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Effects of coal-metakaolin on the properties of cemented sandy soil and its mechanisms

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HIGHLIGHTS

- Coal-metakaolin was used to explore the properties of cemented sandy soil.
- Coal-metakaolin improved the early strength of cemented sandy soil.
- Coal-metakaolin changed the morphology of hydration products in cemented sandy soil.
- Coal-metakaolin changed the porosity and pore distribution in cemented sandy soil.

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ABSTRACT

In this study, effects of coal-metakaolin (CMK) on mechanical and microstructural properties of cemented sandy soil were investigated. The mechanical properties were evaluated by unconfined compressive strength (UCS) and stress-strain relationships. By incorporating CMK, the 28 d UCS was improved by 1.68–2.18 times, the ultimate strain reduced to 1.63–1.75%. Microstructural properties were investigated by using thermogravimetry, X-ray diffraction, mercury intrusion porosimetry and scanning electronic microscopy. The results showed that CMK can accelerate cement hydration, refine pore structure, and improve the interfacial zone between soil particles and binder, due to its pozzolanic nature and fine particle size.

1. Introduction

Cemented soil has been accepted worldwide as a soil improvement technology that uses cement to stabilize soils. It has been proved that the technology is highly advantageous because of the high usage rate of the original soil, low cost, convenient construction, and flexible reinforcing forms. These merits have led to increased popularity of the application of cemented soil technology in the areas of foundation treatment, slope reinforcement, leakage stopping, rammed earth wall engineering, etc. [1,2]. However, in engineering practices, cemented soil technology still has the disadvantages of lower early and final strength. Moreover, the production of cement requires a large amount of energy (850 kcal needed for 1 kg clinker), entails resource consumption (1.7 tons of clay needed for 1 ton of clinker), and produces high carbon emission (for every ton of cement manufactured, approximately 0.94 ton of CO_2 is released into the atmosphere [3,4]). Therefore, the search for a substitute for cement in cemented soil, without compromising its properties, has become a significant and important task for geotechnical engineering researchers.

Some pozzolanic materials, namely fly ash, slag, and silica fume, have been utilized for years as partial substitute forcement in cemented soil. Fly ash is the most widely used pozzolanic material in cemented soil. Researchers have shown that the addition of fly ash to cemented soil can reduce the plastic index of cohesive soil, decrease the expansion of soil, and improve its compressibility. However, it also reduces the early strength of cemented soil [5–8]. Slag used in cemented soil can improve the performance as well as the ultimate strength of cemented soil, but on the downside, it too reduces the early strength of the soil [9–13]. Silica fume enhances the strength and durability properties of cemented soil, but its application in the engineering area is limited due to its high cost, low yield, and secondary pollution [14–16]. Therefore, the

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exploration of other effective substitutes for cement in cemented soil is necessary and urgent.

Metakaolin (MK) is another pozzolanic material that has been applied to cemented soil in recent years. The mechanical properties of cemented clays containing MK have been investigated [17,18]. It was found that MK significantly improved the compactability and strength of cemented soils. Deng et al. [19] reported that MK effectively decreased the hydraulic conductivity of cemented soils. Xing et al. [20] found that there was an optimal MK content for the strength of salt-rich cemented soils. The above mentioned applications and researches of MK in cemented soil indicate that MK can enhance the strength and impermeability of various types of cemented soil, though the improvement effect may vary. However, the pozzolanic reactivity of MK is affected by conditions including geological formation, purity, and grain sizes [21–23]. Thus, the effects of different MKs on cemented soil can differ.

Coal-metakaolin (CMK) is an amorphous substance that is formed by the calcination of coal-kaolin under suitable temperatures. Coal-kaolin is a gangue with more than 80% kaolin content, that is a unique kaolin resource in China, and it has been proved that its reserve is about 1.7 billion tons in China [24,25]. The effective utilization of coal-kaolin and CMK can not only reduce the pollution caused by the stockpiling of coal gangue but also create additional value in certain areas. At present, CMK has some applications in ceramics, electricity, coatings, rubber, and other fields [26], but has not received attention in the construction field. Du et al. [27] found that CMK is superior to silica fume with regard to improvement of the bending strength of concrete. CMK has chemical compositions similar to those of MK, but its molar ratio between SiO_2 to Al_2O_3 is closer to 2.0. Further, the content of non-reactive gredients of CMK is lower than that of MKs produced by several major MK sources elsewhere in the world [28]. CMK has some physical properties similar to those of MK, including small grain size and high surface energy. It is thus interesting and attractive to investigate the effects of CMK on the properties of cemented soils.

