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Influence of sodium silicate and promoters on unconfined compressive strength of Portland cement-stabilized clay

Cong Ma[a], Zhaohui Qin[a], Yingchun Zhuang[b], Longzhu Chen[a,*], Bing Chen[a]

[a]*Department of Civil Engineering, Shanghai Jiaotong University, Shanghai 200240, People's Republic of China*
[b]*Hydrochina Huadong Engineering Corporation Ltd., Hangzhou 310014, People's Republic of China*

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Abstract

Eco-friendly sodium silicate and promoters, which are compatible with cement and are used to obtain super properties, have been developed into a variety of soil stabilizers. This paper investigates the possibility of using cement and sodium silicate admixed with composite promoters to improve the strength of soft clay in Shanghai, China. The influential factors involved in this study are the type of promoters, the proportion of each binding agent, the binder content, and the curing time. The unconfined compressive strength of stabilized clay at different ages is tested. Based on an orthogonal experiment, the selected clay stabilizer (CSCN) is determined. More importantly, it is found that much less CSCN is needed to achieve the equivalent improvement in strength compared with cement, which illustrates that CSCN can be a more effective and eco-friendly clay stabilizer. Mineralogical and microstructural tests are performed to reveal the possible mechanisms controlling the strength development. The effect of CSCN on cement hydration and pozzolanic reactions is discussed. Microstructural analyses confirm the formation of hydration and pozzolanic products, and show that the clay tends to form more compact microstructures after being stabilized with CSCN.

Keywords: Soft clay; Soil stabilization; Unconfined compressive strength; Sodium silicate; Composite promoters

1. Introduction

Clayey soils are found in most regions of South and East China (Gao, 1996). The lower strength of soft clays causes severe damage to pavements, runways, and building foundations, which are founded on these soils (e.g., Horpibulsuk et al., 2006; Kempfert and Gebreselassie, 2006). To improve the strength and stiffness of those less competent soils, soil stabilization with cementitious materials has been widely practiced.

Soil stabilization is a technique that was introduced many years ago for the main purpose of rendering the soils capable of meeting the requirements of specific engineering projects (e.g., Rogers et al., 1997; Gao and Wang, 2014). One of the effective soft ground-improvement techniques is in situ deep mixing. This method was developed primarily to effect columnar inclusions into the soft ground to transform such a whole soft ground into a composite ground (Bell, 1988). Quicklime and ordinary Portland cement slurry (OPC) have been used as binding agents (e.g., Prusinski and Bhattacharja, 1999; Horpibulsuk et al., 2004, 2005; Niazi and Jalili, 2009). However, quicklime reacts with water rapidly, which increases the difficulty of deep mixing. In China, OPC is the most common binder since it is readily available at a reasonable cost

*Corresponding author.
E-mail address: lzchen@sjtu.edu.cn (L. Chen).
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(e.g., Duan et al., 1994; Yu et al., 1997; Huang et al., 2005). However, the energy-intensive production process of OPC is the driving force in studies on alternative cementitious additives (e.g., Gartner, 2004; Meyer, 2009).

Used for soil stabilization, sodium silicate has unique advantages: (i) its reliable and proven performance, (ii) its safety and convenience for construction, and (iii) its environmental acceptability and compatibility (e.g., Rowles and O'Connor, 2003; Ma et al., 2014). Sodium silicates have been developed into a variety of different clay-stabilizer systems. These systems consist of sodium silicate and a reactor or accelerator (e.g., calcium chloride and kaolinite), which can be compatible with cement to achieve high mechanical properties. However, when used as reactors, calcium chloride or Kaolinite can only improve the strength of OPC-sodium silicate-stabilized soils by 20–50% (Kazemian et al., 2011a, 2011b). Montmorillonite-rich clay soil stabilization with powdered sodium silicate and lime was reported, but the low solubility and migration of the lime in the pore liquid inhibited the application of this technique for in situ construction (Rafalko et al., 2007; Sukmak et al., 2013a; Phetchuay et al., 2014). Indeed, sodium silicate was widely used to prepare clay-fly ash geopolymer in previous studies, and the influence of its curing conditions and binder contents has been studied (Sukmak et al., 2013b, 2014; Pangdaeng et al., 2014; Phoo-ngerkham et al., 2013).

