An Assessment of Soil Parameters Governing Soil Strength Increases with Chemical Additives

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ABSTRACT

This study examined the relationship between soil physico-chemical parameters and unconfined strength in various fine-grained soils when mixed with chemical additives. To be considered effective, the soil-additive mixture must exhibit a strength increase of at least 345 kPa (50 psi). The research focused on AASHTO Soil Group Classifications falling under the fine-grained soil category (A-4 to A-7). Additive amounts are given for Fly Ash (FA), Cement Kiln Dust (CKD), and Lime (hydrated and quick lime).

The results of this study suggest that the surface area is perhaps the most important factor in determining if a chemical additive will be effective for stabilization. Out of the eight tested soils, the seven soils with surface areas lower than 150 m^2/g reached the 345 kPa strength gain with the different additives. However, the one soil with a surface area higher than 150 m^2/g never reached the strength gain with any of the additives used at any of the tested percentages.

Introduction

Stabilization of fine-grained soils is an alternative for geotechnical engineers considering the economics of construction with silt or 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 fine-grained 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 unconfined compression tests of soils falling within the A-4, A-6 and A-7-6 AASHTO classifications, stabilized with increasing hydrated lime, cement kiln dust (CKD) and two types of Class C fly ash (from Red Rock and Muskogee, OK) according to American Society for Testing and Materials (ASTM) D4609 Standard Test Method for *Evaluating Effectiveness of Chemicals for Soil Stabilization* (ASTM 2005). The results of this study show that identically classified soils can behave very differently even when stabilizing with the same amount of a particular type of chemical stabilizer. This becomes a problem for engineers when they are trying to determine adequate stabilizer amounts for their subgrade mix-design. This difference in strength gain (behavior) using the same amount and type of stabilizer within the same AASHTO classification will be investigated to determine possible alternative soil parameters that better predict stabilized soil behavior and select additive contents.

Literature Review

It is common practice worldwide to use chemical additives to stabilize fine-grained soils before they are built upon. Highly plastic soils, including many soils found in Oklahoma, are stabilized using these chemical additives. Additives used to stabilize soils include hydrated and quick lime, fly ash, cement kiln dust, and Portland cement. **Table 1** shows the “Soil Stabilization Table” from OHD L – 50 that was developed to provide a quick guide to what additive to use for certain AASHTO M145 classified soils.

Table 1: OHD L - 50 Soil Stabilization Table (ODOT, 2006)

SOIL STABILIZATION TABLE												
ADDITIVE (Expressed as a percentage added on dry over basis)	SOIL GROUP CLASSIFICATION – AASHTO M145											
	A-1		A-2				A-3	A-4	A-5	A-6	A-7	
	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7					A-7-5	A-7-6
PORTLAND CEMENT	4	4	4	4	4	4	5	√	√	√		
FLY ASH					10	10	11	12	12	12		
CEMENT KILN DUST (Pre-Calciner Plants)	4	4	4	4	4	4	5	√	√			
CEMENT KILN DUST (Other Type Plants)	8	8	8	9	9	9	10	10	10			
HYDRATED LIME*										4	5**	5**

A blank in the table indicates the additive is not recommended for that soil group. Recommended amounts include
a safety factor for loss due to wind, grading, and/or mixing. Pre-calciner plants are identified on the Materials Division approved list for cement kiln dust.
√ = Mix Design Required
* = Reduce quantity by 20% when quick lime is used, i.e. 4% x 0.8 = 3.2%, 5% x 0.8 = 4.0%, 6% x 0.8 = 4.8%
** = Use 6% when liquid limit is greater than 50.

A Worldwide Issue

The issue of designing structures and roadways in areas containing problematic soils is not limited to the state of Oklahoma. Many researchers around the world have investigated the use of chemical stabilizers applied to problem soils. Lime, one of the stabilizers to be investigated in this study, is popular with international engineers. In Botswana, for example, hydrated lime is used to stabilize naturally-occurring calcium carbonate deposits, known as calcretes, commonly used as roadway base materials. The lime "is usually added to reduce the plasticity of a material by initiating a flocculation reaction with any clay minerals present" (Lionjanga et al., 1987). Also in Southeast Asia, engineers in Papua New Guinea treat soft clay subgrade soils with lime and Portland cement mixed with local natural resources (Hossain, et al. 2007). One of the more common of these natural resources is volcanic ash. When tested with A-6 and A-7-6 clay soils, the combination of 4% cement and 10% volcanic ash provided the biggest strength increase, increasing the 90-day compression strength of the A-6 soil to 25 times its unstabilized strength and the A-7-6 soil to 10 times its original strength.

Research into the use of fly ash as a stabilizer has shown that the California Bearing Ratio increases when fly ash is added (Singh et al., 2005). Their research in India has shown that increasing the amount of cement in cement-stabilized fly ash mixed with soil increases the unconfined compression strength in a linear pattern. The strength also increased with increasing the curing time of the mixture.

Cement kiln dust (CKD) is also being increasingly used around the world. It is growing in popularity due to its ease of acquisition as it is a waste product of concrete production, one of the most common building materials today. In the United Arab Emirates, Mohamed (2002) performed a study on the use of CKD on soils in arid areas. The results indicate that these silts and sands have increased shear strengths and lower hydraulic conductivities when CKD is added as a stabilizer, making these soils usable for roadway design and as barrier materials for waste containment. According to Miller and Zaman (2000), CKD is an effective soil stabilizer for both cohesive (clays and some silts) and non-cohesive soils (some silts and sands). The CKD effectiveness will be tested in this study on both expansive clay and silt. Their study also compared the effectiveness of CKD from three different sources. They ultimately determined that CKD from different sources results in different strength gains. This fact will not be examined for this study, but a future study on the properties governing the different strength characteristics would be beneficial.

