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Research paper

Stabilization of expansive Belle Fourche shale clay with different chemical additives

Mustafa Dayioglu[a], Bora Cetin[b,*], Soonkie Nam[a]

[a] Department of Civil and Environmental Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701, United States
[b] Department of Civil, Construction and Environmental Engineering, Iowa State University, Ames, IA 50011, United States

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ABSTRACT

Improving the engineering properties of expansive soils is very important in northern plains, Texas and mid-west regions of the United States. In this study, expansive Belle Fourche clay (B) from South Dakota, was mixed with the class C fly ash (FC), class F fly ash (FF) and lime. Swelling pressure (SWP) and unconfined compressive strength (UCS) tests were conducted on samples that were cured at different periods (0, 7 and 28 days). Furthermore, freeze and thaw (F-T) effects on the swelling and strength properties of the clay and selected mixtures were investigated.

Results showed that the SWP of the Belle Fourche clay (B) decreased significantly with addition of lime 4% by dry weight of soil from 235 kPa to almost 0 kPa. Mixing fly ashes also reduced the SWP to 47 kPa and 100 kPa with class C and class F fly ashes, respectively. Increase in F-T cycles reduced the SWP, whereas the SWP increased with 2 and 4 F-T cycles for the mixtures with the fly ashes. However, after 4 cycles, the pressure of the same mixtures decreased. On the contrary, to the clay-fly ash mixtures, F-T did not affect the SWP of the clay-lime mixtures. In terms of strength, chemical treatment increased UCS. The overall effectiveness of the treatment under the curing and F-T was in the order of FC, lime, and FF. The UCSs of the clays treated with these additives were 3.58, 1.82, and 1.63 times higher than the non-treated clay. F-T reduced the UCS of the clay and the clay treated with FF. Although the UCS of the FC and lime mixtures increased within 2 cycles of F-T, they did not show the same strength improving performance with more F-T cycles. It was observed that mixtures with higher liquid limit and plasticity index (PI) tended to have higher SWP and lower UCS. This study claimed that chemically stabilized soils with high CaO content, CaO/SiO_2, CaO/Al_2O_3, and $CaO/(SiO_2 + Al_2O_3)$ ratios had higher potential to decrease SWP of expansive soils and increase UCS of weak soils.

1. Introduction

Mitigation of the swelling and shrinking potential of expansive soils is very critical design aspect of pavement structures when expansive soils are used as a subgrade layer. Expansive subgrade soils undergo large amounts of heaving and shrinking due to seasonal moisture changes, which lead to failure of the upper pavement structure.

The highway subgrade layer is a very critical component of pavement structures. Its primary function is to act as a foundation to provide adequate mechanical support to the asphalt or concrete layer to prevent fatigue and occurrence of rutting failures. Furthermore, the performance of subgrade layers becomes more complex when it is expansive soils. Expansive soils significant characteristics include high plasticity, low strength, high swelling and shrinkage potential (Holtz and Kovacs, 1981). These soils have tendency to swell and soften when their moisture content is increased, or shrink and dry cracked when their moisture content is decreased. As a result of this, expansive soils used in subgrade construction often result in heave-and shrinkage-related cracks in highways and airfield pavements (Punthutaecha et al., 2006; Puppala et al., 2007; Nieto et al., 2008; Bin-Shafique et al., 2010; Puppala and Chittoori, 2012; Estabragh et al., 2013). Furthermore, even kaolinite rich soils can expand considerably if they are contaminated with alkaline and organic leachate (Olgun and Yildiz, 2010 and Chavali et al., 2017).

A large number of studies have been conducted with different types of additives for soil stabilization (Petry and Dallas, 2002; Garzon et al., 2015). However, every soil and chemical additives have their own characteristic and behavior under different conditions. Thus, the effectiveness of the stabilization method depends on various factors such as the type of soils, chemical composition and amount of additives.

Hausmann (1990) mentioned that mitigation techniques for expansive soils could be classified as physical, mechanical and chemical

* Corresponding author.
E-mail addresses: mudayioglu@gmail.com (M. Dayioglu), bcetin@iastate.edu (B. Cetin), soonkie.nam@sdsmt.edu (S. Nam).

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stabilization methods. The same research concludes that due to their efficiency, replicability and reliability, mechanical and chemical stabilization methods are the most recommended methodologies than the physical methods.

Among many chemical treatment methods, dry mixing of the problematic soils with different types of chemical additives such as coal fly ash, lime, cement and calcium chloride has yielded successful results in many studies (Kumar and Sharma, 2004; Kolias et al., 2005; Sezer et al., 2006; Rao and Subbarao, 2012; Estabragh et al., 2013). Estabragh et al. (2013) used lime, cement and coal fly ash to evaluate their effects on the expansive soil properties by mixing a local expansive soil with 5% and 10% lime, 5%, 10%, and 20% cement and 5%, 10%, 15% and 20% class C fly ash (high calcium) by dry weight of soil. Parameters such as swell potential, swelling pressure and unconfined compressive strength of treated soils were measured and compared with those of untreated soils. This study concluded that at the same percentage, the impact of lime to reduce the swelling potential of expansive soil is better than those observed for cement and fly ash mixtures. Zhang and Cao (2002) added 40–50% fly ash and 4–6% lime by dry weight to an expansive soil and studied the effects on its behavior. The finding of this study was that using lime and fly ash to mitigate the swelling potential of expansive soils yields successful results. Guney et al. (2007) claimed that the optimum addition of lime needed for the mitigation of expansive soils should be between 3% and 10% by weight and observed that the addition of extra lime beyond these values did not contribute to any reduction in the swelling potential or an increase in unconfined compressive strength. Similarly, Kumar and Sharma (2004) investigated the effect of different mixing ratio of fly ash on the swelling behavior and the results indicated that fly ash contents $> 20\%$ did not further reduce the swell potential of the soil. Bell (1996) also indicated that further additions of lime beyond 3% did not change the swelling potentials, but increased the other engineering properties of expansive soils such as strength and stiffness.

