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# Analysis of strength development in soft clay stabilized with cement-based stabilizer

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## HIGHLIGHTS

- The mechanical properties of soft clay stabilized with cement-based stabilizer were investigated.
- The predicted models for compressive strength and secant modulus were analyzed.
- The effect of the supplementary cementing materials was confirmed by SEM imaging.

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## ABSTRACT

Sodium silicate and promoters have been widely used as supplementary cementing materials substituting ordinary Portland cement to improve the properties of stabilized soils. In this paper, the developments of mechanical properties of specimens stabilized with cement-based stabilizer, which consists of cement, sodium silicate and composite promoter, is investigated by unconfined compressive strength (UCS) test and scanning electron microscope (SEM). The failure strain and secant modulus are also obtained in UCS tests. The test results indicate that the supplementary cementing materials perform effectively pozzolanic reactions and improve the mechanical properties of cement stabilized clay. The contribution of pozzolanic effect is regarded akin as an addition of cement and the total cement content is the summation of cement content and equivalent cement content of the supplementary cementing materials. According to this premise, the clay–water/cement ratio hypothesis for stabilized clay is proposed for analyzing and assessing the development of the mechanical properties. The phenomenological models for predicting the compressive strength and secant modulus of specimens stabilized with the selected cement-based stabilizer are developed and verified. The comparison of predicted results and laboratory results indicates that the deviation is mostly within 10%. The microstructural analysis observes the changes of cementitious products in stabilized clays and confirms the pozzolanic effect of the supplementary cementing materials. On account of the efficiently pozzolanic effect, the addition of sodium silicate (<2%) and composite promoter (<4%) can be equivalent to several times cement content. Hence, the economic and environmental mix design is developed with the addition of the supplementary cementing materials.

## 1. Introduction

Clayey soils occur in most regions of South and East China [1,2]. Soft clays are often encountered on many civil engineering project sites, 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 [3–5].

Soil stabilization is a technique introduced many years ago with the main purpose to render the soils capable meeting the requirements of the specific engineering projects [6]. One of the effective soft ground improvement techniques is in situ deep mixing [7–10]. This method has been developed during last two decades primarily to pile columnar inclusions into the soft ground to composite ground. It has been applied popularly and successfully in Southeast Asia [11,12]. The commonly used stabilizers include ordinary Portland cement (OPC) and lime, with their stabilization mechanisms being relatively well understood [13–15]. However, the quicklime reacts with water rapidly and it increases the difficulty of deep mixing. In China, OPC is the most common stabilizer since it is

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readily available at reasonable cost [16,17]. Nevertheless, a major issue with OPC is that its production processes are energy intensive and emit a large quantity of $CO_2$ [18,19].

To improve the environmental acceptability and reduce the construction cost of the deep mixing method, the replacement of the cement by supplementary cementing materials such as fly ash and sodium silicate is one of the best alternative ways [20]. Application of sodium silicate for geotechnical works has been reported by many researchers [21–23]. Used as a component of soil stabilizer, sodium silicate has unique advantages: (i) reliable and proven performance, (ii) safety and convenient for construction, and (iii) environmental acceptability and compatibility [22]. In China, liquid sodium silicate with high silica modulus is applied in the improvement of tunnel and subway foundation.

The fundamental mechanical properties of cement stabilized soft clays have been experimentally investigated by many researchers [24–27]. These investigations mainly focus on the influence of water content and cement content on the mechanical properties. Compressive strength development of cement stabilized fly ash–soil mixtures and several models have been studied. Clay–water/cement ratio, which is the ratio of clay water content to cement content (both reckoned in percentage) has been found to investigate the combination effect from both water content and cement content [28]. While the clay water content reflects the micro-fabric of soft clay, the cement content influences the level of bonding of that fabric. Horpibulsuk et al. [29] have introduced a mathematical model for predicting laboratory strength development in cement stabilized clays at various water contents, cement contents, and curing ages.

The strength of stabilized clay is governed by the growth of cementitious products which are controlled by the hydration of cement and the pozzolanic reactions. The role of sodium silicate on the mechanical properties of the cement stabilized clay has been investigated both from micro- and macro observations [22,30]. Sodium silicate reacts with $Ca^{2+}$ generated by the hydration of cement, forming insoluble calcium silicate which polymerizes further to form a gel that binds soil or sediment particles together and fills voids [31]. However, the consumption of $Ca^{2+}$ leads to the lower $Ca(OH)_2$ which reduces the pozzolanic effect.

