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Engineering properties of lightweight cellular cemented clay – fly ash material

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Abstract

Lightweight Cellular Cemented (LCC) material has wide applications in infrastructure rehabilitation and in the construction of new facilities. The roles of water content, cement content, air content, and fly ash (FA) replacement on the engineering properties, including unit weight, flow and strength of LCC clay – FA material, are investigated, analyzed and presented in this article. The engineering properties are strongly controlled by the generalized stress state, w/w_L, where w is the water content and w_L is the liquid limit. The FA replacement reduces w_L, resulting in a change in w/w_L. The workable state, recommended to produce the LCC clay – FA material, is $w > 1.5w_L$. The flowability is independent of cement content and approximated in terms of w/w_L and air content in logarithmic function. The void/cement ratio (V/C), defined as the ratio of the void volume to the cement volume in the mix, is found to be the dominant parameter governing the strength development in LCC clay – FA material. The fabric (arrangement of clay particles, clusters and pore spaces) reflected from both air foam content and water content is taken into consideration by the void volume while the inter-particle forces (levels of cementation bond) are governed by the input of cement (cement volume). A strength equation in terms of V/C at a particular curing time is introduced using Abrams' law as a basis. From the critical analysis of test results, a mix design method to attain the target unit weight, flowability and strength is suggested. This method is beneficial from both engineering and economic viewpoints.

Keywords: Air foam; Cement; Compressive strength; Flowability; Lightweight material; Unit weight

1. Introduction

When infrastructures such as road embankments and bridge foundations are constructed on soft soil deposits, these deposits tend to consolidate and undergo large vertical settlement and lateral deformation during and after construction due to incumbent loads. To solve these problems, the improvement of soft ground by deep mixing technique is commonly applied in Southeast Asia, including Thailand (Arulrajah et al., 2009; Chai and Pongsivasathit, 2010; Horpibulsuk et al., 2004c, 2011b, 2012c). The mechanical behavior of cement admixed clays have been extensively investigated by authors such as Terashi et al. (1979,1980); Kawasaki et al. (1981); Kamon and Bergado (1992); Horpibulsuk et al. (2004a, 2004b, 2010) and Suebsuk et al. (2010, 2011). Instead of improving the soft

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ground (foundation) through often costly ground improvement options, the use of lightweight materials with unit weight of $8-12\,\text{kN/m}^3$ and moderate to high strength as a backfill material to reduce the weight of the structure on the soft clay is an attractive alternative.

A mixture of in-situ clay, air foam agent and cementing agent can be used to form a lightweight material, which is designated as "Lightweight Cellular Cemented (LCC) clay" (Horpibulsuk et al., 2012b). LCC clay is a cost-effective construction material in terms of construction time, material consumption and transportation. Over time, the strength, stiffness and Poisson's ratio of LCC clay increase, enabling further resistance to lateral movement. The LCC clay has been extensively used for highway and port construction in many countries such as Japan and Thailand (Tsuchida et al., 2001; Satoh et al., 2001; Hayashi et al., 2002; Otani et al., 2002; Jamnongpipatkul, et al., 2009; Kikuchi and Nagatome, 2011; Kikuchi et al., 2011).

Recently, the unit weight, strength and compressibility characteristics of LCC clay have been established by Horpibulsuk et al. (2012b, 2013a, 2013b, 2014a, 2014b). The unit weight of LCC clay can be predicted using a phase diagram with the following equation (Horpibulsuk et al., 2012b):

$$\gamma = \frac{\left(\frac{1-V_v}{V_c}\right) G_s\gamma_w(1+w)+G_c\gamma_w}{\frac{1}{V_c}+1} \tag{1}$$

where w is the initial water content of the clay prior to adding cement and air foam (in fraction), G_c and G_s are the specific gravities of cement and soil, respectively, γ_w is the unit weight of water (kN/m^3), V_v is the volume of void in the mix and V_c is the volume of cement in the mix. The equation was developed based on the assumption that all air bubbles (air foam) enter into the pore space when mixed with cement and clay.

