Construction and Building Materials 186 (2018) 174–181

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effects of coal-bearing metakaolin on the compressive strength and permeability of cemented silty soil and mechanisms

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HIGHLIGHTS

- Coal-bearing metakaolin improved the properties of cemented silty soil.
- The optimum mass ratio was found to be 1:6.5–1:4.
- Coal-bearing metakaolin filled both the interfaces and the bulk paste.
- The interfacial transition zone and the pore structure were improved.

ARTICLE INFO

Article history:
Received 16 January 2018
Received in revised form 9 July 2018
Accepted 10 July 2018

Keywords:
Silty soil
Cement
Coal-bearing metakaolin
Permeability
Compressive strength
Microstructure

ABSTRACT

The effects of coal-bearing metakaolin (CMK) on mechanisms, unconfined compressive strength (UCS) and impermeability of cemented silty soil were experimentally investigated in this study. The hydration, pore structure and microstructure of cemented silty soil were improved by incorporating moderate amounts of CMK, according to X-ray diffraction, mercury intrusion porosimetry, and scanning electron microscopy. The UCS and impermeability of cemented silty soil were significantly improved, which is consistent with the microstructural results. However, cemented silty soil with excessive amounts of CMK exhibited inferior properties. The optimum mass ratio of CMK to cement was between 1:6.5 and 1:4.
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1. Introduction

Kaolinite is a phyllosilicate characterized by a rather simple chemical compositions of Si, Al, O, and H [1]. According to different sedimentary environments, kaolinite can be categorized into non-coal-bearing kaolinite and coal-bearing kaolinite. Non-coal-bearing kaolinite is mostly separate ore bed, and its formation has nothing to do with coal. Non-coal-bearing kaolinite is found mainly in the USA, Brazil, France, Britain, China, Germany, etc. The total reserve of non-coal-bearing kaolinite in the world is about 30,000,000,000 ton, it is used in ceramics, papermaking, coatings, rubber, catalysts, plastics and other industries [2–5]. Metakaolin, formed by calcinations of non-coal-bearing kaolinite at 600–900 °C, has the characteristics of small particle size, high activity, stable performance, and pozzolanic effect. Its application in the cement industry had been widely studied [6–17]. [6–9] Showed that partially replacing cement in concrete with metakaolin can improve the strength, resistance to chloride ion penetration and durability of the concrete. Kolovos et al. [14–17] applied metakaolin to cemented soil and found that the cemented soil exhibited good tensile strength, compressive strength, and anti-penetrability when the cement was replaced partially with metakaolin.

Coal-bearing kaolinite, another kind of kaolinite, was found as suspended load deposits in coal swamps, under clays, or as composite residual and hydrothermal kaolinization in coal swamps [1]. It mostly exists at the top or bottom of the coal seam, accompanying gangue or the separate formation of the ore bed. At present, the proven reserve of coal-bearing kaolinite is 1,970,000,000 ton, and expected total reserve is 18,050,000,000 ton, which is more than 60% of the world's non-coal-bearing kaolinite reserve. The coal-bearing kaolinite is mostly extracted

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https://doi.org/10.1016/j.conbuildmat.2018.07.057
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along with coal resources and often discarded as gangue. This not only took up a lot of land, but also caused serious environmental pollution. Therefore, the utilization of coal-bearing kaolinite have become an important research topic for environmental protection and sustainable development [5].

Like non-coal-bearing kaolinite, coal-bearing kaolinite can form coal-bearing metakaolin (CMK) by calcinations at 600 °C–900 °C. The main oxide components of CMK are SiO_2 and Al_2O_3. Compared with metakaolin from other major producing countries in the world, CMK from Shanxi, China has higher purity, with a SiO_2/Al_2O_3 molar ratio closer to 2 (see Table1). Note that the theoretical molar ratio of pure metakaolin is 2.0. The average particle size of CMK is around 1.52 μm. In addition, CMK has high pozzolanic activity, owing to its thermodynamically unstable state [18]. Based on these characteristics of CMK, we can infer that CMK has similar advantages to metakaolin. Thus, it is theoretically feasible to use CMK to enhance the properties of cement-based materials.

