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Mechanical behavior and constitutive relationship of mud with cement and fly ash

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HIGHLIGHTS

- The micro-structures of with different curing time and different addition of stabilizers are observed by using SEM.
- The strength of stabilized mud with cement and fly ash was analyzed combining the results of UCS and SEM tests.
- A novel constitutive model was proposed for stabilized mud accompanied by seven parameters.

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ABSTRACT

In this study, various tests were carried out in order to evaluate the suitability of stabilising high water content waste mud as a fill material. The unconfined compressive strength and elastic modulus of mud treated with different stabilizers were determined. Besides, the relevant micro-structural changes were observed by conducting scanning electron microscopy (SEM). The effects of stabilizers at regular dosage yields (9%) were compared and the optimal additive combination of cement and ash that exhibited favorable strength and elastic modulus was identified accordingly. A field-simulated undrained shear test on the cement and fly ash (FA) mud treated for various curing times (7 and 28 days) was run and the constitutive relationships were derived. The cohesive intercept decreased and failure friction increased over time, while shear strength between the treated mud at 7 and 28 curing days decreased as confining pressure increased. This implies that heaping preloading and other methods imposed during the initial stages of mud treatment can dramatically enhance its strength and reduce the necessary curing time.

1. Introduction

Waste mud generated in the bored pile fabrication process is a complex mixture with poor engineering properties. It is often characterized by high water content, high fluidity, and high water holding capacity, which render it unsuitable for direct use in construction applications. Conventional strategies for waste disposal have several disadvantages including limited capacity, high cost, and environmental concerns [1]. As a result, researchers are exploring new applications for this material waste mud (and other waste materials) produced during construction. Improving mud materials through treatment techniques or other means is worthwhile, not only to mitigate the negative impact on the environment, but to generate a material that can comply with engineering specifications [2–4]. Such an application for treated waste mud is engineered fill; increasing demand and quarrying restrictions have given rise to a shortage of conventional fill materials.

Selecting a suitable stabilizer is a major priority with regards to improving both efficiency and cost of treated soils. Various inorganic additives [5–8] and organic additives [9–11] have been proposed as suitable stabilizers, and traditional inorganic stabilizers (cement, ground-granulated blast-furnace slag (GGBS), fly-ash (FA), lime, and others) are the most commonly applied due to their availability. Due to the possibility of successful waste soil reuse is determined by its mechanical behavior, many studied have carried on research for unconfined compressive strength modulus of elasticity [6,12,13], the undrained shear behavior and constitutive relationships [14–16]. However, due to the particularity and complexity of mud, much of these properties are still unknown.

The focus of this study is on the mechanical behavior and constitutive relationships of waste mud treated with cement and FA.

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The responses of mud samples obtained from the bored pile process were compared after treatment with three additives (cement, FA, and lime) through USC and SEM tests.

2. Experimental methods

2.1. Materials

Waste mud was obtained from a bored pile production facility in Haining, China, and subjected to all basic tests required for soil classification including grain-size distribution, Atterberg limits, and specific gravity. A summary of the basic properties of the sample is shown in Table 1. A SEM image of the virgin mud is shown in Fig. 1, where the particles are arranged in an irregular, laminar pattern with voids of varying size.

The ordinary Portland cement used in this study is P.O. 42.5; the lime is quicklime (CaO) and the FA is Class-I FA (Chinese classification) as described in Table 2.

2.2. Specimen preparation

Again, traditional stabilizers comprised of quicklime (L), Ordinary Portland Cement (OPC), and FA were used in this study. These were added in proportion to the wet weight of mud in the mixed compositions listed in Table 3. T1, T2, and T3 were used to investigate the effects of OPC on the strength of the improved mud. To evaluate the improved efficiency of the three types of stabilizer, T2, T4, T6, T7, T8, T9, T10, and T11 were prepared at the same total amount (9%) and the samples were cured for 28 days. To compare the effect of stabilizer on the inner morphology of the treated mud, T2, T6, T9, and T11 were prepared and also cured for 28 days. All samples were cured under standard curing conditions (temperature 20 ± 2 °C, humidity 95 ± 2%).

Separately, samples were then prepared with an addition of 6% OPC and 3% FA and cured for 3, 7, 28, and 56 days (again under standard curing conditions) to explore the development of microstructures as curing time progressed. Another set of samples were prepared for undrained triaxial compression tests to assess the suitability of the improved mud as a fill material. In practice, the stabilized soil must be cured for some time (several days) after stabilization before use in construction with the curing ceased. Hence, a field-simulated test was performed, where the sample was prepared at the end of the curing time of 6 and 27 days, and tested one day later (i.e. after 7 and 28 days). The mixtures for triaxial undrained tests were exposed to open air without any protection. It should be noted that the mixtures at curing time of 3 and 56 days were impossible to sample effectively due to the high water content of 105.6% and low water content of 8.6%, respectively.

