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Utilization of high carbon fly ash and copper slag in electrically conductive controlled low strength material

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HIGHLIGHTS

- Both high carbon fly ash (HCFA) and copper slag (CS) are electrically conductive.
- Both HCFA and CS are waste materials with low reuse rate.
- CS was reused as a substitute for a fine aggregate in the CLSM.
- Electrically conductive CLSM was developed using both HCFA and CS.
- Various experiments were performed on the developed CLSM.

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ABSTRACT

The aim of this experimental investigation is to develop electrically conductive controlled low strength materials (CLSM) using both fly ash with high content of unburned carbon particles (HCFA) and copper slag as a fine aggregate, both of which are waste materials with low reuse rate. Various experiments, including flow consistency test, bulk density measurement, unconfined compression test, and electrical conductivity (σ_{mix}) measurement were performed on the developed electrically conductive CLSM. For comparison with the results of the developed conductive CLSM, various experiments were also performed on CLSM containing electrically nonconductive particles (low carbon fly ash (LCFA) and sand). The results of this study demonstrate that σ_{mix} of the tested CLSM specimens increases with increasing copper slag fraction in aggregate and the measured σ_{mix} of the CLSM based on HCFA is greater than that with LCFA because both HCFA (or unburned carbon particles) and copper slag are electrically conductive. The measured flow consistency, bulk density, and unconfined compressive strength (UCS) of conductive CLSM were comparable with those of nonconductive CLSM. Therefore, the electrically conductive CLSM can be developed using both HCFA and copper slag. Finally, the relationship between UCS and $1/\sigma_{mix}$ was also investigated in this study.

1. Introduction

The annual recycling rate of fly ash has decreased due to the limited reuse of fly ashes with high content of unburned carbon particles in concrete industry, which is the biggest market for the beneficial reuse of fly ash, according to the regulation of [5]. Thus, the beneficial reuse of high carbon fly ash (HCFA) in non-concrete applications is very important [10,14]. One possible application of the HCFA is its use in controlled low strength material (CLSM) because the construction project require a large amount of material [1,16] and HCFA has been successfully used in manufacturing CLSM [34]. CLSM has characteristics of high flowability, self-cementing, self-compacting, and low compressive strength for future excavation [2]. Because the addition of fly ash in CLSM can increase the flowability and reduce the segregation of CLSM [37,40,48], fly ash is a very important component in making CLSM.

Copper slag is a granular industrial waste produced from ores during the smelting of copper. Although copper slag can be beneficially reused in abrasive tools, road construction, and ballast, a considerable amount of copper slag is still disposed in landfill [26], reflecting the demand for other applications of copper slag. In this aspect, the reuse of copper slag as a substitute for fine aggregate (i.e. sand) in CLSM is promising. Previous researchers

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have investigated the use of copper slag as a fine aggregate in CLSM or concrete [8,17,21,29,36,39,41]. These studies demonstrated that the compressive strength of CLSM or concrete using copper slag is comparable with that using sand as a fine aggregate. Additionally, some studies noted that the use of copper slag as an aggregate reduces bleeding and shrinkage of concrete [21,36].

This study aims at developing an electrically conductive CLSM using HCFA and copper slag as a fine aggregate (or filler) because both HCFA and copper slag are waste materials with low reuse rate and have an electrically conductive characteristic. Various experiments, including flow consistency test, bulk density measurement, unconfined compression test, and electrical conductivity measurement were performed on the developed electrically conductive CLSM. The results of conductive CLSM were compared with those of CLSM containing electrically nonconductive particles (low carbon fly ash and sand).

2. Background

2.1. Electrically conductive CLSM

Several studies have been performed to develop the electrically conductive CLSM because electrically conductive CLSM (or electrically conductive concrete) can be used not only in common CLSM applications such as backfills, structural fills, conduit bedding, and erosion control, but also in other engineering applications such as electromagnetic shielding, deicing roads, secondary anode in a cathodic protection system, and back fill compounds of earthing systems [27,30–32]. In previous studies, several electrically conductive materials (e.g. steel fiber, carbon black, carbon fiber) were added to CLSM to develop electrically conductive CLSM (or electrically conductive concrete) [9,11,33,47]. Among the various industrial by-products, high carbon fly ash (HCFA) has been used in many previous studies to develop electrically conductive CLSM [27,35] because the unburned carbon particles in fly ash are an electrically conductive material [15,20]. Additionally, the copper slag has a very high content of iron (>25% by weight); thus, copper slag has an electrically conductive characteristic [19,44]. Consequently, the aim of this study is to develop electrically conductive CLSM using only the waste materials, which are HCFA and copper slag.