Based on the clay$-$water/cement ratio hypothesis for cement stabilized clay (Miura et al., 2001; Horpibulsuk and Miura, 2001; Horpibulsuk et al., 2003, 2005, 2006, 2011a, 2011b, 2012a; Chinkulkijniwat and Horpibulsuk, 2012) and the parameter void/cement ratio for cement stabilized unsaturated sand (Consoli et al., 2007), Horpibulsuk et al. (2012b, 2013a) have successfully employed the void/cement ratio to analyze and assess the strength development of LCC clay. The void/cement ratio (V/C) is defined as the volume of void to the volume of cement in the mix.

To reduce the cost of the LCC clay, the replacement of the cement by waste materials such as fly ash and biomass ash is a suitable alternative method (Horpibulsuk et al., 2009). Recycling and the subsequent reuse of waste materials reduces the demand for scarce virgin natural resources and simultaneously reduces the quality of waste materials destined for landfills (Arulrajah et al., 2013; Hoyos et al., 2011). This will ultimately lower the carbon footprint and lead to a more sustainable environment (Disfani et al., 2012).

Even though there is available research on the application of FA in civil engineering applications including concrete, green materials, pavement base/subbase and soil/ground improvement (Kawasaki et al., 1981; Kitazume et al., 2001; Kehew, 1995; Hannesson et al., 2012; Kaniraj and Havanagi, 1999; Bin-Shafique et al., 2010; Prabakar et al., 2004; Sukmak et al. (2013a, 2013b), the research on usage of FA to develop a sustainable LCC material is very limited. Recently, Horpibulsuk et al. (2014a) used FA as a supplementary material in the development of a LLC material. The role of FA, water, cement and air contents on unit weight and strength of LCC clay$-$FA material has been reported. A critical analysis and assessment of the strength development in LCC FA$-$clay material using a single structural parameter (fabric and cementation bond) was however absent in the previous study. Besides unit weight and strength of the LCC material, the flowability of the LCC paste (before hardening) is also a required parameter for field construction. The higher flowability results in a lower pump capacity and construction cost.

As per the authors' knowledge, the development of rational predictive equations for strength and flowability of LCC clay$-$FA material using few dominant parameters to date is very limited and will be the prime focus of this research. Based on the critical analysis of this study, a suggested design procedure to attain the target strength, flow and unit weight is finally introduced. This procedure will facilitate mix design for pavement and geotechnical engineering practitioners.

2. Materials and methods

2.1. Soil samples

Bangkok clay was collected from Bangkok Noi district, Bangkok, Thailand at a 3 m depth. The clay was composed of 2% sand, 39% silt and 55% clay. The natural water content was 78% and the specific gravity was 2.64. The liquid and plastic limits were 73% and 31%, respectively. Based on the Unified Soil Classification System (USCS), the clay was classified as inorganic clay of high plasticity (CH). Groundwater was at a depth of about 1.0 m from surface. The clay was classified as low swelling type with free swell ratio (FSR) of 1.1. The FSR is defined as the ratio of equilibrium sediment volume of 10 g of oven-dried soil passing a 425 mm sieve in distilled water (V_d) to that in kerosene (V_k) (Prakash and Sridharan, 2004). This method was employed since it is simple and predicts the dominant clay mineralogy of soil satisfactorily (Horpibulsuk et al., 2007).

2.2. Cement and air foam agent

Type I Portland cement (PC) and air foam agent, Darex AE4, were used in this study. The grain size distribution curve of PC obtained from the laser particle size analysis is also shown in Fig. 1. The specific gravity is 3.15 and the average grain size, D_{50} of PC is 0.01 mm (10 μm), which is larger than that of the tested clay. Darex AE4 is a blend of anionic surfactants and foam stabilizers. It is a liquid air entraining agent used in various types of mortar, concrete and cementitious material.