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Research paper

Strength behavior and microstructural characteristics of soft clay stabilized with cement kiln dust and fly ash residue

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ABSTRACT

This study presents the use of cement kiln dust (CKD) and fly ash (FA) to improve the unconfined compressive strength (UCS) of soft Bangkok clay compared with ordinary Portland cement (OPC). The UCS tests were performed after a curing time of 3, 7, 28 and 90 days. An investigation of each reaction product was conducted using an X-ray diffraction (XRD) technique, and changes in the microstructures of the stabilized clay were observed using a scanning electron microscope (SEM). The test results revealed that a 13% CKD mixture with a partial replacement of 20% FA was suggested as the optimal content ratio to produce a similar long term strength as that achieved using the 10% content of OPC. The UCS of the stabilized clay increased relative to the formation of the primary reaction product, calcium silicate hydrate (CSH), as analyzed using the XRD. The formation of this product reduced the void space in the clay structure resulting in denser and stronger of stabilized clay to correspond with the compressive strength development with time. The change on microstructure of stabilized clay due to the hydration products was evidenced by SEM.

1. Introduction

Bangkok is located in the Chao-Phraya delta river plain, which is comprised of a soft deposit of marine clay layer, i.e., "soft Bangkok clay". The undesirable properties of soft clay, i.e., low shear strength and high compressibility, can be strengthened for construction purposes using a process of clay improvement techniques. The most popular clay improvement technique is deep mixing, which is widely used in Europe and Asia (Xu et al., 2006; Xing et al., 2009). The deep mixing technique uses a machine in situ to mix the soft clay and stabilizer to create a clay mixing column to transfer the load to the deep hardened clay layer. The stabilizer commonly used for deep mixing is ordinary Portland cement (OPC), whose increased clay strength is well established (Miura et al., 2001; Mohammad and Alipour, 2012; Yang, 2012). In Thailand, cement is commonly used as a stabilizing agent in geotechnical projects because it is a general construction material that is locally available and can achieve compressive strength within a month.

The mechanism of strength development in clay stabilized with cement (clay cement) can be explained. When cement and water is mixed with clay, primary and secondary reaction products from the hydration reaction are formed, which affect the improved clay cement properties. The primary products are comprised of calcium silicates hydrates (CSH), calcium aluminates hydrates (CAH) and lime. The secondary products resulting from the pozzolanic reaction between lime and clay minerals, clay silica and clay alumina were continuously formed as CSH and CAH after a curing period. As a result of both reaction products, the clay became denser, stronger and harder, which resulted in an increase in the treated clay strength after curing (Bell, 1993; Chang et al., 2007; Ouhadi and Yong, 2008). In addition, cement kiln dust (CKD) is alternative stabilizer and the mechanism of strength development could also be considered. The CKD is composed of silica, calcium carbonate, calcium sulfate and calcium oxide (free lime), which are minor components of sulfates and chlorides. Since free lime containing binder system reacts with water in the clay, CSH gel is formed due to a pozzolanic reaction and the other products including ettringite, monosulfate and syngenite phase were generated. Thus, the CKD and their hydration products may lead to strength increase of the stabilized clay. Moreover, the combination of CKD and other pozzolanic materials such as slag and fly ash could be more potentially results of mechanical properties (Wang et al., 2004; Peethamparan et al., 2008; Chaunsali and Peethamparan, 2010).

Considering the cost reduction for the deep mixing process, the industrial waste of the alternative stabilizer and the cementitious material was compared with the waste of the OPC. One interesting type of waste is CKD, which is generated in the kiln during the cement manufacturing process. The cement production in Thailand is approximately 30 million tons per year (Thai Cement Manufacturers Association, 2015), and roughly 15–20% becomes CKD (EPA U.S. Environmental Protection

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Agency, 1993; Rahman et al., 2011), which is approximately 4.5–6.0 million tons per year. CKD is a fine particle material removed from cement kiln by exhaust gases and collected using electrostatic precipitator equipment (Najim et al., 2014).

Generally, CKD is primarily composed of groups of calcium carbonate and silicon dioxide, which resemble the cement kiln raw feed but vary in the amounts of chloride, alkalis and sulfate (Kunal et al., 2012). The composition of the CKD is highly variable depending on the raw material, dust collection method, operation system and type of fuel used in each factory (Maslehuddin et al., 2009). Based on the above reasons, it is necessary to investigate the CKD before its application in soft clay improvement. A few studies revealed that the use of the CKD as a potential clay stabilizer is comparable to that of the OPC, and it can be used to increase clay strength, reduce permeability and enhance durability of the clay (Peethamparan et al., 2009; Amadi, 2014; Hashad and Ei-Mashad, 2014).

However, the study shows that the OPC and CKD had a significant increase in the clay strength within a month (Sreekrishnavilasam et al., 2007; Goodary et al., 2012). Several studies suggested that admixing with pozzolanic materials enhanced the long term strength (Kolias et al., 2005; Zentar et al., 2012; Chaunsali and Peethamparan, 2013). Fly ash (FA) has long been understood as an industrial waste with pozzolanic material properties in a concrete field. Fly ash is the industrial waste by-product created from the coal combustion process in power plants that has been pulled out of the boiler by flue gases and collected using electrostatic precipitators into a bag. Generally, the primary chemical composition of FA are silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and ferric oxide (Fe_2O_3), hence it can be regarded as a pozzolanic material (Sezer et al., 2006; Wu et al., 2014). In Thailand, the amount of FA generated from the Mae Moh electric power plant, which is the largest electric power plant, is more than approximately 3.2 million tons per year (Electricity Generating Authority of Thailand, 2015). Using FA would be beneficial for several environmental reasons, such as relieving air pollution, reducing the amount of leachate from FA during storage to seep through the underground water layer and saving natural resources when using FA as a replacement for raw materials used in cement manufacturing process. An increased use of the FA as a partial cement replacement not only adds value of such industrial waste but also presents cost savings in construction projects. A few researchers presented that the FA can be applied in geotechnical projects to enhance clay strength, increase bearing capacity, reduce swell potential of expansive clay, and maintain low permeability of the stabilized clay (Singh et al., 2008; Jongpradist et al., 2010; Kogbara et al., 2013; Voottipruex and Jamsawang, 2014). These studies recommended that a suitable amount of FA should be considered before use due to the variations in its properties at different areas.

