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Preparation and performance of conductive mortar based on lightweight conductive aggregates

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HIGHLIGHTS

- Conductive aggregate was prepared by using porous ceramsite loaded with agar gel.
- The conductivity of conductive mortar was improved by the conductive aggregates.
- The resistivity of conductive mortar with CA can be quantitatively calculated.

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ABSTRACT

In this study, lightweight conductive aggregates (CA) loaded with modified agar gel was prepared, and their influence on the resistivity of conductive cement-based materials was investigated. Results indicate that by impregnation treatment, agar gel was efficiently loaded in porous lightweight aggregates, thus CA with a resistivity of 0.5 Ω·m was obtained. The prepared CA significantly improved the conductivity of cement-based materials, and the modification effect was and related to the altered microstructure of cement matrix and conductive network established by CA, and can be characterized by GEM model. The prepared CA have promising potential for applications related to cement-based composites.

1. Introduction

Cement-based materials generally present poor electrical conductivity (the electrical resistivity of dry concrete is usually in the range from 5.4×10^5 to 11.4×10^3 Ω·m [1,2]) due to that their main components are inorganic solid phases i.e. aggregates, cement clinkers, hydration products (CSH, CH, AFt and etc.) and vapor phases possessing several orders higher electrical resistivity, compared to the liquid phase [3]. Normally, when used as construction materials, it is not necessary for cement-based materials to possess excellent electrical conductivity. However, when applied as special functional materials, e.g. smart sensors, external anode mortar in cathodic protection system, inorganic piezoelectric materials, etc. [2,4–6], their electrical conductivity is very important and can significantly influence the performance.

Therefore, many approaches were made to improve the electrical conductivity of cement-based materials. The most commonly used method was to establish an efficient conductive network by adding either conductive enhancing particles e.g. carbon blacks [7,8], steel shavings [9], iron ores or slags [9] or conductive fibers such as steel-fibers [9], carbon-fibers [10–13], etc. Among them, carbon-fibers are considered to be a suitable conductive component for the preparation of conductive mortar due to its excellent conductivity (10^{-5}–10^{-6} Ω·m [14]) combined with low density, high strength and elastic modulus [15]. It was reported that a satisfactory modification resulting in resistivity, decreased from 10^2–10^6 Ω·m to 1–2 Ω·m or even lower values [14,16,17], can be obtained with a low addition (0.6–2.0 vol% [16,18,19]). Several additional beneficial effects, e.g. increased mechanical properties [20–23] and toughness [24] can be also achieved for conductive mortar based on carbon fibers. However, it was also reported that when carbon fibers were admixed in cement matrix, a good dispersion was difficult to achieve especially with a high addition content [25], leading to a decreased modification effect on the conductivity.

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Moreover, the non-uniform distribution of carbon fibers may result in serious side effects. For example, for some particular applications, i.e. external conductive anode mortar in cathodic protection system, the non-uniform distribution of carbon fibers may lead to over protection or under protection of the reinforcement at specific locations, thus reducing the efficiency of cathodic protection [24].

It is well known that aggregates normally occupy 60–80 vol% in concrete [26]. The most commonly used aggregates (e.g. lime stone) present a poor conductivity with a resistivity in the range of 1.5×10^2–$3 \times 10^2\ \Omega \cdot m$ [9]. Therefore, if the insulating aggregates can be altered to be conductive by special modification methods, the conductivity of cement-based materials will be definitely enhanced. Wang et al. [27] prepared a new type of conductive aggregates by the calcination of magnetically fly ash under reducing atmosphere. The prepared conductive aggregates presented a low electrical resistivity of about 0.1 Ω m and the conductive mechanism was related to the reduction of iron oxides in fly ash to iron under the reducing atmosphere, forming an electron conductive path. Chen et al. [28] used semi-dry mixing method and palletization technique to prepare conductive aggregates incorporated with carbon fibers and carbon black. The prepared aggregates possessed a resistivity in the range of 3.40–7.34 $\Omega \cdot$m due to the efficient conductive network in the aggregate established by carbon fibers and carbon black. However, the influence of the prepared conductive aggregates on the conductivity of cement-based materials was not investigated the above mentioned studies. He et al. [29] prepared a type of conductive aggregates (with a resistivity less than 5 $\Omega \cdot$m) based on graphite and clay by using calcination process under N_2 atmosphere; the addition of the prepared conductive aggregates decreased the resistivity of mortar by one or two orders of magnitude (around 1 $\Omega \cdot$m) in the presence of the same content of carbon fibers. In this study, the prepared conductive aggregates presented tablet shape (with a diameter of 35 mm and thickness of 5 mm), and it was reported that the shape of aggregates may also influence the diffusivity and thus the conductivity of cement-based materials, besides their conductivity [30]. Based on the reported studies, it can be found that the preparation method of the above introduced conductive aggregates were complex (including calcination process (up to 1200 °C) under either N_2 or reducing atmosphere and grinding procedures) and the bulk density of cement-based material was increased. Therefore, the main challenge of the conductive aggregates is preparing them with excellent conductivity, spherical shape and low density by using easy preparation method.