In anti-seepage projects, including earth rockfill dams, landfill, deep foundation pits, and river dykes, it is necessary to adopt cemented soil mixing pile continuous cutoff wall as an impervious body. These cut off walls all required high compressive strength and low hydraulic conductivity. Compressive strength and hydraulic conductivity were the key parameters for the design and quality control of cutoff walls [23]. Because of the variety of soil properties, the strength and hydraulic conductivity of soil stabilized solely with cement often failed to meet construction requirements [24]. In view of this, many researchers had attempted to improve the strength and impermeability of cemented soil by including cementitious supplementary materials, such as fly ash, ardealite, lime, or slag-incorporating cement [25–29]. Recently, nanomaterials, including nano silica, nano calcium carbonate etc. [21,30–34] had been used to consolidate cemented soils. In addition, metakaolin was reported to improve both the strength and the impermeability of cemented marine clay [14–17]; however, the effect of metakaolin in silty soil still remains unknown. Silty soil is a Quaternary period loose river deposit, widely distributed in the middle and lower reaches of such rivers as the Yellow, Huaihe and Haihe rivers in China [35]. Silty soil had the characteristics of poor cohesion, high permeability, and low stability [35,36]. Therefore, the properties of silty soil must be improved before application in anti-seepage projects, such as earth rockfill dams, landfill, deep foundation pits, and river dykes. Application of CMK in silty soil is not only useful in underground anti-seepage engineering projects, but also makes full use of local coal-bearing kaolinite, to protect our environment.

This study first investigated the influence of CMK on the hydration products, pore structure, and microstructure of cemented silty soils. The CMK effect mechanism in cemented silty soil were discussed. Then mechanical properties of CMK-modified cemented silty soils contain unconfined compressive strength and impermeability were conducted. The effect of CMK content and curing ages for the mechanical properties of CMK-modified cemented silty soils were discussed. Finally, the optimal mass ratio of CMK to cement in cemented silty soil was summarized.

2. Materials and methods

2.1. Materials

The materials used in this test included silty soil, CMK, and cement. Silty soil was obtained from a construction site in Taiyuan, Shanxi, China. The physical properties of silty soil were shown in Table 2. According to the Chinese national standard GB 50021-2001 [37], the soil used in this test was categorized as “silty soil.” According to the ASTM D 2487-11 [38], the soil is was categorized as “sandy lean clay”. The particle size distribution of the silty soil was shown in Fig. 1. The particle size of 0.005–0.075 mm accounted for 92.4% of the total soil mass.

CMK was produced by Xinzhou BRIGHT industry Ltd.; it had been formed by calcinations of coal-bearing kaolinite at 800 °C for 40 min. Fig. 2 showed the morphology and X-ray diffraction pattern of CMK. CMK had an irregular flaky structure. The X-ray diffraction pattern of CMK showed diffuse peaks. The ordinary Portland cement (OPC 42.5) used in this study was produced by Taiyuan Shitou cement Co., Ltd. Table 3 showed the chemical compositions of OPC and CMK, as determined by X-ray fluorescence. The grain size distribution of OPC and CMK were determined using

Table 2
Physical properties of silty soil samples.

Properties	Values
Liquid limit (%)	26.4
Plastic limit (%)	18.4
Plasticity index	8.0
Specific gravity	2.70
Soil classification-GB 50021(Chinese standard)	Silty soil
Soil classification-ASTM D2487-11(US standard)	Sandy lean clay

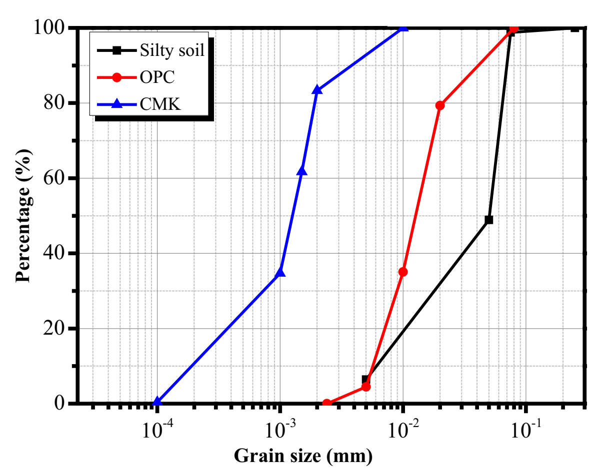

Fig. 1. Grading curves for silty soil, OPC, and CMK.

Table 1
Major origins and compositions of global metakaolin.

Origin	SiO_2	Al_2O_3	Other oxides	SiO_2/Al_2O_3 molar ratio	Data source
USA	53	44.1	2.66	2.04	Kuenzel et al. [19]
Germany	52	40	4.8	2.21	Deng et al. [17]
UK	52.8	39.2	5.2	2.29	Gordon et al. [20]
Czech Republic	53	43	1.2	2.10	Kasım et al. [21]
Hunan, China	49.4	43.9	2.67	1.91	Lu et al. [22]
Shanxi, China	52.62	45.42	1.96	1.97	This paper

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