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Research paper

Enhanced stabilization of highly expansive clays by mixing cement and silica fume

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ABSTRACT

The present study investigated the potential use and effectiveness of expansive clay stabilization using a mixture of cement and silica fume (CSF) as a possibly useful option from environmental, economic, and (or) technical perspectives. In so doing, cement and CSF blend with 10% cement replacement were separately added to a clay sample having high degree of swelling potential, and then, a set of macro and micro level tests were performed under various curing regimes to assess the responses of amendments. The results showed that at ambient condition of 20 °C, highly expansive clays need a large quantity of cement (≥15%) and a curing time of 28 days to get stabilized satisfactorily. In this case, although a higher temperature (40 °C) leads to a decrease in the required time of curing, there is no a remarkable reduction in the optimum content of additive. It appeared that the CSF binary system can expedite the process of stabilization and thus is more efficient in improving the clay engineering properties with a lower amount of binder (to about 33%) and shorter curing ages (by nearly 2 times) compared to the sole cement. In fact, based on the XRD and SEM analyses, the incorporation of silica fume into the cement matrix extends the formation of new cementing compounds and provides a much denser microstructure; two features which were found to be very effective in surpassing the problems associated with expansive clays.

1. Introduction

Expansive soils have a complicated behavior and are generally characterized by detrimental volume changes when subjected to moisture fluctuations (Khemissa and Mahamedi, 2014). The swelling and shrinkage of expansive soils can lead to considerable distortion and failures in the civil engineering structures and geoenvironmental projects (Phanikumar and Singla, 2016). The annual cost of damage to facilities and infrastructures caused by these types of soils is estimated at £150 million in UK, $1000 million in the United States, and several billions of dollars worldwide (Qi and Vanapalli, 2015). The problems associated with swelling soils contribute to the establishment and development of various techniques for improving their very low engineering properties (Celik and Nalbantoglu, 2013; Turkoz et al., 2014; Phanikumar et al., 2015). Amongst the potential methods likely to improve the behavior of such soils, the chemical treatment is an effective technique introduced many years ago. The previous works indicated that different amendments including lime, cement and other chemicals can be utilized to overcoming deficiencies in the performance of expansive soils (Seco et al., 2011; Mahamedi and Khemissa, 2015). Whilst cement has commonly been used for the soil treatment, it may show limited efficiency in some applications (Cuisinier et al., 2011; Saride et al., 2013; Deng et al., 2015). For example, the cement-stabilized soils may experience volume instability in post-stabilization periods. This could be attributed to the growth of high expansive minerals (e.g. ettringite) which are formed from the free Ca^{2+} ions of unconsumed additive reacting with the sulfate minerals in the soil pore fluid (Rao et al., 2008; Verástegui-Flores and Di Emidio, 2014). Moreover, the environment temperature may causes a significant impact on the performance of cement based stabilizers, because it can influence the kinetics of cementitious formation and therefore the mechanical properties of the hardened cement paste (Kuo and Shu, 2015). In addition, the production of cement is an energy-intensive process and emits a large content of greenhouse gas into the atmosphere. Accordingly, researchers are working on strategies to developing alternative agents or additives, especially those that are more effective and less costly, to improve the soil engineering parameters (Cokca et al., 2009; Kalkan, 2011; Zhang et al., 2014; Goodarzi and Salimi, 2015).

Silica fume (SF) is a by-product material produced in large amounts throughout the world from the manufacture of silicon or ferrosilicon alloys. The proper disposal of SF, as an industrial waste, is one of the major issues for environmentalists since leaving it directly in the environment may cause severe health problems (Zhang et al., 2016). On the other hand, the amorphous structure, high SiO_2 content, and large specific surface area make the SF reactive to the alkali product of cement to produce the additional amounts of calcium-silicate-hydrate (CSH) phase, enhancing the bonding of solid phase and improving the strength of

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cement-SF binary system considerably. Furthermore, the particles of SF are 100 to 150 times smaller than the cement grains and because SF particles have near-perfect spheres, they can occupy the micro voids in the matrix and provide a much denser structure, which in turn may decrease the permeability of the system and therefore increase its resistance to the aggressive environment (Asavapisit et al., 2001; Koksal et al., 2015). Apart from pozzolanic activity and filling effect of SF, this material may affect the hydration kinetics (Benaicha et al., 2015; Liu et al., 2015); this is because SF particles may prepare more nucleation sites, a process that accelerates the hydration reactions of cement and contributes towards a decrease of the setting times (Muller et al., 2015). Therefore, SF, as an additive, can partially be replaced with cement, which could result in promoting the performance of the cement, contributing to waste recycling of SF, and also reducing the production demand for cement, thus mitigating carbon emissions since it has been reported that the production of one ton of cement, on average, generates 0.7 to 1 tons of carbon dioxide (Tsai et al., 2014). However, in spite of the fact that the positive effects of SF on the concrete and cement-based stabilization/solidification of hazardous waste have been previously investigated in several studies (Coz et al., 2009; Saraya, 2014; Abo-El-Enein et al., 2015), there is a lack of detailed works on the potentials of cement/silica fume blend for the treatment of swelling soils. Thus, the present research was conducted to address the efficacy of SF in enhancing the geo-mechanical characteristics of cement-stabilized highly expansive clays. For this propose a set of macro and micro level tests including electrical conductivity (EC), pH value, swelling, unconfined compression strength, consolidation, permeability, X-ray diffraction (XRD) and scanning electron microscope (SEM) analyses were performed on the natural and treated swelling clay samples at various curing regimes.

