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Effect of organic matter on strength development of self-compacting earth-based construction stabilized with cement-based composites

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HIGHLIGHTS

- The effect of organic matter on the strength development of self-compacting poured earth is quantitatively evaluated.
- The mathematical models for predicting the compressive strength are proposed and their precision is verified.
- The influence of organic matter on phase changes of stabilized specimens is confirmed by XRD and SEM-EDS.

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ABSTRACT

As an environmentally-friendly construction technique, modern rammed earth stabilized with Portland cement has attracted growing interest recently. Some organic clays with high water content are used to prepare self-compacting poured earth in South China. In this study, cement-based composites (CSCN) were employed to substitute Portland cement, and the influence of organic matter (humic acid powder, HAP) on strength development of self-compacting poured earth was investigated using reconstituted organic clay by unconfined compressive strength (UCS) test, X-ray diffraction (XRD) and scanning electron microscope (SEM). Due to the reduction of hydration products by adding HAP, the contribution of HAP was regarded as the consumption of CSCN and the quantitative analysis of consumption effect defined as consumption index (*OCI*) was investigated by the clay-water/CSCN ratio hypothesis. The interrelationship of *OCI* to curing time and the mathematical models for predicting the compressive strength of CSCN stabilized self-compacting poured earth with any HAP content were proposed. It was observed that the *OCI* values decreased with the increase of CSCN content and curing time. The precisions of consumption index and strength prediction models were verified by comparing predicted results and experimental results, and their deviation was mostly within 10%. The influence of HAP on phase changes in stabilized self-compacting poured earth was confirmed by XRD and SEM-EDS analysis, and the amounts of hydration products decreased significantly as increasing the HAP content.

1. Introduction

In the past decade, sustainable development draws widespread attention due to the growing urban size and population, energy consumption and environmental contamination [1]. In China, the energy consumption of construction accounts for one third of total energy costs, and huge amounts of carbon dioxide are produced during the building processes of modern construction [2]. To reduce the energy consumption and carbon dioxide emission, several alternative techniques, such as soil-based or rammed earth construction, have been studied [3,4]. In order to improve the mechanical properties and durability of earth-based construction, projected amounts of cementitious materials were employed. The most common cementitious material used in South-East China is ordinary Portland cement.

In Fujian and Guangdong province, South China, huge amounts of silty clays could be generated during the clean-up operation of rivers, lakes and epeiric sea. The methods to dispose the silty clays with high water content mainly include sediment disposal and direct application. The soils with low water content after the precipitation can be compacted to prepare rammed earth buildings with compressive strength of over 2.5 MPa [5]. However, the sediment disposal occupies a great amount of cultivated land and emits unpleasant gas [6]. The reclamation and silt stabilization are the common direct applications of the silty clays in South China. And the reclamation has been regarded as an effective measure to resolve the land shortage as cities and industries expand. To

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improve the silty clays, the predetermined amount of cement is used as silt stabilizer and the earth-stabilizer mixture with a slurry consistency is obtained. The fluid mixture without compaction energy is convenient for construction and it can be regarded as self-compacting poured earth [3,7].

Generally, the compressive strength of about from 0.4 MPa to 1.5 MPa can meet the requirement of the reclamation and silt stabilization. However, many of marine clays in South-East China, especially in lakeside and seaside areas, are organic soils [8,9]. It is generally known that the sufficient organic matter in organic soils can affect the engineering properties of soils and soil-based constructions [10]. The typical characteristics of organic soils include high water content, high compressibility, low pH value and low shear and compressive strength. Even though the contents of organic matter of most soils in South-East China range between 0.2% and 7.5%, the earth-based construction prepared by organic clays with the projected stabilizer content is characterized by high compressibility and low strength [11,12]. To improve the strength of organic clay-based construction, higher content of cement have to be used, which may result in more energy consumption. Therefore, the high efficiency cement-based composites could be employed to prepare self-compacting poured earth. As reported in [13,14], the strengths of poured earth stabilized with 12% cement-based composites were nearly equivalent to those stabilized with 20% cement.

To understand the mechanism of organic matter in stabilized earth, some researchers studied the influence of organic matter on cement hydration and pozzolanic reaction [15,16]. The acidic organic matter can perform neutralization reaction with OH^- generated from cement hydration, hence reducing the amount of calcium silicate hydrate gels. Due to the more H^+ existing in the diffuse double layer of the clay colloids, more OH^- has to be consumed to activate the clayey particles, which will weaken the pozzolanic reaction between hydrated lime and active minerals. In addition, the organic matter with more functional groups absorbs on the surface of hydration products easily, which influences the stability of the structures formed by calcium silicate hydrate gels and soil particles [17].

