Construction and Building Materials 123 (2016) 336–345

Contents lists available at ScienceDirect

Construction and Building Materials

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

Variables controlling strength development of self-compacting earth-based construction

Cong Ma, Bing Chen, Longzhu Chen *

Department of Civil Engineering, Shanghai Jiaotong University, Shanghai 200240, PR China

HIGHLIGHTS

- Fundamental parameters controlling strength development of CSCN stabilized earth are investigated.
- Total cement content hypothesis accounting for curing time is proposed.
- The phenomenological models based on fundamental parameters for strength development are established.

ARTICLE INFO

Article history:
Received 10 April 2016
Received in revised form 1 July 2016
Accepted 8 July 2016

Keywords:
Self-compacting earth-based construction
Variables
Phenomenological models
Strength development
Porosity

ABSTRACT

As an environmentally-friendly construction technique, modern rammed earth generally stabilized with ordinary Portland cement has attracted growing interest recently. In this study, cement-based composite (CSCN) consisting of cement, sodium silicate and composite promoter is employed to substitute ordinary Portland cement, and self-compacting earth-based specimens without compacting energy are prepared. The variables controlling strength development are investigated by unconfined compressive strength (UCS) and physical property tests. The total cement content (C) is proposed based on the pozzolanic effects of the supplementary cementing materials in CSCN, and the relationships of pozzolanic factors to curing time are also analyzed. The ratio of the porosity to total cement content (n_t/C) combines together the variables C, curing time and fundamental parameters of stabilized earth, and the relational expression between strength and n_t/C is put forward. To normalize the fundamental parameters, the multiple linear regression is employed to analyze the after-curing unit weight (γ_t) and total water content (w_t), and the power regression is used to analyze the after-curing specific gravity (G_{st}). Subsequently, the phenomenological models for strength development of CSCN stabilized earth are established. A series of specimens are used to evaluate the precision of the phenomenological models, and the comparison of predicted strength and actual strength implies that the deviation is generally within 10%.

1. Introduction

For the past few years, sustainable development draws more attention due to the growing energy consumption and environmental contamination [1]. In China, the energy consumption of construction accounts for one third of total energy costs, and vast carbon dioxide is produced during the building process of modern construction [2]. To reduce the energy consumption and carbon dioxide emission, several alternative techniques, such as earth-based or rammed earth construction, have been studied [3,4]. The designed amounts of cementitious materials were employed in order to improve the properties of earth-based construction. The most common cementitious material applied in South-East China is ordinary Portland cement [5,6]. If the soils are mucky soils or soft clays with high water content in coastal areas of southeastern China, the earth-cement mixture can have a slurry consistency. For the fluid mixtures, compacting energy is not needed to prepare specimens, instead, a homogeneous specimen can be achieved only by vibrating for a few seconds. Under such circumstances, the earth-based construction obtained only by vibration process is generally called as self-compacting earth-based construction as defined in the previous study [7].

It is generally known that the production of ordinary Portland cement generates a large volume of CO_2, which is one of the potent greenhouse gases [8]. There is evidence that about one ton of CO_2 can be emitted through the generation of the equivalent ordinary Portland cement [9]. To control the usage of ordinary Portland cement in civil engineering, fly ash, GGBS and sodium silicate are used to substitute a portion of cement [10–15]. Due to the high

* Corresponding author.
E-mail address: lzchen@sjtu.edu.cn (L. Chen).

http://dx.doi.org/10.1016/j.conbuildmat.2016.07.017
0950-0618/

water content in self-compacting earth-based construction, the soil stabilizers should be high-efficiency in order to achieve the projected engineering performance. A type of cement-based composites named as CSCN which consists of cement, sodium silicate and promoters can be used to prepare self-compacting earth-based construction [13,16,17].

To understand the mechanism of strength development of cement stabilized earth, several variables were proposed by some previous researchers [18–20]. The cement content in earth-based construction is calculated by the weight of dry earth and defined as the parameter C_i. Some early researchers considered that C_i was the dominant factor controlling the strength development. Moreover, the total water content (w_0) in earth-cement mixture is another significant factor. The relationships between unconfined compressive strength (q_u) and cement content or total water content were explored and reported. Subsequently, a parameter (w_0/C_i) was put forward and the phenomenological models between q_u and w_0/C_i were obtained from exponential curve multiple regression analysis [21–23]. Nevertheless, the w_0/C_i neglects the influence of curing age (t) on strength development and the w_0 and C_i are both initial state of the soil-cement mixture, rather than the condition of stabilized earth after some days of curing. In addition, the w_0/C_i consists of only two parameters and the earth properties are not taken into account. That is to say, the models between q_u and w_0/C_i for different types of earths stabilized with cement exhibit great difference. In order to improve the precision and applicability of the parameter w_0/C_i, it is imperative to investigate the influences of the earth properties and the condition of stabilized earth after some days of curing on the strength development.