2.2. Electrical conductivity

The electrical conductivity (σ_{mix}) of CLSM can be determined by the sum of particle conduction (electronic conduction via the contacts between particles) and pore water conduction (ionic conduction through the pore water) [25,27]; thus, σ_{mix} can be expressed as follows [13]:

$$\sigma_{mix} = \sigma_p \cdot \frac{(1-n)}{T_p^2} + \sigma_w \cdot \frac{n}{T_w^2} \quad (1)$$

where σ_p and σ_w = electrical conductivities of the particles and pore water, respectively in S/m; n = porosity; T_p = particle tortuosity; and T_w = pore water tortuosity. Eq. (1) indicates that the particle conduction (K_p, the first term in Eq. (1)) decreases with an increase in porosity (or water content) due to the decrease in the volume fraction of particles (or solid), while the pore water conduction (K_w, the second term in Eq. (1)) increases with an increase in porosity due to the increase in the volume fraction of the pore space. Additionally, Eq. (1) demonstrates that K_p and K_w are determined by σ_p and σ_w, respectively, reflecting that the CLSM containing electrically conductive particles, which have high values of σ_p, will show greater electrical conductivity than the CLSM containing electrically insulating particles, which have very small values of σ_p. It should be noted that both K_p and K_w will contribute to the measured electrical conductivity of CLSM at the early curing stage; however, the magnitude of K_w will gradually decrease with an increase in curing time due to the hydration process, resulting in the discontinuity of the pore water phase path for K_w. This implies a huge increase in T_w in Eq. (1); thus, the electrical conductivity of CLSM at the later curing stage may be determined solely by particle conduction [25,27], leading to:

$$\sigma_{mix} = \sigma_p \cdot \frac{(1-n)}{T_p^2} \quad (2)$$

Comparing Eqs. (1) and (2) demonstrates that the measured electrical conductivity of the hardened CLSM is smaller than that of the fresh CLSM because of the absence of pore water conduction.

3. Experimental program

3.1. Materials

CLSM typically consists of cement, fly ash, fine aggregate, and water. In addition to ordinary Portland cement and distilled water, two types of fine aggregates (sand and copper slag) and two types of fly ashes (fly ash with high content of unburned carbon particles (HCFA) and fly ash with low content of unburned carbon particles (LCFA)) were selected for the production of CLSM in this study.

The chemical compositions of each material were characterized by X-ray fluorescence (Axios minerals, PANalytical) and are shown in Table 1. The loss-on-ignition (LOI) values of HCFA and LCFA are 19.20% and 1.67%, respectively. The sand used in this study is mainly composed of SiO_2, and the Fe_2O_3 content of copper slag is 64.60% by weight.

The index properties of the tested fly ashes, sand, and copper slag are shown in Table 2, and the particle size distribution curve is shown in Fig. 1. Both fly ashes are silt-sized materials, having a relatively smaller specific gravity than typical soils. The median particle sizes of sand and copper slag are very similar, but the specific gravity of copper slag was much greater than that of sand due to the high content of iron (Table 2).

3.2. Sample preparation

Nineteen CLSM mixtures were prepared for performing various experiments; Table 3 shows the mix ratios of the 19 specimens used in this study. The testing program shown in Table 3 can be divided into 4 Cases (A-1, A-2, B-1, and B-2): Cases A-1 and A-2 are used to examine the effect of copper slag fraction as a fine aggregate on the flow consistency, bulk density, unconfined compressive strength, and electrical conductivity of the developed CLSM, while Cases B-1 and B-2 are used to examine the ratio between HCFA and copper slag on the engineering properties of the developed CLSM.

Cement, fly ash, and fine aggregate (sand or copper slag) were mixed in dry condition for 10 min. Then, a predetermined amount of water at the water content (weight of water/weight of solid, including fly ash, fine aggregate, and cement) shown in Table 3 was added to the dry mixtures and mixed for another 20 min. Note that water contents of all specimens except HCFA50 and HCFA52 in Table 3 satisfy the flowability recommended by [3]. The fresh CLSM mixtures were poured into a metallic 50 mm cubic mold without compaction and the molds were sealed in a plastic bag to avoid water loss. All specimens were demolded after 2 days of curing and were kept in a moisture chamber at ambient temperature of 23 ± 2 °C and relative humidity of 99% until testing. All experiments were performed at 3, 7, 14, and 28 days of curing, and all