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Sustainable improvement of soft marine clay using low cement content: A multi-scale experimental investigation

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HIGHLIGHTS

- Effect of low cement content is significant on macro and micro structure of soft clay.
- The fundamental parameters relationships for low and highly cemented clays are established.
- This study can be helpful for the low cement-treated dredged clays land reclamation projects.

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ABSTRACT

The sustainable utilization of dredged soft clays for land reclamation requires a lower strength with lesser cement content as compared to traditional cement-treated clays. The mechanical behavior of soft clays at low cement content can differ from clays treated with higher content. For land reclamation, the required cement content is generally used up to 10%. Hence, this study is focused on analyzing the sustainable utilization of soft clays treated with cement content lower than 7%. Additionally, a comparison is drawn between a low-cement-treated soft clay with the highly cemented clays to determine the difference in mechanical behavior. Shanghai soft clay is reconstituted with cement content from 0 to 6%. The experimental investigation indicates that the low cement content has a significant effect on the microstructure, compression characteristics, compressive strength, undrained stress paths, and stress-strain behavior. However, the effect of curing time on such characteristics is limited. The mechanical behavior of low-cement-treated soft clay is similar to the highly cemented clays with respect to the relationships of compressive strength with strain at failure, yield stress and clay-water/cement ratio but is different with respect to deformation modulus versus compressive strength. The outcomes of this study can help to choose the minimum required cement content for the fill materials of land reclamation projects.

1. Introduction

Large volumes of dredged materials (DMs) are produced during the construction and maintenance of marine infrastructures. Just in Shanghai, the generation of DMs exceeds 70 million m^3 annually, and >2.5 billion m^3 of DMs have already been dumped into the surrounding ocean [1]. Dumping of DMs has become a challenge due to the unavailability of new disposal sites in the ocean or on land. A sustainable solution is to use DMs as cement-treated fills for land reclamation. The DM is a very soft clay with low shear strength ($c_u < 50$ kPa) and higher natural water content than the liquid limit. For land reclamation, the required cement content is usually not >10% [2]. Its required strength is much lesser than the traditional cement-treated soils and the strength development rate is lower at low cement content [3].

The strength development rate with the increment of cement content is divided into four zones; the inactive zone (Zone I), clay-cement interaction zone (Zone II), transitional zone (Zone III), and the cement-clay interaction zone (Zone IV) [3]. The boundary values of these zones vary with the types of clay and cement used. The boundaries of Zones I and II are normally in the range 10–15% and up to 50% respectively [4,6]. Zones of cement-treated clays with respect to strength development rate are in Fig. 1. Zone I is not fully inactive and some effect of the cement content can be expected on geotechnical characteristics [4]. The influence of cement content on strength within Zone I is quite different from that within Zone II [5]. A vast amount of research work has been conducted within Zone II to examine the mechanical behavior and microstructural characteristics of cement-treated soft clays in the past [3,6–13]. The range of cement content covered

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Nomenclatures

C	cement content	s_t	Sensitivity
C_c	compression index	u	excess pore pressure
CSL	critical state line	w_c	clay-water content
E_{50}	deformation modulus	w_L	liquid limit
e	void ratio	w_n	natural moisture content
e_{100}	void ratio at 100 kPa pressure	w_p	plastic limit
e_0	initial void ratio	ε_a	axial strain
GCL	generalized compression line	ε_f	strain at failure during unconfined compression test
G_s	specific gravity	η	dimensionless parameter of E_{50} *vs.* q_u relationship
I_p	plasticity index	σ'_v	effective consolidation pressure
P'	mean normal effective stress	σ_Y	yield stress
PSD	pore size distribution	σ_{Hg}	surface tension of mercury
q	deviatoric stress		
q_u	unconfined compressive strength		

