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STABILIZATION OF OKLAHOMA EXPANSIVE SOILS USING LIME AND CLASS C FLY ASH

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ABSTRACT: This study uses lime and Class C fly ash, an industrial byproduct of electric power production produced from burning lignite and subbituminous coal, to study the plasticity reduction in highly expansive natural clays from Idabel, Oklahoma. This study is important, especially in Oklahoma, because most of the native soils are highly expansive and cause seasonal damage to roadways and structures. The addition of lime or fly ash helps to arrest the shrinkage and swelling behavior of soil. Four soil samples with the same AASHTO classification (A-7-6) were used in this study to show shrinkage variability within a soil group with the addition of lime and Class C fly ash. The plasticity reduction in this study was quantified using the linear shrinkage test. It was found that soils classified within the same AASHTO group had varying shrinkage characteristics. It was also found that both lime and fly ash reduced the linear shrinkage, however, the addition of lime reduced the linear shrinkage to a greater degree than the same percentage of Class C fly ash. Even though it takes much less lime than fly ash to reduce the plasticity of a highly expansive soil, it may be less expensive to utilize fly ash, which is a waste product of electric power production. Lime also has a lower unit weight than fly ash so weight percentage results may be misleading.

INTRODUCTION

Expansive soils, found in every state, cover one-fourth of the United States. Expansive clay soils undergo large amounts of heaving and shrinking due to seasonal moisture changes. These movements lead to cracking and buckling of the infrastructure built on the expansive soils and result in billions of dollars of damage annually (Jones and Holtz 1973; Jones and Jones 1987; Nelson and Miller 1992). In 1980, the annual cost of expansive soil damage in the U.S. was estimated to be $7 billion, 1/3 of which was attributed to single family and commercial buildings (Wray and Meyer 2004). Allowing for annual inflation and population growth, it is likely that total annual damage costs from expansive clay soils in the U.S. today well exceeds $15 billion. Although not life-threatening or cataclysmic as compared to other natural events, expansive soils are certainly a natural hazard. In fact, expansive soil damage exceeds the average annual damage caused by floods, hurricanes, earthquakes, and tornados combined. Despite this alarmingly high cost of infrastructure damage, expansive soils are not listed on the Federal Emergency Management Agency's (FEMA) list of costliest natural disasters. Expansive soils

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are frequently overlooked as a major problem because they take years to cause extensive damage. However, in reality, expansive soils are a widespread and costly natural hazard.

Stabilization of expansive soils is an alternative for geotechnical engineers considering the economics of construction with expansive clay soils. Mechanical stabilization, such as compaction, is an option; however many engineers have found it necessary to alter the physicochemical properties of clay soils in order to permanently stabilize them. The results presented in this paper are part of a larger study that seeks to validate the Oklahoma Department of Transportation's (ODOT) recommended additive contents for stabilizing expansive soils in Oklahoma. ODOT recently published their OHD L-50 Standard "Soil Stabilization Mix Design Procedure" which gives guidelines on additive percentages to be used with soils classified by AASHTO M145 (AASHTO 2002). One of the concerns with these guidelines is that soils which fall into the same AASHTO category (i.e., A-6, A-7) may react differently to the same type and amount of additive listed in the table because of variations in mineralogical, physical and chemical constituents of the soil. Another concern is the lengthiness of a traditional full mix design approach used to select appropriate additive contents. In order to refine and optimize the recommendations in OHD L-50, various simple and inexpensive laboratory methods are being investigated for selecting additive contents. This paper presents the results of multiple linear shrinkage tests on four samples of a highly expansive soil (AASHTO classification A-7-6) from Idabel, Oklahoma (180 miles SE Norman, OK) with increasing lime and Class C fly ash contents to show the differences in shrinkage arrest. This shrinkage arrest will soon be correlated with an increase (or decrease) in unconfined compressive strength according to American Society for Testing and Materials (ASTM) D4609 Standard Test Method for *Evaluating Effectiveness of Chemicals for Soil Stabilization* (ASTM 2005) to define an empirical relationship to potentially be used in selecting additive contents.

The focus of this study used the highly expansive soil from an embankment along State Route 70 near Idabel to study the effects of calcium lime and class C fly ash on reducing shrinkage and swelling behavior. The calcium lime was purchased from the local agriculture farm store and the class C fly ash was obtained from the Tulsa Plant in Lafarge, Oklahoma. In particular, a comparison is made between the different additives to examine the possible alternative of using class C fly ash instead of lime as the primary method of reducing shrinking and swelling in areas of highly expansive soils.