In this study, a novel type of lightweight conductive aggregates was designed and prepared based on ellipsoidal porous ceramsites loaded with modified agar gel by using impregnation method. The conductivity and micro/macro properties of the conductive mortar based on the prepared lightweight conductive aggregates were then investigated. Further, the general effective media model was applied to illustrate the influence of lightweight conductive aggregates on the conductivity of mortar.

2. Experiment

2.1. Materials

Ordinary Portland Cement OPC PII 42.5 (China Resources Cement Holdings Ltd) was used in this study. The chemical composition of the used cement is listed in Table 1. The lightweight aggregates used in this study were commercially porous ceramsites, and the chemical compositions and basic physical characteristics are presented in Table 2. Ordinary sands used in this study were siliceous river sands. In order to keep the volume and surface area of the interfacial transition zone constant, the particle size of ordinary sands was kept the same as the used porous ceramsites.

Agar powders $(C_{12}H_{18}O_9)_n$ used in this study was plant tissue culture grade with a gel strength of 1300 g/cm^2 (code: H8145). Agar is a mixture of seaweed polysaccharides with the main molecular group of b-D-galactose and 3,6-anhydro-a-Lgalactose (LA) repeating units [31]. In this study, agar gel was modified by the addition of graphite powders and electrolytes to further improve its conductivity. The detail information of graphite powders used for the preparation of modified agar is as follows: median diameter of 33.0 μm; specific surface area of 0.111 m^2/g; carbon content > 98%; 0.45% Fe content and 0.5% dry loss. Other chemical regents applied for the agar modification, e.g. NaOH and $NaNO_2$ were analytical grade regents. It was reported that agar dissolved in water above 90 °C [32], and possessed excellent gelling ability when cooling at very low concentration (0.04%) [33]. Therefore, by applying heating and subsequent cooling procedures, agar gel can be efficiently loaded into porous ceramsites to prepare the lightweight conductive aggregates.

Deionized water was used for the preparation of modified agar solution, and tap water was used as the mixing water for the preparation of conductive mortar specimens.

Titanium (Ti) mesh with dimensions of 38 mm $\times$ 40 mm and wire diameter of 0.5 mm was used as electrode plates in sample preparation for 4-point DC resistivity measurements.

2.2. Sample preparations

2.2.1. Preparation of modified agar gel solution

The mixture and preparation procedure of the modified agar gel solution was listed in Table 3. It was reported that ions in concrete pore solution can be one of the important reasons for improving the conductivity of cement-based materials [34,35]. Similarly in this study, NaOH and $NaNO_2$ were added in agar gel to further increase its ionic conductivity. During the preparation, different components were added in the order and conditions as shown in Table 3. The uniform distribution of graphite powders in the solution (with a viscosity of 0.1–0.2 Pa·S) was achieved under the mixing condition.

2.2.2. Preparation of lightweight conductive aggregates

In this study, lightweight conductive aggregates (CA) loaded with modified agar gel were prepared by impregnation method as shown in Table 4. Before impregnation, porous ceramsites were pre-dried in oven at 100 °C until the weight was constant. The modified agar gel was heated at 90 ± 5 °C before mixing with ceramsites to obtain a low viscosity for better impregnation effect. After mixing for 2 min at 80 °C, the mixture of solution and ceramsites were stewed and cooled to 40 °C for 10 min before screening. Finally, ceramsites were screened with a round hole sieve (φ3.5 mm) and then placed in a fridge at 0 °C for agar gelation. In this way, the modified agar solution was incorporated into the internal pores in ceramsites and the lightweight conductive aggregates were obtained. The density of the prepared lightweight conductive aggregates was in the range of 0.87–1.1 g/cm^3.

2.2.3. Preparation of agar gel specimens with different air contents

Due to the spherical morphology, it is very difficult to directly measure the electrical resistivity of single lightweight conductive aggregate (CA). CA is consisted of spherical ceramsite, air voids, internal pores and modified agar gel phase, among which only modified agar gel phase is conductive (air voids and ceramic phase are considered as insulating materials). Therefore, the conductivity of CA is mainly depended on the loading capacity (defined as weight alteration of ceramsites before and after impregnation) of agar gel during the preparation. Further, the internal pores of the prepared CA in this study was not fully loaded with agar gel (characterized by light microscopy, as shown in Fig. 1): the agar solution was first infiltrated and adsorbed on the internal wall of ceramsite and the rest agar solution was then filled in the pore space (under high loading capacity circumstance). As a result, the tortuous and complicated internal gel structure (conductive path in CA) can be considered as agar gel with air voids.

Based on the above characteristics, agar gel specimens with different air content were designed and prepared to evaluate the resistivity of CA as follows:

Table 1
Chemical composition of OPC PII 42.5.

Chemical compositions/wt.%													
CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	TiO_2	MnO	Na_2O	SrO	P_2O_5	NiO	Loss
65.01	20.69	5.71	4.18	2.52	0.61	0.61	0.31	0.16	0.08	0.05	0.03	0.03	3.23