The aim of this paper is to achieve an OPC-based clay stabilizer which has the equivalent enhancement of the mechanical properties as a higher content of OPC. The effect of a single promoter and composite promoters on the strength development of samples stabilized with OPC and sodium silicate was investigated. The unconfined compressive strength was used as a practical indicator to investigate the strength development. The binders consisting of OPC, sodium silicate, and composite promoters were studied through an orthogonal experiment which can ascertain the optimal proportion of each component. The changes in minerals and the microstructure are examined by X-ray Diffraction (XRD) and a scanning electron microscope (SEM). On the basis of strength observations and a mineralogical characterization, the possible mechanisms controlling the strength development are discussed.

2. Materials and methodology

2.1. Soil sample

The soil sample used here is soft clay collected from the Shanghai Jiao Tong University campus in Shanghai, China, at a depth of 6 m. The soil contains highly fine particle contents, similar to many marine soft clayey soils. A particle size analysis was performed on the soil by following the standard method. About 100% and 80% of the soil are finer than 2 mm and 0.075 mm, respectively, so that clay and fine sand are the major components of this soil. Its specific gravity is 2.70. The liquid and plastic limits are approximately 42% and 24%, respectively. According to the Unified Soil Classification System (USCS), this soil is a CL soil based on two aspects: the liquid limit is smaller than 50% and the plasticity index is higher than 17%. The natural water content and pH value were approximately 41% and 7.14%, respectively. The chemical composition and morphology of the clay are shown in Table 1 and Fig. 1, respectively.

2.2. Binding agents

ASTM Type I ordinary Portland cement (hereinafter called OPC) was used for all stabilized clay mixtures in this study. The chemical composition of OPC is also shown in Table 1. The density and specific surface area of OPC are 3.13 g/cm^3 and 3630 cm^2/g, respectively.

Sodium silicate (SS), a syrupy liquid, is used as the second binding agent. It consists of SiO_2 (29.48%) and Na_2O (9.52%), and the silica modulus (molar ratio of SiO_2 and Na_2O) is 3.2. The density and pH are 1.43 g/cm^3 and 11.98, respectively.

Sodium hydroxide (NaOH, SH), a flaked solid at room temperature, was used to improve the pH value of the stabilized clay. Calcium hydroxide ($Ca(OH)_2$, CH), a powdered material, can react with pozzolanic material and produce

Table 1
Chemical composition of clay and OPC.

Oxide	Chemical composition (%)	
	Clay	OPC
Silicon dioxide (SiO_2)	57.02	21.60
Calcium oxide (CaO)	3.63	64.44
Aluminum oxide (Al_2O_3)	16.42	4.13
Ferric oxide (Fe_2O_3)	6.79	4.57
Magnesium oxide (MgO)	3.68	1.06
Sodium oxide (Na_2O)	0.81	0.11
Potassium oxide (K_2O)	3.59	0.56
Sulfur trioxide (SO_3)	0.05	1.74
Loss on ignition (LOI)	6.43	0.76

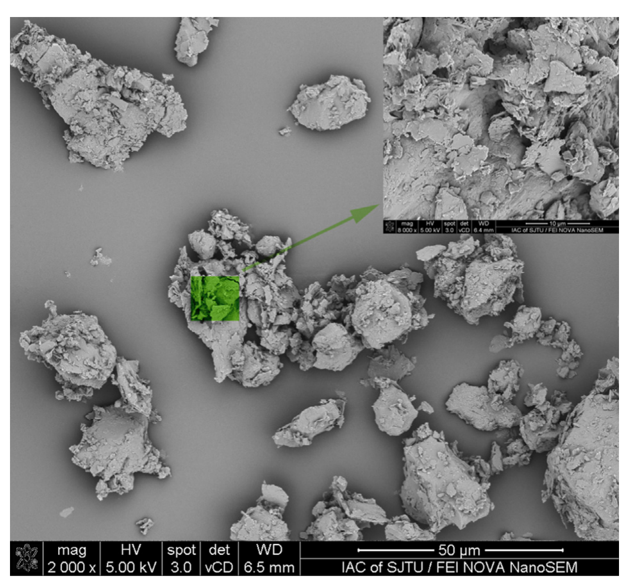

Fig. 1. SEM photos of the soft clay.