Sandy soil is a type of foundation soils widely distributed in nature. Unlike other soils, the composition of the sandy soil is single and contains little clay minerals; therefore, the action mechanism of CMK in the cemented sandy soil is not affected by the active material in the soil. The objective of this study was to examine the effects of CMK on the properties of cemented sandy soil and its mechanisms. Different proportions of CMK and cement were used as binder material to stabilize the sandy soil. The mechanical properties, namely unconfined compressive strength (UCS) and stress-strain relationship, of cemented sandy soils were explored. X-ray diffraction (XRD), thermogravimetry (TG), mercury intrusion porosimetry (MIP), and scanning electronmicroscopy (SEM) were used to study the chemical compositions, pore structure, and microstructure of cemented soil, in order to explain the reinforcing mechanism of CMK on the properties of cemented soil.

2. Materials

2.1. Sandy soils

The sandy soils used in this study were obtained from a construction site in Taiyuan (Shanxi, China). Sandy soils are widely distributed in Taiyuan, so the research presented in the current study, using cement to stabilize sandy soils, is important and meaningful in this area. The specific gravity of the sandy soils is 2.68. The grading curve of the sandy soils used in the current study is shown in Fig. 1. The soil has 2%, 87%, and 11% of silt, sand, and gravel, respectively. The uniformity coefficient (C_c) and coefficient

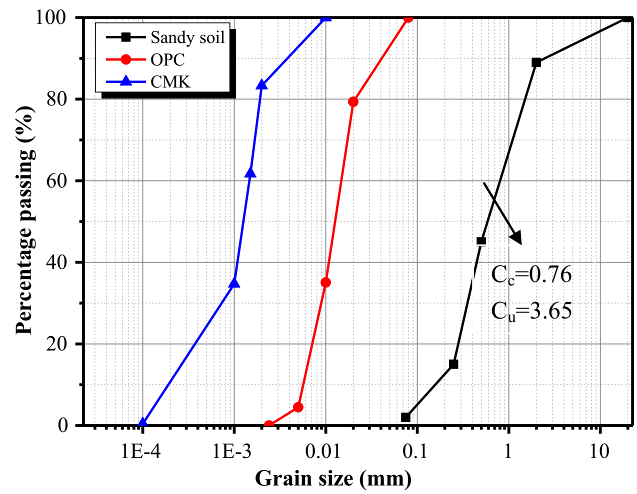

Fig. 1. The grading curves for materials.

of gradation (C_u) of the sandy soil are 0.76 and 3.65, respectively. According to Chinese standard GB50021-2001(2009 version), the sandy soil belongs to the category of 'poorly graded coarse sand'.

2.2. Cement and CMK

The ordinary Portland cement (OPC) and CMK in the experiment were produced in Taiyuan, Shanxi, China. The CMK was produced by Shanxi Jinyu-Kelin Technology Co., Ltd. It was produced by heating coal-kaolin for 40 min at 800 °C. The OPC was from Taiyuan Shi-Tou Cement Co., Ltd. Table 1 shows the chemical compositions of the OPC and CMK measured by an X-ray fluorescence test. The specific gravity of the OPC and CMK was 3.15 and 2.60, respectively. Fig. 1 shows the grain size distribution of the OPC and CMK as tested by a Rise 2022 laser particle sizer. The average particle size of the OPC was 14.85 μm, and the specific surface area was 0.485 m^2/cm^3. The average particle size of the CMK was 1.52 μm, and the specific surface area was 4.74 m^2/cm^3. As shown in Fig. 2, the CMK particles had thin, plate-like morphology and stacked together due to their high surface energy.

3. Experiments

3.1. Sample preparation

Table 2 shows the mix proportions of the cemented soils. In this study, we used an additional 15% binder to stabilize the sandy soils. The term 'binder' refers to the combination of cement and CMK. In the binder, different amounts of CMK were used to partially replace cement, to investigate the effects of CMK on the properties of the cemented sandy soils. It should be noted that the binder content in this study, 15% of the sandy soils, was determined according to the design guideline of cemented soil pile established in JGJ 79-2012. For all mix proportions, the water to solid materials (soils and binder) ratio was kept at 0.15. In this study, it was found that that ratio kept the fresh mixtures workable. The volume ratio of binder and soil in cemented soil was calculated, as shown in Table 2. It should be noted that the dry density varied little, even when different amounts of CMK were used to replace cement.

After air drying, the as-received sandy soils were sieved by a 2 mm sieve and dried by oven at 105 °C to a constant weight. The dry materials, namely sandy soil, cement, and CMK, were blended for 1 min using a mixer. Then the correct amount of water was poured