion resistance. The resistivity of conductive concrete was lower than that of soil [32]. The contact area between the electrode and soil could be enlarged by laying conductive concrete around the metal grounding electrodes and the grounding resistance could be reduced [33]. Currently, conductive concrete was mainly used as auxiliary grounding material in grounding engineering by casting around the vertical grounding body through mechanical press or directly casting around the level ground [34,35]. However, researches about the grounding characteristics and model of conductive concrete are notably lacking.

Carbon fiber is a good candidate to modify electrically conductive concrete for engineering application because of its high conductivity and tensile stress. Meanwhile, carbon black particles can effectively improve the conductivity of cement matrix. Combining carbon fiber and carbon black provides conductive concrete materials both high conductive performance and excellent mechanical properties. In this paper, the carbon fiber-carbon black composite electrically conductive concrete was used as a new grounding material, and its basic grounding characteristics such as conductivity, temperature stability and mechanical properties were studied. The concrete was used to made rod grounding electrodes which were laid in parallel on the bottom and side walls of the foundation ditch of transmission tower to build new type of stereo grounding grid. Considering parallel grounding effect, the computational model of grounding resistance of conductive concrete stereo grounding was established based on the calculation of grounding resistance of the metal electrodes. The validity of the model was verified through testing the grounding effect of the stereo grounding grid in practical grounding engineering of transmission towers.

2. Experimental methods

2.1. Materials

The raw materials of the conductive concrete were Portland cement, fly ash, silica fume, natural river sand and high range polycarboxylate water reducer. The chemical compositions of the cement, fly ash and silica fume were given in Table 1. Two different types of electrically conductive fillers, carbon fibers and carbon blacks, were employed in this study. The first ones were PAN-based carbon fibers, with average length of 10 mm and density of 1.8 g/m^3. The latter ones were acetylene black particles, with average diameter of 40 nm and density of 2.0 g/cm^3.

The basic mix proportion of the concrete was as follows: *m* (cement): *m* (fly ash): *m* (silica fume)=0.75: 0.2: 0.05, water-binder ratio of 0.25, and sand-binder ratio of 1.4. The density of concrete was 2.2 g/m^3. The mixing amounts of carbon fiber and carbon black were calculated based on their volume fraction in the concrete. The volume fraction of both carbon fiber and carbon black were 0.05% and 0.05%, 0.1% and 0.1%, 0.3% and 0.3%, 0.5% and 0.5%, respectively.

2.2. Methodology

First, the sand and carbon fiber were put into a mortar agitator and evenly stirred for about 1 min to make the mix uniformly. Then, the cement, fly ash, silica fume, carbon black as well as water were poured into the mortar agitator then stirred for 2 min. Furthermore, the high range polycarboxylate water reducer was put into the mortar agitator then the mixtures were stirred until to the desired workability. Finally, the mixtures were poured into the 40 mm × 40 mm × 160 mm steel moulds for the specimens in which there were four spiral copper electrodes. The electrode arrangement of the specimens is shown as Fig. 1. The moulds were vibrated to make the mixtures compacting. After curing, the resistivity was tested every seven days. The resistivity of the material is calculated as Eq. (1) where *U* is the voltage and *I* is the current.

$$\rho = \frac{R \times S}{L} = \frac{R \times 4 \times 4}{4} = 4\frac{U}{I} \tag{1}$$

ECC must meet the requirements of basic properties such as conductivity, temperature stability and mechanical performance as grounding material. Through testing the resistivity of the specimens, the contents of carbon fiber and carbon black were optimized and the concrete with good electrical conductivity was produced. The changes of resistivity along with the increase of age and temperature were studied. On this basis, the 40 mm × 40 mm × 160 mm specimens were prepared for the strength test. The ECC rod grounding electrodes were prepared for grounding resistance test. The rod grounding electrodes were 500 mm length and its radius were 17 mm. The soil resistivity and grounding resistances were measured using ZC29B-1 ground resistance tester.

3. Computational model of the grounding resistance

3.1. Assumptions of the model

Some assumptions are made about the computational model as follows:

1) The resistivity of the earth from the grounding to the infinity is assumed as a constant.
2) The grounding electrodes are homogeneous and every part of the grounding electrodes has the same resistivity.
3) The buried depth of the parallel grounding electrode is deeper than the resistance region and the distance between the grounding electrodes is greater than two times the resistance region.

3.2. The resistance of ECC rod grounding electrode

The grounding electrodes of which the grounding resistance can be obtained rigorously in theoretically are spherical grounding electrode and rotary spheroid grounding electrode [36]. The resistance of the spherical grounding electrode and rotary spheroid grounding electrode can be calculated by following equations:

$$R = \frac{\rho}{2\pi r} \tag{2}$$

Table 1
Chemical compositions of cementitious materials (%).

Materials	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	K_2O	Minors	LOI
Cement	63.70	20.30	4.83	3.25	3.28	2.67	1.28	0.60	3.26
Fly ash	7.50	49.10	32.50	4.78	0.80	0.58	1.88	2.31	1.60
Silica fume	0.42	93.43	0.69	1.07	1.21	0.41	1.19	0.55	1.03