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Durability against wetting–drying cycles of sustainable Lightweight Cellular Cemented construction material comprising clay and fly ash wastes

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HIGHLIGHTS

- Waste materials: fly ash and in-situ clay.
- A green Lightweight Cellular Cemented (LCC) clay.
- Role of cement, air and FA content on durability.
- Predictive wetting–drying (w–d) cycled strength equation.

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ABSTRACT

The viability of using waste materials such as clay and fly ash (FA) for developing a sustainable Lightweight Cellular Cemented (LCC) construction material is investigated in this paper. LCC clay has a wide range of applications in infrastructure rehabilitation as well as in the construction of new facilities. The durability against wetting–drying (w–d) cycles is an important parameter for service life design of LCC clay; however, studies on this aspect to date are very limited. The role of cemented soil structure (fabric and cementation bond) on w–d cycle strength of LCC clay are investigated, analyzed and presented in this paper. The strength reduction with increasing number of w–d is attributed to degradation of the cemented structure. The degradation index, qualifying the rate of degradation with number of w–d cycles, is proposed in term of initial soaked strength (without w–d cycle). Using the degradation index, the predictive w–d cycle strength equation at different number of w–d cycles is furthermore proposed. The applicability of the proposed equation is validated using a separate test data. This approach of predicting w–d cycle strength is beneficial from both engineering and economic points of view.

1. Introduction

There is a myriad of problems associated with the engineering construction in soft clay deposits, particularly in coastal regions in Southeast Asia such as Chao Phraya Plain in Thailand, Mekong Delta in Vietnam and Cambodia, Central Plains of the Philippines, Coastal Plains of Malaysia, Indonesia, Singapore, Hong Kong, Korea, Japan and Taiwan. This soft soil, located in marine or estuary environments, have low shear strength, low bearing capacity and high natural water content, resulting in high compressibility potential. To mitigate future issues with construction on these soft soil deposits, the deep mixing technique is frequently applied [1–8]. The mechanical behavior of cement admixed clays have been extensively investigated by authors [9–15]. The role of physical properties of soil on the strength development is recently investigated by Goodary et al.

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[16]. They reported that soils with a high specific surface (fine particles) needed less amount of cement to provide the same strength and durability as those with low specific surface (coarse particles). Instead of improving the soft ground (foundation) through the costly deep mixing method, the usage of Lightweight Cellular Cemented (LCC) construction materials is an attractive and economical alternative in construction applications such as in embankment, pavement pipe bedding and backfilling. LCC material is a mixture of aggregate, air foam agent and cementing agent.

The usage of recycled waste materials such as Construction and Demolition (C&D) materials incorporating recycled concrete aggregate, crushed brick, and reclaimed asphalt pavement [17–19] has been applied in recent years in a wide range of applications such as embankment fills, pipe-bedding and pavement base/subbase. The usage of recycled waste materials in sustainable manner in the development of LCC materials will further support zero-waste directives currently implemented in many developed and developing countries. Incorporation of waste materials in the development of LCC material will reduce the carbon footprint of our future infrastructures.

A sustainable LCC material made from in-situ and waste clay obtained directly from construction sites has been extensively used for highway and port constructions in Southeast Asian countries such as Japan and Thailand [20–26]. To reduce the cost of the LCC clay from an economical and environmental perspective, the replacement of cement by fly ash (FA) is an attractive method. It was evident from the flowability test (undertaken using a flow cone with 117 mm in height and 254 mm diameter at base and 117 mm diameter at top) that FA reduces the plasticity and improves the flowability of the LCC clay mixture before hardening [27,28]. At the same water content and cement content, the LCC clay with higher FA replacement ratio exhibits higher strength than that with lower FA replacement ratio. The use of FA as a supplementary cementitious material in concrete is also well recognized for improving durability of concrete [29,30]. The incorporation of FA results in considerable pore refinement [31], which leads to a low porosity and discontinuous pore structure. Consequently, the permeability of the concrete reduces and the durability of the concrete increases [32].

