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Compaction and shear strength characteristics of colemanite ore waste modified active belite cement stabilized high plasticity soils

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A B S T R A C T

An experimental investigation was undertaken to evaluate the mechanical behavior of soil–cement mixtures. The primary motivation for the study was to investigate the innovative use of colemanite ore waste (CW) modified active belite cement (BC) in soil stabilization engineering (applications). The specific objectives of the research were to evaluate and compare: (1) compaction characteristics, (2) unconfined compressive stress-axial strain behavior, (3) unconfined compressive strength, (4) Young's secant modulus of elasticity, and (5) undrained shear strength characteristics of belite cement (BC)–clay and ordinary portland cement (OPC)–clay mixtures. BC and OPC were mechanically mixed with clay in five different dosages, i.e. 1.0%, 2.5%, 5.0%, 7.5% and 10.0% by using dry weight of clay, separately. Compaction characteristics of untreated soil, BC–clay and OPC–clay mixtures were evaluated at standard Proctor compaction energy. For a meaningful comparison of unconfined compression and triaxial test results, all specimens (untreated soil, BC–clay and OPC–clay mixtures) were prepared at maximum dry unit weight and optimum water content. Cylindrical samples of 50.0 mm in diameter and 100.5 mm in length were compacted in three layers and their strength characteristics were investigated at 1-, 7-, 14-, and 28-days curing times. Results of unconfined compression tests showed that cement dosage less than 5% has little effect on unconfined compressive strength (UCS) and exhibits ductile type of failure for both OPC–Clay and BC–Clay mixtures. In contrast, for cement content equal or greater than 5%, cement treatment significantly improved UCS and displayed brittle stress–strain behavior especially for BC–Clay mixtures. Similar behavior is obtained from undrained triaxial tests. The variation of undrained cohesion intercepts with respect to cement type, cement content and curing time is more sensitive than that of undrained internal friction angle.

1. Introduction

It was reported in the Intergovernmental Panel on Climate Change (IPCC) that most of the increases in temperature (or global warming) observed since the middle of the 20th century was caused by gradually increasing concentrations of greenhouse gases (IPCC, 2007). According to the Kyoto Protocol, which is an international agreement linked to the United Nations Framework Convention on Climate Change (UNFCCC), CO_2 is the most important anthropogenic greenhouse gas and cement production generates more CO_2 emission than any other industrial process. Due to large quantities of fuel used during manufacture and the release of carbon dioxide from raw materials, the cement industry contributes to about 5% of global anthropogenic CO_2 emissions (Worrell et al., 2001). In the near future, the field of cement application will expand in parallel with new developments. Therefore, conducting researches to find alternative raw materials and to reduce energy consumption in cement production is of global concern. In this context, colemanite ore waste (CW), the by-product of the reaction of colemanite ore and sulfuric acid generated during the production of boric acid, modified active belite cement (BC) is produced in Turkey. This study aims to investigate the usability of this innovative CW modified active belite cement (BC) in soil treatment applications.

Before introducing a detailed discussion of the current literature on the mechanical stabilization of fine grained soils with cement, the reader will be informed briefly about colemanite mineral, colemanite ore waste (CW), CW modified active belite cement (BC), and superiority of BC over ordinary portland cement (OPC) with regard to environmental impacts elaborated in succeeding paragraphs.

2. Colemanite ore waste (CW)

Colemanite, which is an important borate ore, is mainly used in the production of various boron compounds such as boric acid,

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borax and boron oxide (Garrett, 1998; Helvaci and Alonso, 2000). During the production of boric acid, a large quantity of about 120,000 tonnes of colemanite ore waste (CW) is generated per year (Yakar et al., 1999). This CW causes various environmental problems when discharged directly to the environment. Moreover, the disposal of this huge quantity of CW is becoming more expensive each year due to the requirement of a large area of land and it poses a serious problem in terms of potential environmental pollution (Boncukcuoglu, et al., 2002). Studies on the reclamation of CW have been showing progress in different research areas and through several applications; this material has been turned into replacement materials of natural gypsum in cement production (Yakar et al., 1999; Boncukcuoglu, et al., 2002; Targan et al., 2002; Elbeyli et al., 2003; Olgun et al., 2007).

3. Colemanite ore waste (CW) modified active belite cement (BC)

Being the most important raw material of cement production, limestone ($CaCO_3$) is primarily used for CaO requirement. During the calcination process ($CaCO_3 + \text{energy} \rightarrow CaO + CO_2$), limestone ($CaCO_3$) is calcined at a temperature above 900 °C and as a result of this process a high amount of CO_2 gas is emitted to the atmosphere. On the other hand, colemonite contains CaO component in its constitution, thus it can be directly used in cement production without any pre-calcination operation. Using approximately 3–5% CW in the process of cement production, the amount of $CaCO_3$ to be used in cement production is reduced (Targan et al., 2003; Yakar et al., 2003). Consequently, using less amount of $CaCO_3$ in cement production yields less energy consumption and therefore less CO_2 emission. Moreover, addition of CW prevents the formation of C_3S (alite) phase, and instead of C_3S (alite), a more active and stable belite phase of C_2S (belite) is formed. That is why the cement is called as belite cement (BC). Since C_2S phase is formed at a temperature not more than 1325 °C, the clinker sintering temperature decreases from 1450 °C (for OPC) to 1325 °C. The decrease in temperature provides approximately 8.6% energy saving. During the production of industrial pilot scale, CO_2 emission is reduced approximately 25% (Saglik et al., 2009). Thus, considering the above discussion, BC production seems to be more environmental friendly when compared to OPC production. Therefore, it is important to conduct researches on the usability of BC cement in different engineering applications.