2. Materials and methods

2.1. Materials and sample preparation

The difficulties associated with swelling soils have generally occurred in clays that contain predominantly expansive lattice type minerals such as montmorillonite (Al-Mukhtar et al., 2012). Besides, smectite clay (rich in montmorillonite) is widely utilized in the landfill liners and cover systems (Goodarzi et al., 2016). Hence, in this study, smectite was used as source material for all experiments. The engineering properties of the clay sample were measured according to ASTM methods (ASTM, 2006), and its geo-environmental characteristics were also determined using the procedures described in the EPA manual (EPA, 1983). The XRD and chemical analyses showed that the clay sample contains high amount of montmorillonite and its main exchangeable cation is sodium ions. Therefore, it can be considered as a Na^{+}-dominant montmorillonite (Na-m) which has a high tendency to swelling (Seco et al., 2011). The engineering and geo-environmental properties of the clay sample are given in Table 1. Sole cement and a mixture of cement/silica fume (CSF) with 10% cement replacement were used as additives for stabilization of the expandable clay sample. The cement was replaced with 10% SF because higher percentage of replacement might have occupied the pore spaces and could have limited the extent of cement hydration reactions (Asavapisit et al., 2001; Muller et al., 2015). The chemical compositions of the used cement and SF were determined by the XRF analysis and are given in Table 2. As it can be seen, the SF has a noticeable amount of SiO_2 which can react with the alkali product of cement (Koksal et al., 2015; Liu et al., 2015) to form additional amounts of cementing compounds.

The amendments including sole cement and the CSF blend were separately added in dosages ranging from 2.5 to 20% in dry mass to the expansive clay sample. Prior to mixing, all the constituents were oven dried and passed through a No. 200 sieve. The clay-additive mixtures were blended with the needed amount of water for each test and then were placed in air-tight plastic bags and cured in a warm humid chamber at different temperatures (20 °C and 40 °C) and with a relative humidity of 85%. At the end of each curing period (i.e. 1 to 28 days), the experiments were performed to investigate the effects of cement and CSF blend on the geo-mechanical parameters of the composite samples.

Table 1
Engineering and geo-environmental properties of the clay sample.

Characteristics	Quantity measured
Mineral composition in decreasing abundance	Montmorillonite, quartz, calcite
Soil-pH	10.15
EC, mS/cm	1.05
SSA, m^2/g	420
CEC, cmol/kg	76
Clay fraction, %	77
Specific gravity, G_S	2.77
Plasticity index (PI), %	312
Soil classification	CH
Swelling potential, %	140.7
Compression index, Cc	1.15
Maximum dry density, gr/cm^3	1.27
Optimum moisture content, %	42
Unconfined compression strength, kPa	510

Where EC stands for electrical conductivity; SSA for specific surface area; and CEC for cation exchange capacity.

2.2. Macro and micro level experiments

To investigate the chemical reactions between the clay lamellae system and the agents, a series of batch equilibrium tests were performed according to the EPA (1983). For this purpose, suspensions of clay samples with the different amounts of additives were first prepared at a 1:20 clay-water ratio and then were equilibrated (shaken for 2 h on a horizontal shaker). After this, the pH and EC of the clay-additive slurries were recorded both immediately (2 h) and after 1 to 28 days of curing.

As in many previous studies (Cuisinier et al., 2011; Aldaood et al., 2014; Zhang et al., 2014; Goodarzi and Salimi, 2015), the unconfined compression strength (UCS) test was used to evaluate the effectiveness of stabilizers. For performing the UCS tests, the clay/additive mixture required for the maximum dry density was weighed and thoroughly mixed for a period of 10 min to attain homogeneous samples. The distilled water needed as the optimum moisture content was also added to the sample. The wet homogenized mixture was then placed inside cylindrical steel mold with 35 mm in diameter and 70 mm in length. To ensure uniformed compaction, each sample was subjected to a static compression force using a hydraulic jack to achieve the desired dry density. After extrusion of the samples from the molds, they were cured as the mentioned method for the sample preparation and the UCS tests were performed following ASTM D-2166. To determine the compression behavior of the natural and treated swelling clay, the specimens were first prepared in a way similar to that used for the UCS test and they were confined in the oedometer ring, 50 mm in diameter and

Table 2
Chemical compositions of used cement and silica fume (SF).

Chemical composition	Percentage in weight (%)	
	Cement	SF
SiO_2	21.52	90.6
Al_2O_3	4.95	1.47
Fe_2O_3	3.82	1.93
CaO	63.49	1.52
MgO	1.55	0.42
Na_2O	0.48	0.63
K_2O	0.75	1.31
P_2O_5	<0.1	0.28
SO_3	2.13	0.41
TiO_2	<0.1	<0.1
Loss of ignition	1.11	1.33