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Assessment of strength development of slag cement stabilized kaolinite

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HIGHLIGHTS

- A series of unconfined compressive strength of soft clay improved with slag cement material are performed.
- The UCS at other curing ages estimated from the early strength on Day 3 is proposed.
- The UCS rapidly decreases with clay-water/cement ratio w_c/c increasing when the value of w_c/c less than 6.0.
- The UCS increases with cement-to-soil ratio C/S increasing.

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ABSTRACT

Due to low strength and high compressibility, soft clay should be improved to increase its strength, and decrease the permeability and the ground settlement for a better construction condition. Nowadays the sustainability is much more important, so recycled materials such as fly ash and slag have been widely used and replaced the part of cement in soft ground improvement. The slag cement has been applied to improve the strength of soft soil in previous studies. The UCS (unconfined compressive strength) at the 28 days is an important index to evaluate the quality for improved soil. Thus, an assessment of the UCS from the early strength is desirable and will be helpful for safety evaluation and analysis of ground improvement under the construction phase. In this study, a series of UC test are conducted on slag cement treated soil with five types of slag cement-to-soil ratios (C/S ratio, is the ratio of binder over dry soil by weight) are 15%, 20%, 25%, 50%, and 75%. In addition, the initial water contents of 1.8 times, 2.0 times, and 2.2 times of the liquid limit of kaolinite is chosen to simulate the condition of soft ground improvement with cement. The UCS was tested at the ages of 3, 7, 14, 28 and 56 days.

Test results show that when the curing time reaches 14 days, the development of strength slows down significantly. Thus, the strength of specimens cured longer than 28 days has a slight growth or no increase against the curing time. The UCS rapidly decreases with clay-water/cement ratio w_c/c increasing when the value of w_c/c less than 6.0, but the trend of reduction becomes smooth when the value of w_c/c greater than 6.0. In addition, the UCS increases with cement-to-soil ratio C/S increasing. Thus, the UCS increases as clay-water/cement ratio decreasing and cement-to-soil ratio increasing. Namely, the UCS increases with the amount of slag-cement when the water content and the weight of soil are fixed. Furthermore, on the basis of both Gallavresi's equation and Abrams' law, the modified models of UCS are proposed in this study that can predict the UCS at other curing ages from the early strength on Day 3, and the factor of curing age is built in these modified models. From the comparison of UCS values obtained from tests and prediction models, the overall MAPE values are 18.79% and 18.00% for modified Gallavresi's equation and Abrams' law, respectively. These two MAPE values are between 10% and 20%. Thus, the prediction models established in this study have a good predictive ability.

1. Introduction

Soft clays are often encountered on many civil engineering projects, such as deep excavation, underground construction, and land

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reclamation, which lack sufficient strength to support the loading either during construction or throughout the service life. To improve the strength and stiffness of those less competent soils, soil stabilization with cementitious materials has been widely practiced [1–5]. As a result, an increase in bearing capacity and a decrease in compressibility shall be achieved. In engineering practice, it is desirable to know the amount of cement required for the improvement of a target soil before implementing the treatment process; thus, a series of laboratory tests would be performed to determine the amount of cement needed in a mix to achieve the expected strength [6]. For ground improvement applications, various strengths may be used to assess the quality of ground improvement. However, the most commonly used engineering property for QC (quality control) and QA (quality assurance) is UCS (unconfined compressive strength) [7–11]. Other engineering properties (such as shear strength, tensile strength and modulus etc.) may be investigated from different test or established by correlation with UCS for the design when other's assessment of stability is needed. When high amounts of cement are used, the properties of improved soil tend to concrete or cement mortar, and the conventional CU (consolidation undrained) and CD (consolidation drained) tests do not appropriately be applied. Thus, the unconfined compressive strength q_u of the cement-treated soil is an important index of effectiveness for soil improvement. Zhang et al. [12] indicated that the water content and cement content were the important factors of the strength development for cement-treated soil. Some approaches of the compressive strength were developed based on factors of water content, cement content and curing age [6,12–15]. In addition, the 28-day compressive strength is usually considered as the design strength [16]. Thus, developing a predictive model to determine the compressive strength at the later stages according to its early strength will be very helpful for the safety assessment and analysis of structures [17–19].