In this study, two clay stabilizers, OPC and CSCN consisting of OPC, sodium silicate and composite promoter were used. To investigate the performance of clay stabilizers, the following properties of the stabilized clays were determined: unconfined compressive strength ($q_u$), failure strain ($\varepsilon_f$), and secant modulus ($E_s$). The methods for assessing the strength development of stabilized clay are verified on the basis of the clay–water/cement content ratio hypothesis. The pozzolanic effect of sodium silicate and composite promoter is estimated by calculating the equivalent cement content. The mathematical models for predicting the compressive strength and secant modulus of CSCN stabilized clay are developed. Furthermore, the microstructures of clays stabilized with OPC and selected CSCN stabilized clays were investigated with the aid of SEM imaging, respectively.

## 2. Experiment details

### 2.1. Materials

The soil sample is a kind of soft clay collected from the Shanghai Jiao Tong University campus in Shanghai, China, at a depth of 6 m. The soil contains high fine particle content, similar to many marine soft clayey soils. Particle size analysis was performed on the soil by following the standard methods [32,33], about 100% and 80% of the soil are finer than 2 mm and 0.075 mm, so clay and fine sand are the major components in this soil. Its specific gravity is 2.699. The liquid and plastic limits are approximately 42.36% and 24.27%, respectively. According to the Unified Soil Classification System [34], this soil is a CL. The natural water content and pH value were approximately 41.38% and 7.138%. The chemical composition of the clay is shown in Table 1.

**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 |

The binding agents consist of Portland cement and the supplementary cementing materials. ASTM Type I ordinary Portland cement (hereinafter referred to as cement, OPC) was used for all stabilized clay mixtures in this study. The chemical composition of OPC is also shown in Table 1. The supplementary cementing materials are sodium silicate and composite promoter. Sodium silicate (SS), a syrupy liquid, consists of $SiO_2$ (29.48%), $Na_2O$ (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. Composite promoter (CN) consists of sodium hydroxide and calcium chloride at the mass ratio of 1:1. And sodium hydroxide and calcium chloride used in this study are both chemically pure.

### 2.2. Casting, curing, and testing of specimens

In order to investigate the mechanical properties of OPC and CSCN stabilized clays, different contents of clay stabilizers were admixed with specific amounts of oven-dry clay. For preparing the samples, the water was added through a two-step process. Firstly, the predetermined quantity of water was initially mixed with the oven-dry clay, and the mass ratio of water and clay was 0.7. Then the rest of the water was blended with the binders at the mass ratio of 0.5, and the binders consisting of the desired amount of promoter, OPC and sodium silicate were added by the weight of dry clay. The soluble promoter was added into the mixtures in the form of solution, and the sequential mixing with $CaCl_2$ solution followed by NaOH solution was selected. Initial mixing was carried out in a laboratory mixer for at least 10 min and the mix was subsequently transferred to a cubic mold (70.7 mm in length). For squeezing the air and achieve a homogeneous mixture, the mold was put onto vibrating table to vibrate for at least 2 min. Then, the mold was sealed and stored in the curing room (20 ± 2 °C, 98 ± 2% RH) for 7 days. Afterwards, the stabilized samples were demolded and put into airtight vinyl bags in the curing room until the testing ages.

The unconfined compressive strength (UCS) test was performed on the samples after 7, 28, 60 and 90 days of curing. The rate of vertical displacement was fixed at 0.5 mm/min. At least three replicates of each sample set were prepared and tested under the same conditions to assure reproducibility. In most cases, the results under the same testing condition were reproducible with low mean standard deviations, SD ($SD/\bar{x} < 10\%$, where $\bar{x}$ = the mean strength value). The failure strain ($\varepsilon_f$) of the stabilized specimens was determined in UCS tests. The secant modulus ($E_s$) is defined as the ratio of one half of the compressive strength to the axial strain corresponding to this stress.

To confirm the pozzolanic reactions of the supplementary cementing materials and examine the micromorphological change of the stabilized specimens, SEM imaging was performed on selected samples. SEM samples were prepared by following a procedure suggested in previous study [35]. A 1 × 1 × 1 cm cubic specimen was trimmed off and then air dried in a desiccator at ambient temperature. The dried specimen was broken into two parts and the debris on the surface was removed with an adhesive tape. The specimen was mounted on an alumina stud with conductive tapes, and then sputter coated with gold–palladium alloy.

## 3. Clay–water/cement ratio and pozzolanic effect hypothesis

According to ASTM C 595, a pozzolan is defined as “a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide to form compounds possessing cementitious properties (pozzolanic activity).” Based on this concept, sodium silicate can be regarded as a pozzolan. For composite promoter consisting of $CaCl_2$ and NaOH, the permeation of $CaCl_2$ and NaOH solutions is expected to facilitate the precipitation of $Ca(OH)_2$ according to the reaction:

$$CaCl_2 + NaOH \rightarrow Ca(OH)_2 + 2NaCl \quad (1)$$