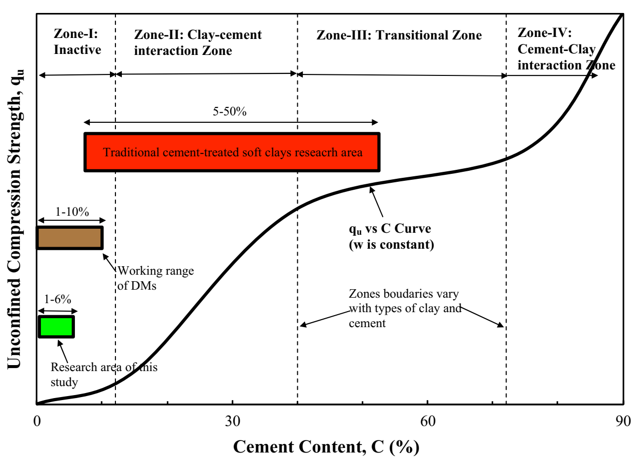

Fig. 1. Zones of cement-treatment of soft clays based on unconfined compressive strength development.

in aforementioned studies is generally from 5 to 50%. The effect of cement content on the microstructure of soft clays has been also investigated by using scanning electron microscopy and mercury intrusion porosimetry [6,14]. The compressibility, stress-strain behavior, strength development, and deformation modulus for soft clays treated at different curing times, clay-water contents, and cement contents have been examined by many researchers [15–26]. Zhang et al. [27] and Nguyen [7] proposed the constitutive models to analyze the effect of cementation on the mechanical behavior of cement-treated clays and to compute the cementation degradation.

In Zone I, some studies have been carried out to investigate the strength behavior of clayey soils. However, the detailed investigations on the compressibility and stress-strain characteristics of soft clays are also quite limited. Zhang et al. [4] conducted a series of unconfined compression tests on cement-treated clays within Zone I and Zone II, and developed the correlation models for land reclamation projects to predict compressive strength on the basis of cement content and water content. Hassan and Ravaska [8] investigated strength and permeability characteristics within Zone I and Zone II by using different types of Finnish soft clays. Mengue et al. [28] evaluated the effectiveness of cement treatment of compacted lateritic soil at low cement content (3%, 6% and 9%) as a road material and discussed the mechanical characteristics with respect to unconfined compressive strength, California bearing ratio, tensile strength, and shear strength. Liu et al. [29] performed a series of triaxial tests to determine the stress-strain behavior of Shanghai dredged soft clay treated with cement contents of 4% to 7% and also investigated the cement content effect on peak stress, cohesion and friction angle. The stabilization mechanism including mineralogical changes, elemental composition, the formation of cementitious products and filling in of pores due to cementation can be investigated by structural characterization [30,31]. To the authors' best knowledge, there is a scarcity of the literature on the microstructural behavior of soft clays performing the scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP) at low cement content.

In the literature, the detailed studies on the behavior of dredged soft clays treated with cement content <5% are limited. Hence, the aim of this study is to determine the feasible utilization of dredged soft clays treated at such a low cement content for land reclamation. Additionally, most of the relationships between fundamental parameters of cement-treated clays (*i.e.*, E_{50} *vs.* q_u, ε_f *vs.* q_u, σ_y *vs.* qu, qu *vs.* w_c/C, qu *vs.* pH-value, e/e_{100} *vs.* σ'_v *etc.*) have been developed at high cement content. The detailed discussion on the geotechnical characteristics, microstructure, and the relationships between fundamental parameters of soft clays in the aforementioned range of cement content is insufficient. This study is conducted to determine the mechanical and microstructural behavior of soft clay treated with low contents of cement (Zone I).

The study layout is divided into four parts. Firstly, to investigate the effect of low cement content on the microstructure of soft clay. For this, SEM and MIP tests were performed to examine the arrangement of fabrics and pore size distribution respectively. In the second part, a comprehensive study on the mechanical properties of treated soft clay is carried out by performing an oedometer test, unconfined compression test, and consolidated undrained triaxial (CU) test. In the third part, relationships between fundamental parameters for soft clay treated within Zone I are established. In the last part, relationships are developed between the fundamental parameters of highly cement-treated soft clays (Zone II) and compared with the relationships developed for Zone I. For this, the data of different cement-treated soft clays is extracted from the literature.

2. Experimental investigation

2.1. Materials

Yangtze River has deposited a large amount of fine sediments in the last 20,000 years in the Shanghai region where the thickness of