Applied Clay Science 155 (2018) 74–83

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Research paper

An integrated strength-calculation model for earth-based construction prepared by organic clay

Cong Ma[a], Youjun Xie[a], Guangcheng Long[a,*], Bing Chen[b], Longzhu Chen[b]

[a] School of Civil Engineering, Central South University, Changsha 410075, PR China
[b] Department of Civil Engineering, Shanghai Jiaotong University, Shanghai 200240, PR China

ARTICLE INFO

Keywords:
Earth-based construction
Compressive strength
Reconstituted organic soil technique
Physical indexes
Strength-calculation model

ABSTRACT

The earth-based construction with unique advantages of wide source of raw material and low carbon emission has attracted growing attention recently In South China, raw soils which have been used for hundreds of years are mainly organic clays with high contents of water and organic matter. This research uses reconstituted organic soil technique to prepare earth-based construction and investigate the key variables controlling compressive strength by measuring compressive strength (q_u) and physical indexes including unit weight (γ_t), water content (w_t) and specific gravity (G_{st}). The cementitious material used is a high-efficiency stabilizer named as CSCN, and organic clay is obtained by mixing humic acid powder (HAP) with raw clay. The presence of HAP is regarded as the consumption of CSCN, and total CSCN content (C_T) can also be calculated. Firstly, a parameter taking into account the key variables is expressed as the ratio of void ratio to total CSCN content (e_t/C_T) and the relationship of q_u to e_t/C_T is analyzed by a power function. Physical indexes of stabilized earth are dependent upon the initial physical properties and influenced by C_T value, actual CSCN content, HAP content and curing time. And then, the calculation formulae for physical indexes are obtained by the multiple linear regression and power regression analysis by defining dimensionless ratios of the after-curing physical indexes to the initial ones. Ultimately, a strength-calculation model with a deviation between calculated strength and experimental results less than 10% is established based on e_t/C_T. The model is proved to be very useful for the design and preparation of earth-based construction with organic matter.

1. Introduction

During the last decade, sustainable development has attached increasing attention due to the environmental pollution and climate change (Pérez-Lombard et al., 2008). And it is commonly believed that the construction and operation of modern buildings consume a huge amount of energy and emit massive greenhouse gas. Therefore, one of the traditional architectures, rammed earth construction whose base material is raw soil, has been reported and applied as an alternative and environmentally friendly method recently (Hall and Djerbib, 2004). For improving the durability and mechanical properties of earth-based structure, the use of a small quantity of cementitious materials is essential. Among the cementitious materials, Portland cement and cement-based composites are commonly employed (Arrigoni et al., 2017). Because the raw soil distributed in southeastern China has high water content, the earth-based construction can be obtained by only mixing and vibration processes without compaction energy.

Earth-based constructions such as earth towers of the Hakks have been used for a long time in Fujian province, South China. During the preparation process of earth-based constructions, the precipitation and compaction energy which may occupy huge areas of cultivated land and emit some unpleasant gases are necessary (Ciancio et al., 2014; Phetchuay et al., 2016). Therefore, earth-based construction without compaction process can be employed to replace conventional rammed earth. Indeed, many raw soils in South China are organic clays. Although the organic matter content varies from 0.2% to 7.5%, constructions prepared by organic clays are characterized by high compressibility and low strength which is too low to meet the strength-requirement of construction. The common solution is to increase cement content, which leads to cost increase and environmental pollution (Sánchez-Monedero et al., 2004). For this reason, some alkaline minerals such as sodium silicate and some industrial waste residues such as fly ash and phosphogypsum were employed to develop high-efficiency cement-based soil stabilizers (Cai et al., 2006; Kalkan, 2009; Shen et al., 2009; Kazemian et al., 2011). Among the high-efficiency stabilizers, a cement-based composite named as CSCN significantly reduces the usage of cement in preparing earth-based construction, and 12% CSCN can achieve the equivalent strength with about 20% cement

* Corresponding author.
E-mail address: scc2005@csu.edu.cn (G. Long).

https://doi.org/10.1016/j.clay.2018.01.014
Received 17 August 2017; Received in revised form 14 January 2018; Accepted 16 January 2018

(Ma et al., 2014, 2015, 2016b, 2016c, 2018). The efficiency of CSCN in organic clay was also verified (Ma et al., 2016a).

Factors influencing the compressive strength of earth-based construction were studied by many researchers (Kaniraj and Havanagi, 1999, 2001; Horpibulsuk et al., 2003, 2012; Ciancio et al., 2014; Ma et al., 2014, 2016c; Phetchuay et al., 2016; Arrigoni et al., 2017). Among the numerous parameters, stabilizer content, water content and curing time are the three most important factors. Relationships between compressive strength and curing age were analyzed by linear model, logarithmic model and hyperbolic model. The hyperbolic model was regarded as the most accurate and practical one because it could reflect the initial and final states of earth-based construction more truly (Kaniraj and Havanagi, 1999, 2001). Although the above models can predict compressive strength, their accuracy and applicability are insufficient to determine reasonable stabilizer contents in order to meet the designed strength of earth-based construction. Therefore, soil-water/cement ratio (w_c/C) taking into account both cement content and water content was proposed and power functions were used to analyze the relationship of strength to w_c/C (Horpibulsuk et al., 2003, 2012). It is obvious that the obtained strength-calculation models can help engineers design earth-based construction; nevertheless, the same design proposal may be inapplicable in different types of soils because the physical and chemical properties are also factors affecting the mechanical properties of earth-based construction.