BACKGROUND

Measuring the shrinkage characteristics of a soil can help to delineate clay mineralogy (montmorillinitic-illitic-kaolinitic) and shrink/swell potential of a geologic deposit. The linear shrinkage is a measure of the average oven dry length of the sample after shrinkage to the original length which occurs at an initial water content at or above the Liquid Limit. The Linear Shrinkage Test appears to have been first introduced by the Texas Highway Department in 1932 (Heidema 1957) and is currently described as a standard test procedure in British Standard BS 1377:1990.

The bar linear shrinkage test was found to be the most reliable calcrete soil constant in road construction (Netterberg 1978) and most significant indicator of plasticity/cohesion for a gravel-wearing course material (Paige-Green 1989). Haupt (1980) and Emery (1985) performed studies to determine subgrade moisture prediction models and indicated that the inclusion of the bar linear shrinkage produced as good, if not better, prediction models than the inclusion of any of the other Atterberg Limit results. Paige-Green and Ventura (1999) conclude from their evaluations of various bar linear shrinkage tests performed that the bar linear shrinkage test is a more effective test to indicate material performance than the more traditional Atterberg limits.

Using the Linear Shrinkage Test to quantify the shrinkage arrest of soils mixed with a stabilizer (e.g., fly ash or lime) may be a potentially useful and relatively quick method for selecting additive contents for various types of soils, instead of engaging in a lengthy mix design process. The optimum additive content for soils is currently defined by unconfined compression strength as detailed in the American Society for Testing and Materials (ASTM) D4609 Standard Test Method for *Evaluating Effectiveness of Chemicals for Soil Stabilization* (ASTM 2005). ASTM D4609 provides procedures to examine unconfined compression strength, moisture susceptibility, and changes in moisture density relationships of chemically stabilized soil. Bell (1996) presented a study using the linear shrinkage test with montmorillonite and different percentages of additive lime and showed that the shrinkage decreased with additional lime addition, but that it was not a linear decrease. His study also showed that unconfined compression strength does not increase linearly with the addition of lime and excessive addition of lime actually reduces strength. In fact, it has been shown that with additions of 6% lime and above, the decreases in strength can be quite significant and Al-Rawi (1981) noted that at times the decreases may exceed 30%. There were no correlations made between amount of shrinkage and strength.

A few papers have been presented on the effect of Class C fly ash on engineering properties of expansive soils (e.g., Cokca 2001; Cocka and Turker 2002, Senel et al. 2002; Kumar and Sharma 2004;) however, none used shrinkage reduction as an indicator to select adequate additive contents.

INVESTIGATION

In this study, one highly plastic soil from four varying locations along a road cut, classified in the same AASHTO A-7-6 category, was tested using the linear shrinkage apparatus and two chemical additives, lime and Class C fly ash. In addition to the multiple Linear Shrinkage tests performed with the chemical additives, other laboratory characterization tests included natural moisture content, Atterberg LL, PL and SL, total specific surface area (SSA), carbonate content and hydrometer analysis to determine the clay fraction (CF) (< 0.002 mm). Because the soil was so highly plastic, the soil was submerged in water overnight to achieve a more workable sample. The next day, excess water was removed from the top of the soil. Then the soil was pressed and stirred removing any solid materials such as rocks and plants until a homogeneous mixture was achieved. The soil was then placed in the

Atterberg testing apparatus and tested to determine the blow count. Water was added or evaporated until a blow count of 15 was achieved. The soil was then mixed until homogeneous. At this point, the raw soil was tested to determine a baseline shrinkage value. Then, the two additives were included by percent weight. The additive and soil was mixed until a homogeneous mixture was obtained. The higher the percent additive, the longer it took to mix the soil because of decreased workability. After the soil was properly mixed, the soil was covered and allowed to cure for 24 hours (Ferguson 1999).

The Linear Shrinkage Limit test was performed with approximately one hundred and fifty grams of soil. A third of the soil was placed in a greased brass mold approximately 140 mm long and 25 mm in diameter. The soil was placed in the mold in three layers and tapped against a flat surface in between the layering to remove air bubbles from the soil. The sample was allowed to air dry for four hours. Then the soil sample was placed in an oven at 105˚C for 18 hours.