The in-situ LCC clay as a stabilized engineering fills and pavement materials generally encounters with w–d cycles from the change of weather during wet (rainy) and dry (summer) seasons. This is particular relevant for tropical countries such as Thailand, as well as parts of Australia and China. The w–d cycles result in tension and surface cracks, which can damage the stabilized pavement structure [33–36]. Even though there is available research on the strength development in LCC clay, the investigation of durability against the wetting–drying cycles (w–d cycles), a critical aspect for infrastructure design such as in engineering fills and pavements, is very limited and is the prime focus of this research. The investigation of the service life of the LCC clay via wetting and drying test is significant and is another focus of this research. The strength of LCC clay is dependent upon the cemented soil structure (fabric and cementation bond) [37]. As such, tests with a wide range of water contents, air contents, FA contents and cement contents of the LCC clay are undertaken to understand the role of both fabric and cementation bond on the w–d cycle strengths. Based on the analysis of the test results, a rational empirical relationship between w–d cycle strengths and initial soaked strength (without w–d cycles) is proposed. This equation can facilitate the determination of a suitable mix proportion of LCC materials to meet the strength requirement at a target service life. This research will enable waste excavated soft clay traditionally destined for landfill to be used in a sustainable manner as an aggregate in LCC materials, which is significant in term of engineering, economical and environmental perspectives.

2. Theoretical background

For a LCC clay at a water content between 1.5 and 3.0 times the liquid limit, the strength is determined exclusively by the water-void to cement, wV/C [38]. This parameter is defined as the product of initial clay water content (before mixing with cement and air foam) times V/C, where the water content is expressed in fraction. The parameter V/C is defined as the ratio of volume of voids to the volume of cement in the mix. Strength is independent of water content, air content and cement content in the mix. Based on extensive test results, Horpibulsuk et al. [38] have proposed a predictive strength equation in term of curing time, and wV/C for the LCC Bangkok clay as follows:

$$\left\{\frac{q_{(wV/C)_D}}{q_{(wV/C)_{28}}}\right\} = \left[\frac{(wV/C)_{28}}{(wV/C)_D}\right]^{1.27}(0.027 + 0.300\ln D) \tag{1}$$

where $q_{(wV/C)_D}$ is the strength of LCC clay to be estimated at water-void/cement ratio of (wV/C) after D days of curing and $q_{(wV/C)_{28}}$ is the strength of LCC clay at water-void/cement ratio of (wV/C) after 28 days of curing. The unit weight (in kN/m^3) is determined in term of water content, cement content and V/C by using Eq. (2) [27,39]:

$$\gamma = \frac{\left(\frac{G_c G_s \gamma_w^2 (1+w)}{C} + G_c\gamma_w\right)}{\left(\frac{G_c\gamma_w}{C}+1\right)} - (V/C)\left(\frac{G_s\gamma_w(1+w)}{\frac{G_c\gamma_w}{C}+1}\right) \tag{2}$$

where w is water content (in fraction), G_c and G_s are the specific gravities of cement and soil, respectively, γ_w is unit weight of water (kN/m^3) and C is cement content (kg/m^3). Eq. (2) was developed based on the assumption that all air bubbles (air foam) enter into the pore space when mixed with cement and clay. With the variation in water content and cement content, the air content required to attain the required V/C is determined:

$$A_c = (V/C)\frac{C}{G_c\gamma_w}(1 + wG_s) - wG_s \tag{3}$$

3. Materials and methods

3.1. Materials

3.1.1. Soil sample

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 as shown in Fig. 1. The natural water content was 80% 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 encountered at a depth of approximately 1 m below the 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) [40]. This method was adopted since it is simple and predicts the dominant clay mineralogy of soil satisfactorily [41]. Table 1 summarizes the chemical composition of Bangkok clay using X-ray fluorescence (XRF). Even though Bangkok clay is classified as low swelling types, moderately high clay content of up to 55% may cause swelling and shrinkage on the LCC clay during w–d cycles. This effect will be examined in this paper.

3.1.2. Cement and air foam agent

Type I Portland cement (PC) and air foam agent, Darex AE4, provided by the Grace Construction Products Ltd., were used in this study. The grain size distribution curve, obtained from the laser particle size analysis, and chemical composition of PC are also shown in Fig. 1 and Table 1, respectively. The specific gravity is 3.15 and the D_{50} is 0.01 mm (10 micron), which is larger than that of the tested clay. The air foam agent 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.