To solve these problems, Lorenzo and Bergado proposed several fundamental parameters including void ratio (e), unit weight (γ) and specific gravity (G_s) and explore the relationship of the parameters of stabilized earth after some days of curing to t and C_i [24,25]. The ratio of void ratio of stabilized earth to cement content (e_t/C_i) was proposed and proved to reflect the comprehensive influence of w_0, C_i and t on the strength development of stabilized earth. Furthermore, the phenomenological models between q_u and e_{ot}/C_i were also put forward to predict the strength of stabilized earth with different total water contents.

For CSCN stabilized earth, the addition of sodium silicate and promoters may affect the void ratio and specific gravity due to their pozzolanic effects. The previous studies investigated the influences of sodium silicate and promoters on the strength development on the basis of a hypothesis of regarding the supplementary cementing materials as the extra addition of cement [16,17]. And it was defined as equivalent cement content (C_e) which varied with curing age due to the varying pozzolanic effects with time. However, the relationship of C_e to t and the influences of the fundamental parameters of stabilized earth were not studied systematically.

A high-efficiency cement-based stabilizer, CSCN, was employed to prepare self-compacting earth-based specimens in this research. The relationship between the C_e of the supplementary cementing materials in CSCN and curing time is proposed by exponential regression analysis. Based on the after-curing water content (w_t), unit weight (γ_t) and specific gravity (G_{st}) of stabilized earth specimens obtained in the laboratory, the relationships of these parameters to curing time and total cement content (C) are explored by multiple linear regression analysis. Subsequently, the phenomenological models accounting for several variables are developed to predict the strength of CSCN stabilized earth. Furthermore, the precision of the models is testified by analyzing the deviation between the predicted strength and experimental results.

2. Experiment procedure

2.1. Materials

To analyze the influences of earth properties on strength development, artificial soft clay was used to prepare self-compacting stabilized earth specimens in this study. The artificial soft clay is a mixture of oven-dry clay and water at a designed proportion. The original soft clay is a type of marine clay and obtained from the campus of Shanghai Jiao Tong University in Minhang, Shanghai. Its initial water content and specific gravity are 41% and 2.70, respectively. The liquid limit and plasticity index are about 42% and 18%. The soft clay was oven dried and then crushed, and the crushed dry clay was sieved (2-mm sieve). Its chemical composition is shown in Table 1. The analysis of the particle size for this earth is shown in Fig. 1.

The cement-based composites named CSCN was employed as a stabilizer to prepare stabilized earth specimens. The preparation of CSCN was discussed in previous study [17], and it includes three components. The proportions of ordinary Portland cement, sodium silicate and composite promoter in CSCN are 62.5%, 12.5% and 25%, respectively. ASTM Type I Ordinary Portland cement was employed in the experiments, and it has a compressive strength of 42.5 MPa at 28 days of curing. Table 1 presents the oxide proportion of OPC. Sodium silicate is a kind of melicera liquid, and its concentration and density are about 39% and 1.43 g/cm^3. The mass contents of SiO_2 and Na_2O in liquid sodium silicate were 29.48% and 9.52%, and the molar ratio of silicon dioxide (SiO_2) to sodium oxide (Na_2O) is 3.2. The composite promoter is prepared by mixing of sodium hydroxide (NaOH) solution and calcium chloride ($CaCl_2$) solution, and the flaky NaOH and the granular $CaCl_2$ are both chemically pure.

2.2. Methodology

The details of the specimen mixtures are shown in Table 2, and the percentage values in Table 2 were all calculated by the weight of oven-dry earth. The results obtained from Series I are used for analyzing the variables controlling strength development and establish the mathematical models. Series II are used to evaluate the precision of the predicted values calculated by using the mathematical models. To prepare the self-compacting specimens, the designed amount of water was firstly mixed with dry earth to obtain fluid mixtures, and the ratio of water to earth

Table 1
Chemical Composition of Clay and OPC.

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

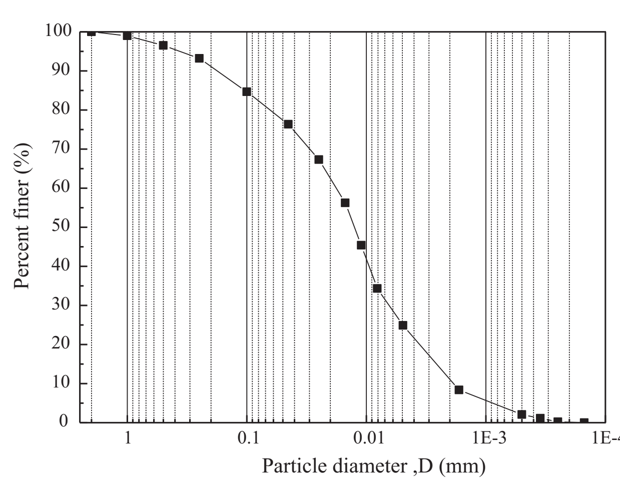

Fig. 1. Grain size distribution curves of the soft clay.