After the soil was dry, the mold was removed from the oven and allowed to cool. The length of the soil sample was measured three times with digital calipers and the average was used to calculate linear shrinkage using the equation:

$$LS = \left(1 - \frac{L_{avg}}{L_o}\right) \times 100 \qquad [1]$$

where:

LS = Linear Shrinkage (%)
L_{avg} = Average Length (mm)
L_o = Original Length of Brass mold (mm)

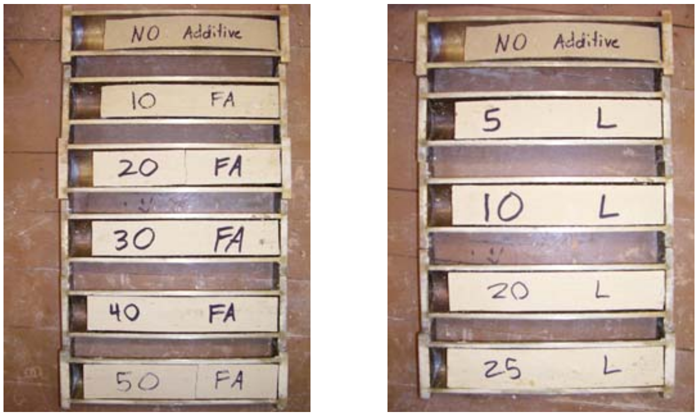
RESULTS

Table 1 provides the data from the tests performed.

TABLE 1. Control Soil Properties.

Soil	Depth	Moisture Content	CF	LL	PL	SL	LS	Total SSA	Total Carbonates
	m	%	% < 2 μm	%	%	%	%	m^2/g	%
1	0.50	20.70	58.4	65	24	9.3	16.8	134	4.36
2	0.98	24.72	69.1	76	23	6.4	16.2	185	5.77
3	0.76	24.71	64.7	74	23	9.1	17.4	237	2.49
4	0.44	32.19	70.2	79	25	6.2	16.8	253	9.74

Each soil classified as A-7-6, clayey soil, according to AASHTO M-145-91 (AASHTO 2002). The soils tested are arranged in order of increasing total surface area 134 to 253 m^2/g. A photograph of the linear shrinkage tests from Soil #1 with lime and fly ash is shown in Figure 1.



a. b.

FIG 1. a. Soil with fly ash additive, 0-50%; b. Soil with lime additive, 0-25%.

The Class C fly ash was from the Lafarge Company in Tulsa, Oklahoma and contained 24.23% lime (CaO), which is similar to typical Class C fly ash (FHWA 1995). The Tulsa plant reported a loss on ignition (LOI) of 0.16% and specific gravity of 2.61. They also reported that there was no free lime present in the Class C fly ash. The lime source was Hi-Yield® horticultural lime from Washington State with a specific gravity of 0.48.

Linear Shrinkage Curves

The shrinkage curves for the four soils from the Linear Shrinkage Tests with two chemical additives, Class C Fly Ash and lime are presented in Figure 2 through Figure 5. The linear shrinkage for each of the soils without additives is between 16 and 17.5%. It can be seen that the shrinkage decreases with the addition of the class C fly ash and lime, however the lime is twice as effective at arresting shrinkage than the class C fly ash for the same percentage by weight added.

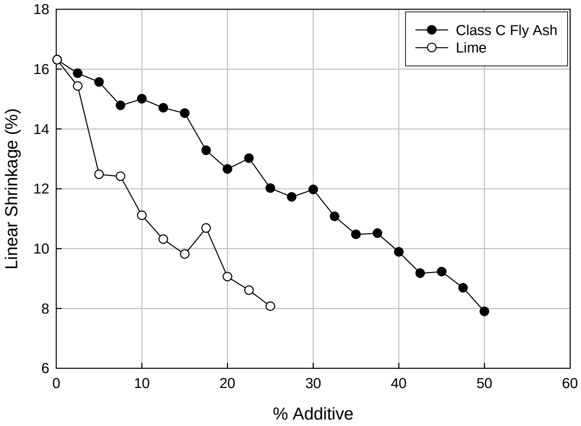


FIG 2. Soil 1 Reduction in Shrinkage due to Stabilizer Additive.

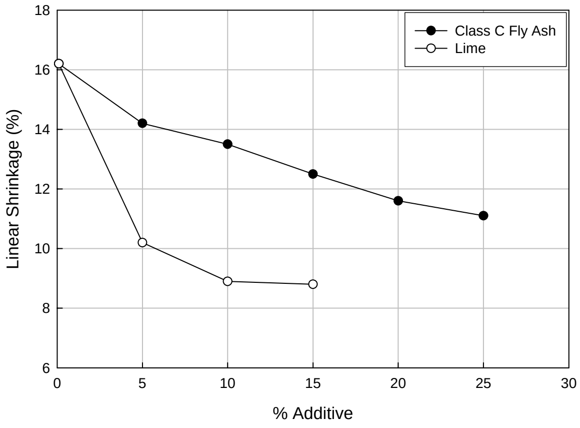


FIG 3. Soil 2 Reduction in Shrinkage due to Stabilizer Additive.