With the growth of economy, our demand for steel and iron continuously increases, and the industrial byproducts derived from the steelmaking process have increased over time. Steel slag is a by-product of steel production, which accounts for approximately 15% by mass of the steel output. Therefore, it is important to study the effectiveness of replacing natural resources with recyclable materials such as steel slag for the sake of environmental and social sustainability [18]. Furnace slag is one of the steel slag, it can be divided into two types by its making procedure, including blast furnace slag (BFS) and basic oxygen furnace slag (BOFS). The properties of BOFS are similar to natural gravel, hence, they are used in makeshift pavements for construction or as filling materials. As for BSF, its major chemical components are CaO, SiO_2, and Al_2O_3, which are similar to those of Portland cement [20]. It is cementitious and can be made into slag powder, and usually be used as part of concrete or mortar material to replace the cement [17,21,22]. The slag powder also has been widely used to replace the cement in the cement-treated soil for experimental or case of in-situ study [23–33].

With sustainable development and reuse of waste materials as a starting point, the addition of furnace slag powder to replace the cement of cement-treated soil is worth investigating. Additionally, the 28th-day compressive strength is typically used as the design strength for structure. Understanding the early-stage compressive strength of slag cement-treated soil will be beneficial for safety evaluation and analysis under the construction phase. In this study, a series of compressive strength tests are conducted on slag cement treated soil with five types of slag cement-to-soil ratios (C/S ratio, is the ratio of binder over dry soil by weight) are 15%, 20%, 25%, 50%, and 75%, respectively. To investigate the effectiveness of the soft ground improvement, the initial water contents of 1.8 times, 2.0 times, and 2.2 times of the liquid limit of kaolinite was chosen to simulate the condition of soft ground improvement with cement. These modified prediction models are evaluated based on Gallavresi's equation and Abrams' law encompassing such influence factors as the clay-water/cement ratio and the age is proposed.

2. Experiment

2.1. Materials

2.1.1. Kaolinite

Each soil type has its own mineral composition, particle size and distribution, thus, the characteristics of strength should be depended on soil type. Zhang et al. [12] indicated that the strength behaviors are different for different types of base clays and stabilizing agents, at that time, the characteristics of strength of cement-treated soil for 16 types of clay are discussed. To reduce the dependency on clay or cement type, Tan's normalization approach [34] is used, and the UCS are evaluated and compared for different type of soil [12]. In this study, to avoid the effect of soil for different batch, the pure clay of kaolinite is adopted. Thus, if the normalized approach of strength is used, the test and analysis results could be as a reference for similar soil type and mix ratio.

The kaolinite used in this research was acquired from CHU SHIN Chemical Co., Ltd [35]. It was packaged in dry powder with natural water content around 1.25%. The natural water content of kaolinite was small enough to ignore; thus, the kaolinite was considered as completely dry when calculating the mix ratio. The specific gravity (Gs), liquid limit (LL), plastic limit (PL) and plastic index (PI) of kaolinite are 2.64, 84%, 31% and 53%, respectively. The grain size distribution curve of kaolinite is shown in Fig. 1. According to the Unified Soil Classification System (ASTM D2487), this kaolinite was classified as clay with high plasticity (CH).

2.1.2. Slag cement

The slag cement was provided by CHC Resources Corp, a company specially processing the industry by-products into the new and useful construction materials in Taiwan [20]. The slag cement used in this research is named "Type HSC_{301} Soil improvement agents", and is composed of water quenches slag, Portland cement

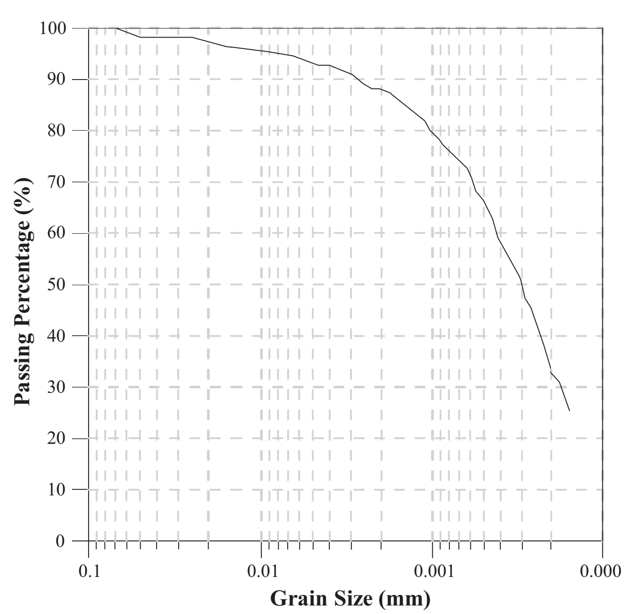

Fig. 1. Grain size distribution curve of kaolinite (following by ASTM D422).