The primary objective of the current study is to determine the strength of the stabilized clay using cementitious materials as stabilizers, such as OPC and CKD, and partially replacing the CKD with pozzolanic material using FA. Based on a compressive strength test, the increase in strength of the treated clay was compared with the reaction products from the hydration process, which were investigated using an X-ray diffraction (XRD) analysis. The changes in the stabilized clay structure were observed using a scanning electron microscope (SEM).

2. Experimental program

2.1. Materials

The typical soft Bangkok clay was used as the base clay in this study. The clay sample was collected from a depth of 2–6 m at a construction site near Bangkok, Thailand. The geotechnical properties of the base clay were determined by the ASTM Standard Test Methods and are summarized in Table 1. The natural water content was 93%, and the liquid limit and the plastic limit was 88% and 36%, respectively, which corresponds to a liquidity index of 1.1. Thus, this clay, when remolded, can be transformed into a viscous form to flow like a liquid. The specific gravity was 2.66, and the undrained shear strengths ranged from 4 to 10 kPa and were obtained from an unconfined compression test. According to the Unified Clay Classification System (USCS), the clay can be classified as clay CH with a high plasticity. The chemical composition of the clay was performed using an X-Ray Fluorescence (XRF) analysis, as indicated in Table 2, to reveal the primary compositions of the clay to be SiO_2, Al_2O_3 and Fe_2O_3. The stabilizers used in this study were OPC, CKD and FA. The chemical compositions of the stabilizers and the base clay were determined using the XRF analysis, as indicated in Table 2. The specific gravity of the OPC Type I was 3.15. The primary compositions of the commercial OPC Type I were CaO and SiO_2 as well as Al_2O_3 and Fe_2O_3. The particles of the OPC were observed using an SEM micrograph (Fig.1a), which illustrates that the particles have a rough surface, sharp corners and are non-uniformly shaped. The CKD was obtained from the cement factory, which is located in the Saraburi province of Thailand. The compositions of the CKD consist primarily of CaO and SiO_2 with Al_2O_3 and Fe_2O_3, which are similar to those found in the OPC. The CaO and SiO_2 contents in the CKD are lower than that in the OPC. The specific gravity of the CKD was 2.73, and the fineness ranged between 3000 and 3400 cm^2/g. Fig. 1b illustrates the SEM micrograph of the CKD particles, which revealed that the particles of the CDK were similar to that of the OPC in terms of roughness and sharpness.

The FA used in this study was supplied from the Mae Moh electric power plant, which is located in the Lamphang province of Thailand. The chemical composition of the FA consists of high SiO_2 contents with Al_2O_3, Fe_2O_3 and CaO. According to the ASTM standard (ASTM C618-12a, 2012), FA is classified as a class C for pozzolanic material properties, for which the composition summations of $SiO_2 + Al_2O_3 + Fe_2O_3$ are between 50% and 70% by dry weight. The specific gravity of the FA was 2.53, and the fineness ranged between 3200 and 3600 cm^2/g. The SEM micrograph (Fig. 1c) indicated that most of the particle shapes of FA were spherical.

The grain size distribution (GSD) curves for the OPC, CKD and FA were obtained using laser particle size analysis, and the GSD curves for the soft clay were obtained using a hydrometer analysis (ASTM D422-63, 2007). These curves are plotted together for comparison, as shown in Fig. 2. The GSD curves for the OPC, CKD and FA were similar

Table 1
Geotechnical properties of base clay.

Properties	Standard test method	Value
Natural water content (%)	ASTM D2216-10, 2010	93
Liquid limit (%)	ASTM D4318, 2010	88
Plastic limit (%)	ASTM D4318, 2010	36
Plasticity index (%)	ASTM D4318, 2010	52
Liquidity index	ASTM D4318, 2010	1.1
Clay content (%)	ASTM D422-63, 2007	70
Activity	ASTM D422-63, 2007	0.74
Wet unit weight (kN/m^3)	ASTM D7263, 2009	14.9
Specific gravity	ASTM D854-92, 1994	2.66
Undrained shear strength (kPa)	ASTM D2166/D2166M-16, 2016	4–10
Soil classification (USCS)	ASTM D2487-11, 2011	CH

Table 2
Chemical composition of base clay, OPC, CKD and FA.

Compound	Base clay	OPC	CKD	FA
Silicon dioxide (SiO_2)	61.17	18.43	14.94	37.34
Alumina oxide (Al_2O_3)	21.64	4.95	4.07	18.63
Ferric oxide (Fe_2O_3)	9.32	3.29	2.27	13.17
Calcium oxide (CaO)	1.03	66.35	53.89	17.85
Magnesium oxide (MgO)	1.68	0.86	1.84	3.92
Sulfur trioxide (SO_3)	1.15	3.18	10.96	3.51
Potassium oxide (K_2O)	2.53	1.22	3.62	2.98
$Na_2O + TiO_2$ + other	0.57	0.15	2.78	1.96
Loss on ignition (% by mass)	0.91	1.57	5.63	0.64