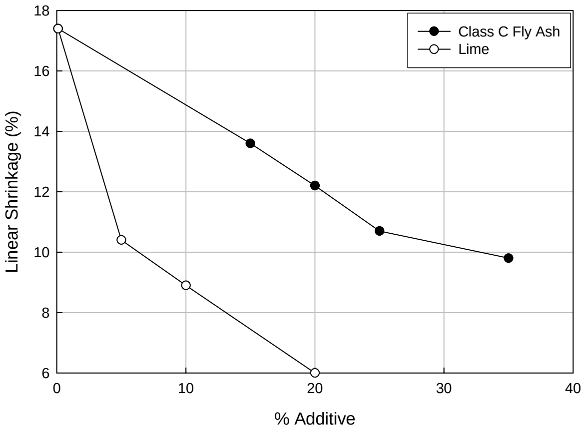


FIG 4. Soil 3 Reduction in Shrinkage due to Stabilizer Additive.

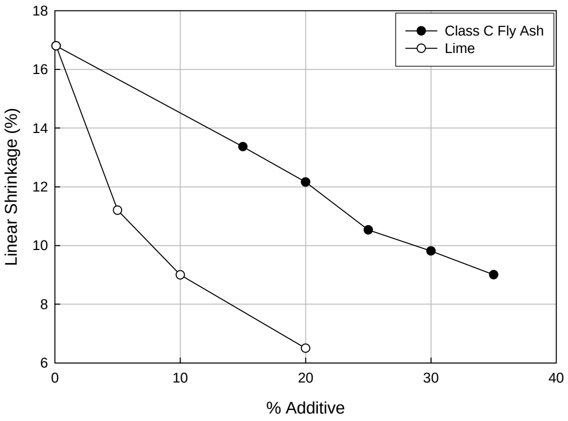


FIG 5. Soil 4 Reduction in Shrinkage due to Stabilizer Additive.

DISCUSSION

The addition of lime and class C fly ash to highly plastic clay showed a reduction in shrinkage with increasing additive percentages. However, the addition of lime arrested the shrinkage at almost twice the rate of class C fly ash. The shrinkage arrest was not linear but occurred more readily with small amounts of additive and the rate of shrinkage arrest slowed as the amount of additive increased. The linear shrinkage decreased from approximately 4 to 7 % with the addition of 5% lime, while the linear shrinkage only decreased approximately 1% to 2% with the addition of 5% class C fly ash. Mixing the soil became increasingly difficult with the addition of more than 15% lime by weight. When comparing both the addition of lime by weight and fly ash by weight, it must be noted that the specific gravity of lime is 5.4 times smaller than that of fly ash, therefore the volume of lime added is significantly greater and the workability of the lime and soil decreased at a much lower additive percentage than the workability of the fly ash and soil. Figure 6 presents the amount of shrinkage arrest for each soil according to percent additive.

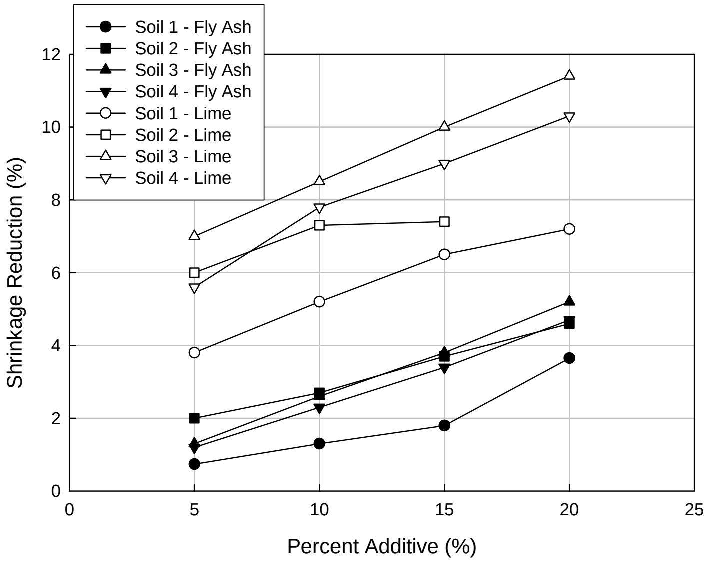


FIG 6. Amount of shrinkage reduction in percent (%) with increasing additive content.