Hampton and Edil (1998) explained the stabilization mechanism of chemical additives by the formation of a rapid hydration process and a cation exchange procedure, which form larger lumps than the initial soil particles. The pozzolanic reaction products are calcium silicate hydrates (C-S-H) and calcium aluminate silicate hydrates (CASH). Those products play an important role in the increase of stabilized soil strength. Edil et al. (2006) evaluated the effect of fly ash on the strength of fine grained inorganic and organic soils. California bearing ratio (CBR) test and resilient modulus (MR) tests were performed on fly ash-soil mixtures at optimum and wet side of the optimum moisture content and the results indicated that for inorganic soils both CBR and MR values increased with fly ash addition, whereas for organic soil no significant change was observed. In another study, Tastan et al. (2011) conducted unconfined compression and resilient modulus tests on fly ash stabilized organic soils and found that increasing moisture content reduces the effect of pozzolanic reaction on strength and the effect of fly ash stabilization depends on soil mineralogy and fly ash characteristics.

Fly ash amendment also yields successful results on the stabilization of highway base layers. The studies conducted by Cetin et al. (2010) and Bin-Shafique et al. (2010) indicated that the fly ash amendment improved the engineering properties of highway base/subbase layers significantly. Cetin et al. (2010) also performed a cost analysis and mentioned that fly ash stabilization may result in significant cost reduction while the total cost is mainly affected by the traffic volume, construction location and pavement drainage conditions. Arora and Aydilek (2005) studied the performance class F fly ash-lime stabilized soils as highway base layers by conducting unconfined compression, CBR and resilient modulus tests. The results indicated that the strength of a mixture is highly dependent on the curing period, compaction energy, cement content, and water content at compaction.

The findings of the studies mentioned above show that addition of chemical additives such as lime and fly ash yields successful results in mitigation of excessive swelling and increasing of strength. However, the amount of material to be added varies significantly depending on the properties of the expansive soil as well as the chemical additives. Each study suggested that different chemical additives be used with different percentages by weight, and compacting at different moisture contents etc. Thus, for any different soils and chemical additives, an independent study has to be conducted to determine the optimum amounts for the chemical additive percentages. For those reasons, due to the unique properties of the expansive soil, Belle Fourche clay, and chemical additives used in this study, the effective dosage of chemical additives to improve the engineering properties of Belle Fourche clay was evaluated.

Furthermore, there have been many research conducted on the freeze and thaw effects on soils. However, there is limited information about the effects of freeze and thaw cycles on swelling pressure. Therefore, in this study, laboratory tests have been performed to identify the relation between freeze and thaw cycles and swelling pressure.

It is well known that index properties of soil additive mixtures and CaO, SiO_2, and Al_2O_3 contents of the additives are very important to affect the mineralogy and geotechnical engineering properties of expansive soils. However, there is not enough studies to correlate these factors to the change in mineralogy and engineering properties of expansive soils. The current study investigates these gaps and establish relationships between physical and chemical properties of soil-additive mixtures and support these changes with changes in mineralogy of the original soil specimen.

The main objective of this study is to improve the engineering properties (strength and swelling pressure) of Belle Fourche clay (B), which is obtained from Belle Fourche Shale that is one of the most common expansive shales in South Dakota (Brandner, 2009), to provide adequate foundation for pavements and structures built in South Dakota. To achieve this goal, the locally available Belle Fourche clay (B) was mixed with 3 different chemical additives: class C fly ash, class F fly ash and lime. Swelling pressure and unconfined compression strength tests were conducted on the soil and soil-additive mixtures. In addition, the impacts of freeze-thaw, curing period, additive type, and additive content on the engineering properties of Belle Fourche clay (B) were investigated. Moreover, correlations were investigated between the engineering properties of mixtures and their respective liquid limit, plasticity index, CaO content, CaO/SiO_2, CaO/Al_2O_3, and $CaO/(SiO_2 + Al_2O_3)$ ratios.

2. Materials

In this study, three different additives, a C-type fly ash, F-type fly ash and lime, and expansive Belle Fourche clay (B) were tested. Belle Fourche clay (B) is an expansive soil that is originated from the Belle Fourche Shale. Belle Fourche clay (B) samples were collected from Rapid City, SD and pulverized, and sieved through No. 40 sieve before it is mixed with other additives. Fig. 1 shows the Belle Fourche clay (B) before and after grinding process completed.

Fig. 2 shows that Illite and Montmorillonite minerals are the dominant clay minerals present in Belle Fourche clay (B). Ismail and El-Shamy (2009) and Zhang et al. (2016) also studied with shale that possess similar Illite, kaolinite, and montmorillonite percentages. It is classified as high plasticity clay (CH) while additives show no plasticity according to Unified Soil Classification System. The specific gravity (G_s) of the clay soil, Class C fly ash, Class F fly ash, and lime were 2.67, 2.6, 2.53, and 2.1, respectively (Table 1). Fig. 3 shows the grain size distribution of the materials and indicates that 100% of lime and Belle Fourche Clay consist of fine-grained soil particles while 10% and 4% of Class F and Class C fly ash are sand size particles, respectively. Belle Fourche clay (B) is a soil with high expansion potential according to the charts and tables provided in van der Merwe (1964), Sridharan and Prakash (2000), and Holtz et al. (2011). According to these references, any soil with liquid limit (LL) and plasticity index (PI) between 40–60