Considering that situation, some researchers introduced the physical indexes of raw soils into strength-calculation models. Consoli et al. put forward the calculation method of porosity (η) of earth-based construction and proposed some formulae to predict the strength based on the ratio of porosity and cement content in volume (Consoli et al., 2007, 2009, 2010, 2012). Lorenzo and Bergado (2004, 2006) studied the change in after-curing physical indexes with curing time through measuring the physical properties of earth-based construction at different curing ages. Likewise, a dominant parameter (e_t/C) was defined as ratio of after-curing void ratio to cement content, and an exponential function was employed to establish the strength-calculation models. Therefore, the models taking into account physical indexes have more extensive application in different types of soils. In addition, organic matter in raw soil has significant impact on physical properties. For example, it is no doubt that the presence of organic matter decreases the unit weight and increases the void ratio. Nevertheless, organic clay was always regarded as an integral research object in previous researches, which may neglect the impact of organic matter.

In this research, the high-efficiency stabilizer CSCN is used. Although several dominant variables governing compressive strength of CSCN stabilized earth were studied, the influence of organic matter on physical indexes of stabilized earth is not involved (Ma et al., 2016c). Reconstituted organic soil technique is employed in this study, and humic acid is used as organic matter in organic clay. Series of experiments were carried on specimens with different contents of CSCN and huimic acid. Testing items include unconfined compressive strength (q_u), unit weight (γ_t), water content (w_t) and specific gravity (G_{st}). Based on the total CSCN content (C_T) hypothesis, the relationships of the physical indexes to C_T value and humic acid content are investigated. And a key parameter (e_t/C_T) defined as the ratio of void ratio to total CSCN content is proposed to establish a strength-calculation model taking into account stabilizer content, organic matter content, curing time and physical indexes of raw clay. In addition the precision of the strength-calculation model is evaluated by comparing calculated values with experimental values. Finally, the application of CSCN and the obtained strength-calculation model in other clays is provided.

2. Experimental approach

2.1. Materials

To simulate the actual organic clay and obtain accurate results, reconstituted organic soil technique is introduced for preparing earth-based construction. In this study, reconstituted organic clay is obtained by mixing a projected content of humic acid into crushed original Shanghai clay. The original clay is obtained from the Minghang Campus of SJTU at a depth of 6 m in southwest Shanghai. The oxide composition of Shanghai clay is presented in Table 1. The liquid and plastic limits are approximately 42.4% and 24.3%, respectively. And its plasticity index is 18.1%. Its specific gravity and compression index are 2.70 and 1.1 MPa^{-1}, respectively. The detailed basic properties of original Shanghai clay are shown in Table 2. Its particle size distribution is characterized by laser particle diameter analyzer with a wide range of measuring from 0.01 μm to 2800 μm. The particle size analysis of the original clay with about 80% particles finer than 75 μm is shown in Fig. 1. The original clay is classified as a CL based on the Unified Soil Classification System. Fig. 2 shows the mineralogical composition of the original Shanghai clay, containing smectite, kaolinite, illite, clinochlore and quartz (Yi et al., 2015). The original clay was dried in a vacuum oven at about 105 °C for at least five days in order to eliminate the organic matter. The oven-dried clay is crushed and then sieved by a 2-mm sieve. In order to confirm the application of the obtained strength-calculation model in other types of clays, two practical projects in Hangzhou, Zhejiang Province and Fuzhou, Fujian Province are enumerated in this study. The basic properties of Hangzhou clay and Fuzhou clay are also presented in Table 2.

Table 1
Oxide composition of the original Shanghai clay and OPC.

Oxide	Chemical composition (%)	
	Shanghai clay	OPC
SiO_2	57.02	21.60
Al_2O_3	16.42	4.13
CaO	3.63	64.44
Na_2O	0.81	0.11
MgO	3.68	1.06
Fe_2O_3	6.79	4.57
K_2O	3.59	0.56
SO_3	0.05	1.74
LOI	6.43	0.76

Humic acid powder (HAP) with pH value of 3.55 employed in experiments is black, and it is the generation of plants and animals which had been buried for thousands of years. The main composition elements of HAP with the fundamental structures of aromatic and cycloparaffinic rings are carbon, oxygen, nitrogen and hydrogen. HAP has more than 85% of humic acid, and its main impurity is fulvic acid.

The used high-efficiency clay stabilizer including three components, cement, sodium silicate and composite promoter, was studied and reported in published works (Ma et al., 2014, 2015, 2016a,b,c, 2018). The recommended cement content in CSCN is fixed at 62.5%, and the mass ratio of composite promoter to sodium silicate is always 2:1. The composite promoter includes sodium hydroxide (NaOH) and calcium chloride ($CaCl_2$), and the mass ratio of NaOH and $CaCl_2$ is 1:1. This promoter can not only significantly enhance the strength due to the

Table 2
The basic properties of the studied clays.

Properties	Shanghai clay	Hangzhou clay	Fuzhou clay
Unit weight, γ_0, (kN/m^3)	17.23	17.10	15.39
Water content, w_0 (%)	41.4	45.5	69.3
Specific gravity, G_s	2.70	2.73	2.71
Liquid Limit (%)	42.4	45.0	47.9
Plastic Limit (%)	24.3	25.5	25.7
Plasticity index, PI (%)	18.1	19.5	22.2
Void ratio, e	1.18	1.38	1.92
Organic matter (%)	0.84	2.63	4.65