The differences in shrinkage behavior with the addition of lime or fly ash between the four soils from the same site can be attributed to differences in mineralogy. It is well known that the engineering characteristics of fine-grained soils are dominated in large part by the physico-chemical interactions present in the clay-electrolyte system and surface phenomena, which are in turn related to both the amount of clay and the clay mineralogy. Soil 1 shows the least shrinkage arrest with the additions of both the lime and fly ash and also has the lowest specific surface area at 134 m^2/g, while Soils 3 and 4 have the highest shrinkage arrest using both lime and fly ash and also have the highest surface areas at 237 and 253 m^2/g respectively. The extent of chemical reactions in treated soils, and hence the degree of stabilization, is related to the specific surface area.

The term "Specific Surface Area" (SSA) refers to the area per unit mass of soil and is usually expressed as m^2/g. There is strong evidence in the literature that indicates that specific surface area may be the single most important contributing factor that controls the engineering behavior of fine-grained soils. For example, studies have shown that there is a strong relationship between specific surface area and the swelling potential of soil (e.g., Dos Santos & Castro 1965; Low 1980; Ross 1978; Dasog et al. 1988). Natural clay deposits can have a wide range of total surface area since the combination of external and internal surface areas may vary simply because of the mixed layer minerals that may exist and the variations in clay mineralogy. Additionally, the clay mineral fraction that is part of the overall grain-size distribution can vary greatly. Consequently, the type of clay mineral present in soil is of major importance in determining the effect of specific surface area on soil properties. Since the surface area of a soil is controlled by the grain-size distribution and clay mineralogy, it can be considered an "inherent" soil property (Lutenegger and Cerato 2001; Cerato and Lutenegger 2002, 2005).

The differences in shrinkage reduction using the fly ash additive are much less than the differences shown with the lime additive. Also, the fly ash reduced the shrinkage less than half that of the lime for the same additive percentage by weight. Soil #2 did not react in the same way to the lime and fly ash additive contents than did the other three soils. The addition of lime past 10% did not seem to have an effect on the shrinkage reduction. Between 5% and 20% additive content, Soil #2 only saw 2.5 and 1.5 % reduction in shrinkage for fly ash and lime respectively, whereas the other three soils saw reductions around 3 and 5% for fly ash and lime respectively. The amount of shrinkage decrease (or strength increase) in a clay soil that can be produced by adding lime (or fly ash containing lime) is dependent on the pozzolans present. When pozzolans are present they react readily with lime to improve the strength (reduce the shrinkage or swelling) of the soil-lime mixtures. Expansive soils respond more quickly to strength increases. If the soil and lime mixture has no more pozzolans create the reaction, then the shrinkage properties of the soil will not improve, but stay constant. It is possible that there was some other soil component in Soil #2 that was stopping this reaction that contributed to this different behavior. More testing, including X-ray diffraction analyses (XRD) are forthcoming.

In order to determine empirical correlations between the amount of shrinkage arrest and appropriate additive contents for subgrade stabilization that ODOT can utilize, it will be necessary to measure the strength gained (or lost) with increasing percentages of chemical additives. Currently, ASTM D 4609 is used to determine if an additive is appropriate and reports that a soil must show an increase in strength of at least 50 psi. It is hypothesized that the strength of the stabilized soil will decrease even before the shrinkage arrest rate decreases, because passed a certain additive content, the stabilizer adversely affects the cohesion properties of the soil. This was shown in Bell's (1996) work, where while the shrinkage arrest continued up to 10% lime additive there was a decrease in strength after only 4% added lime. This threshold will obviously depend on mineralogy and therefore, SSA, and this will be used in the correlation as well.

CONCLUSIONS

This study focused on using the Linear Shrinkage test to quantify the amount of shrinkage arrest in high plasticity clay using both lime and Class C fly ash. This data is being used to refine and optimize the recommendations in OHD L-50 Standard "Soil Stabilization Mix Design Procedure," by studying statistical relationships (correlations) between simple indicator test results and stabilized soil properties. The value of the resulting correlations is that it may be possible to reduce the uncertainty associated with simply using the recommended additive contents in the Soil Stabilization Table and avoiding a full mix design. This may be especially valuable during construction when unexpected variations in the subgrade soil are encountered and a quick means of testing is desired to guide the adjustment of stabilizer content. It was found that the amount of shrinkage arrest caused by the addition of both lime and fly ash correlated well with the raw soils' specific surface area. The higher the surface area, the more shrinkage arrest occurred. This relationship will be examined further when unconfined compression tests are performed to link increase in strength with decrease in shrinkage and mineralogy. A secondary objective satisfied by the selection of both lime and fly ash as stabilizers, is the cost benefit of possible future use of class C fly ash in road bed stabilization. The high unit weight of fly ash relative to lime more than makes up for its lag in shrinkage reduction by weight percentage. If favorable results are found in future studies on fly ash in soil stabilization, departments of transportation could see large reductions in material costs.

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