4. Review of literature on modification of clay soils with cement

The modification of clay soils with cement to improve their engineering properties is well recognized and widely practiced. Through stabilization, the plasticity of soil is reduced, it becomes more workable, and its compressive strength and load bearing properties are improved. Such improvements are the result of a number of chemical processes that take place in the presence of cement (Bhattacharja and Bhatty, 2003). Several factors such as plasticity of soil, types and amounts of cement, mixing and compaction methods, curing conditions, gradation and pulverization, etc., affect the performance of stabilized soil. These issues were previously discussed by several authors (Bell, 1976; Petry and Kelly, 1988; Lasisi and Ogunjide, 1984; Bell, 1994; Prusinski and Bhattacharja, 1999; Mohammad et al., 2000; Bhattacharja et al., 2003; Druss, 2003; Anagnostopoulos and Chatziangelou, 2008). The findings of some of these studies are critically reviewed below.

The influence of various mineralogical components of soil on the changes in physical properties and the development of strength in compacted soil–cement mixtures is investigated by Croft (1967). It has been revealed that soil composition can be used to predict successful stabilization. In another study Croft (1968) has determined the suitability of soil for cement stabilization by chemical and mineralogical compositions and texture of a soil. It is stated that chemical and physical properties do not characterize soils uniquely with regard to their response to cementitious stabilizing agents. In the same manner, Bell (1976) has treated three of the principal components found in clays, i.e. kaolinite, montmorillonite and illite, separately with varying amounts of cement. The obtained results have revealed that kaolinite appears to have little effect on the hydration of cement and that the hardening proceeds normally. Well organized illite may be regarded as inert as far as cement stabilization is concerned. By contrast, clay minerals with montmorillonite have a profound influence on the hardening of cement. In another study, Temimi et al. (1998) have proved that clay masses containing more than 5% montmorillonite cannot be stabilized with economically justified amounts of cement.

The effect of cement content on soil–cement mixtures cured for different periods of time were examined by means of unconfined compression and modulus of elasticity measurements. The highest proportions of cement usually gave better improvement in values (Lasisi and Ogunjide, 1984; Bell, 1994). In one study, Aytekin and Nas (1998) conducted a series of unconfined compression and direct shear box tests under laboratory conditions to investigate the effect of the addition of variable amounts of OPC on the strength of three different soils of CL, CH, and ML. The results of these tests indicated that the best stabilization was achieved by incorporating between 5 and 10% cement dosages. Similarly, another study (Basha et al., 2005) recommended the addition of 6–8% cement as an optimum amount from the viewpoint of plasticity, compaction and strength characteristics, and economy.

Lasisi and Ogunjide (1984) stated that the finer the grain size range, the higher the compressive strength was. In another study, Petry and Kelly (1988) found considerable differences in the strength of a highly active clay soil, depending on gradations used to make specimens. They also reported that Portland cement is more effective in strength, provided that the gradation is fine enough.

In a laboratory study, Mohammad et al. (2000) examined the performance of four different cement-stabilized soil mixtures. The results indicated that there was no significant difference in performance between the plant-mixed and in-place-mixed cement-treated soil mixtures. Mohammad et al. (2000) also reported that increases in compaction effort as well as those in curing period maintained or significantly amplified the unconfined compressive strength.

Cement stabilized soil is usually compacted by different mechanical methods to increase its strength and durability. In one study, Kenai et al. (2006) investigated the effect of different compaction methods on the performance of stabilized soil. The investigated compaction methods were either static compaction by applying static pressure using a universal compression testing machine, dynamic compaction by using drop weight method, or static compaction coupled with vibration. The study revealed that dynamic compaction with about 8% cement content appears to give the best performance for the investigated soil.

Lorenzo and Bergado (2004) found that the fundamental parameters such as after-curing void ratio and cement content are sufficient to characterize the strength of cement-admixed clay at high water contents. The results of unconfined compression tests proved the ratio of after-curing void to cement content in order to combine the influences of water content, cement content, and curing time on the strength of cement-admixed clay. In another study, Zhang and Tao (2008) investigated 7 days unconfined compression strength (UCS) of low plastic silt clay at six different cement dosages and four different molding moisture contents. The test results indicate that the water–cement ratio of cement-stabilized soil has a dominant influence on the 7 days UCS of stabilized samples.

In the present investigation, under the light of the above discussion, the effect of different BC and OPC dosages on compaction characteristics and time-dependent strength behavior has been investigated on a laboratory scale to provide a one-to-one comparison on the performances of BC- and OPC-stabilized high plasticity clay.