Generally, fulvic acid and humic acid are confirmed as the main components of organic matter existing in organic soils. Judged from the results reported in previous studies, the strength development of stabilized earth was mainly affected by the addition of black humic acid. The black humic acid has an intense chemical affinity and selectivity to calcium ion (Ca^{2+}) and performs chemical reaction with hydrated lime [$Ca(OH)_2$] accompanying the formation of insoluble calcium-based humic acid [18]. This insoluble matter can absorb on the surface of cement and clay particles, which interferes with the hydration and pozzolanic reactions [19]. Moreover, lower pH values caused by massive humic acid may hinder the dissolution of clay minerals [17]. Nevertheless, the effects of humic acid on the strength development are not completely understood, and the quantitative analysis methods are not very common in previous studies.

In this study, a high-efficiency clay stabilizer (cement-based composites, CSCN) was employed to prepare self-compacting rammed earth. To investigate the effect of humic acid on the strength development of stabilized poured earth, a research program including experiments on series of specimens prepared with different contents of CSCN and humic acid was performed. Based on the unconfined compressive strength (q_u) obtained in laboratory and the hypothesis of clay-water/CSCN content ratio, the negative effects of humic acid on the strength development can be quantitatively evaluated and the mathematical models were set up. To confirm the mechanism of humic acid, phase changes in stabilized self-compacting poured earth were observed by X-ray diffraction (XRD) and scanning electron microscope (SEM).

2. Experiment details

2.1. Materials

In order to achieve precise results, reconstituted organic clay was used to prepare self-compacting rammed earth in this study. The reconstituted organic clay is a mixture of ordinary soft clay and humic acid at a designed proportion. The ordinary soft clay is a type of marine clay and obtained from Shanghai Jiao Tong University campus in Shanghai, China, at a depth of 6 m. It has high content of fine particle, and about 80% of the soil are finer than 0.075 mm. The specific gravity of this clay is 2.699, and the liquid limit and plasticity index are about 42% and 18%, respectively. According to the Unified Soil Classification System, this soil is a CL. The soft clay was oven drying and then crushed, and the crushed dry clay was sieved (2-mm sieve). Table 1 and Fig. 1 show respectively the chemical composition and morphology and mineralogy of the clay.

Black humic acid generated from the remains of plants and animals after long-time decomposition is a type of complex organic acid. The fundamental structures are aromatic rings and cycloparaffinic rings which have multiple adsorption, complexation and chelation functional groups. The black humic acid powder (HAP) used in this study is a kind of high-purity natural humic acid, and the content of pure humic acid is higher than 85% and the other ingredients are mainly fulvic acid. The pH value of HAP is 3.55.

The cement-based composites named CSCN was employed as a clay stabilizer to prepare self-compacting rammed earth. CSCN consists of three components, and the mass ratio of Portland cement, sodium silicate and composite promoter is 5:1:2. Ordinary Portland cement (ASTM Type I OPC) was used in this study, and its 28-day compressive strength can reach 42.5 MPa. The chemical composition of OPC is shown in Table 1. Sodium silicate used in this study is a syrupy liquid and the concentration is 39%. The weight of SiO_2 and Na_2O are 29.48% and 9.52%, and the molar ratio of SiO_2 and Na_2O calculated by the ratio of the weight to relative molecular mass is 3.2. Its density and pH values are 1.43 g/cm^3 and 11.98, respectively. Chemically pure sodium hydroxide (NaOH) and calcium chloride ($CaCl_2$) were employed to prepare composite promoter.

2.2. Methodology

The specimen mixtures and the corresponding designations are shown in Table 2, and the addition of CSCN and HAP for each mixture was calculated by weight of the dry clay. The results from Series I are applied to analyze the negative effects of humic acid 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 poured earth specimens and simulate the high water content of sludge, the water to solid ratio was about 0.6–0.7 and the predetermined quantity of water was added in two steps. Firstly, the mixture of oven-dry clay and HAP was blended for at least 5 min, and then, the water was added into clay-HAP mixture. The mass ratio of water and the dry clay was 0.7. To obtain the homogeneous specimens, the fluid mixture was sealed and stored in polyethylene plastic bags. Secondly, after 5 days of curing in the curing room (20 ± 2 °C, 98 ± 2% RH), the mixture was put back into the mixer and the predetermined content of CSCN was added. The rest water was initially mixed with CSCN and the mass ratio of water and CSCN is 0.5. Soon afterwards, the mixture was poured into the PVC moulds in three layers. For squeezing the air existing in the mixture, about 35–45 s of vibration was performed on PVC moulds after the completion of each layer. Compaction energy was not needed and the consistency of organic clay-CSCN mixture was applicable by only vibration process. Then, the moulds were wrapped and sealed by polyethylene thin film, and those were all cured in the curing room. The stabilized specimens were demolded at 7 days of curing, and the specimens were also sealed in polyethylene plastic bags and stored in the curing room until the testing ages. At 7, 28, 60, 90 and 120 days of curing, the unconfined compressive strength (UCS) tests with the vertical loading rate of 0.5 mm/min were undertaken. The experimental result for each specimen was the average value of at least three replicates which were prepared and tested under the same condition.

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