2.3. Test methods

Cylindrical samples (50 mm diameter × 50 mm height) were prepared by static compaction at a rate of 0.1 mm/min. Due to the high water content, sampling the mud mixed into 9% FA was impossible. The UCS and elasticity modulus of the specimens were measured on an electro-hydraulic servo universal testing machine (WAW-1000A).

For scanning electron microscope (SEM), samples were sliced to a height less than 2 mm, dried under low-temperature conditions, injected with epoxy fix resin, polished, gold-sputtered, and scanned under a professional SEM apparatus (Rili S-4800). Due to some samples with high water content (FA-treated mud), they were put into oven with low temperature as mentioned above a few times to form some structure before slicing. The undisturbed side of each slices was scanned to reduce the effect of the cutting process.

A set of six cylindrical samples each 39.1 mm in diameter and 80 mm in height were prepared in a split-part mould by compacting materials in six layers, each subjected to 98 blows with a hand compactor [17]. Because the ultimate use of the treated mud was, ostensibly, for roadbed fill material, high confining pressure generally did not need to be considered. The samples were subjected to lateral stresses of 30, 60, 100, 200, 300, and 400 kPa and triaxial compression tests were performed on a TKA triaxial apparatus (Fig. 2).

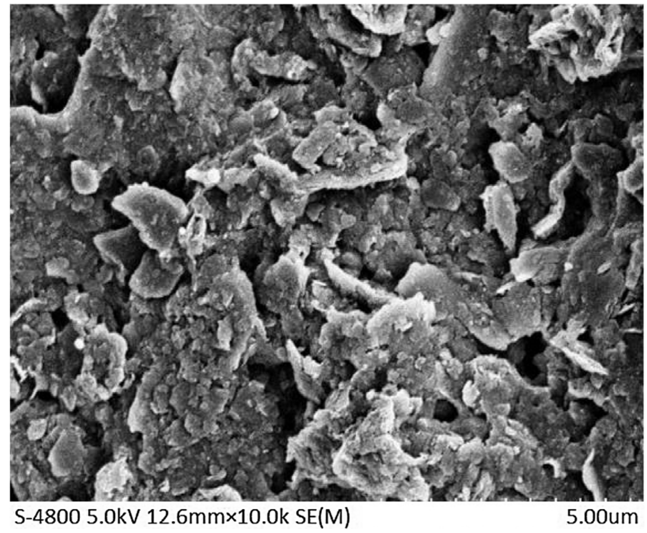

Fig. 1. SEM micrograph.

3. Results and discussion

3.1. Comparisons among mud samples treated with different stabilizers

Micro-structural examinations were conducted by gathering SEM images of mud samples with the addition of 9% OPC, 9% L, 9% FA, and 6%OPC + 3% FA after 28 curing days, as shown in Fig. 3 (observations at μm scale). In order to investigate and compare the inner-structure characteristics (e.g. shape, size and texture) effectively, different scale were necessary for the four images in Fig. 3.

Fig. 3a shows the effect of OPC treatment on morphological structure. Several aggregated soil matrices of varying size were found with the formation of cementitious materials, as shown in Fig. 3a. The aggregates were tightly joined to the bar crystal ettringite and cementitious materials, forming an interlocking pattern with generally strong structural features.

There was no such strong cemented pattern of aggregated particles within the soil matrix added into 9% L, as shown in Fig. 3b, but instead smooth particle surfaces, an abundance of open voids, and relatively little cementation of aggregated particles. These features resulted in a loose structure and low strength (as also verified by the UCS results shown in Fig. 4). The strength of lime-treated mud was up to six times lower at the same total dosage (9%) compared to the mud mixed into cement. To this effect, it is reasonable to conclude that OPC has a significant effect on mud stabilization with high water (rather than lime) content.

As shown in Fig. 3c, there was little consumption of FA during the treatment process, so most soil particles maintained their original shapes. Cementitious materials and bonding features were only produced in the contact surface between the soil and FA particles, which is why the UCS samples of extremely low-strength FA-treated mud were unsuccessful. The FA-treated mud had practically no voids within the soil matrix in comparison to the soil supplied with OPC and L, indicating that FA filled the aggregated particle pores instead of forming chemical reactions.

Table 1
Properties of natural mud.

Properties	Natural water content	Specific gravity	Liquid limit	Plastic limit	Clay	Silt	Sand
Value	120 ~ 135%	1.234	45%	25.10%	33%	57%	10%