Chemical stabilizers have also been applied to granular soils. In Saudi Arabia, cement is being tested for its efficiency in stabilizing the sabkha soils, very low-density sands mixed with saltwater and salt brine (Al-Amoudi, 1994). While not a fine-grained expansive soil, the problem with these soils is that their low densities and strengths make them unusable for construction until chemical stabilizers or other methods are used. The cement was found to increase both the density of the sand and the unconfined compression strength.

Properties Being Investigated

It is expected that several different soil parameters, other than Atterberg Limits currently used for classification purposes, will have an effect on the efficiency of chemical stabilizers used in fine-grained soils. Many studies have already been performed on stabilizers and researchers have found factors that influence the compressive strength of the soil. Typically, geotechnical engineers currently use Atterberg limits to judge the effectiveness of stabilizers, however, they have found several instances where the Atterberg limits cannot predict stabilized strength even though they have identical limits to that of soils that have been successfully stabilized in the past. In other words, while convenient for classification, Atterberg Limits are not adequate in all cases for determining amount of stabilizer to use for road-way sub base design because they alone cannot explain soil behavior; other more fundamental soil properties are needed.

Miller and Azad (2000) performed a study on the influence of a soil's type on stabilization attained using CKD. Their study investigated several parameters, including the pH of the soil. Using data gathered from pH tests performed one hour after mixing a soil with CKD, they found that "Results of unconfined compression tests…indicate that the pH response can be used to predict relative performance of CKD-treated soils" (Miller and Azad, 2000).

Arabi et al. (1988) investigated the effectiveness of stabilizers by performing abrasion tests. Their study used a ball mill to examine the degree of bonding and compared the abrasion results to the increases in strength. Their study noted, "Clearly, as the degree of interlocking of soil particles increases during curing, larger forces are required to overcome this bonding and to break up the particles." While they only tested one soil with lime as a stabilizer, they developed an empirical relationship between their measured abrasion factor and the corresponding increase in compression strength. The abrasion factor will not be tested during the course of this study, but the concept has the potential to become an important test for strength increases due to the ease of testing.

Another potential factor is the curing time of the soil-additive mixture. This was investigated by Stavridakis (2006) who tested samples at curing times of 28, 35, and 42 days. Curing time is one of the factors that will be addressed in this study, as well. The unconfined compression test samples will be tested after 14 days of curing in a 100% humidity room and Atterberg limits will be run at 0 and 14 days of curing to determine any differences. Other properties already tested during the course of this study are the cation exchange capacity and the specific surface area of the soil-additive mixture. These have already been proposed as important factors affecting the increase in soil strength with chemical additives.

The specific surface area of clay can tell a great deal about the expansion potential of the soil. "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" (Cerato and Lutenegger, 2002). The specific surface area is one of the properties that will be tested during the course of this research study. A future extension to this project could involve examining the bonding between the chemical additives and the individual soil particles to see how the specific surface area differs.

Experimental Procedure

In this study, 8 soils from AASHTO M145 Classification groups A-4, A-6 and A-7-6 were tested and analyzed for similarities and/or differences in behavior when stabilized with varying amounts of three types of stabilizer. Preliminary preparation of the soil involves processing it passed the No. 10 sieve and placing the soil in a 100% humidity room for 24 hours before taking the initial water content. Analysis and testing of the soil samples consists of three methods: compaction, unconfined compression tests (UCT) and Atterberg limits.

As can be seen in **Table 1**, it has been suggested that soils in the A-4 group be stabilized with 12% FA and 10 % CKD. Therefore, three soils were chosen from this group and stabilized with varying percentages of these two stabilizers to determine at what stabilizer amount the 345 kPa strength gain above the raw soils strength is achieved, as well as determine the strength gain differences between the identically classified soils.

4% hydrated lime and 12% FA are recommended for A-6 soils, and only 5% hydrated lime is recommended for A-7-6 soils, except for the note that 6% should be used when the Liquid Limit (LL) exceeds 50%.

Sample Preparation and Compaction

The purpose of compaction is to develop a moisture-density curve and determine the optimum moisture content (OMC) of the soil with the selected additive amount. Samples are prepared by mixing the selected additive amount and the water required to achieve the desired moisture content with the soil. The mixed sample is then compacted using a modified version of the Standard Proctor compaction method ASTM D698 (ASTM 2005), known as the Harvard Miniature method. This method uses a drop hammer of the same height but with 1/10th the weight of the Standard Proctor hammer. The soil is compacted into five equal layers at 10 blows per layer in the Harvard Miniature mold and water content samples are taken from the top and bottom of the compacted specimen. This procedure is repeated with five different water contents to develop a compaction curve for each of the additive types and percentages.

Unconfined Compression Testing (UCT)

UCT samples are made at the optimum moisture content determined from the compaction curves. At least three samples are made with each selected additive amount at its respective OMC. Using a minimum of three samples allows for a more accurate determination of the average strength. Water content samples are again taken from the top and bottom of the compacted specimen to ensure consistency among all samples for UCT testing. The prepared UCT samples are sealed with plastic wrap and placed in a sealed plastic bag to cure in the humid room for 14 days before conducting the tests.

Unconfined compression tests were conducted on a strain-controlled triaxial testing frame. Displacement readings were read from a dial gauge and the applied load was measured by an electronic load cell. The strain rate used for the tests was 0.0281 inches per minute (2% strain rate based on sample height). Readings were taken every 0.005 inch until the sample failed. The maximum load was converted to the unconfined compression strength (kPa) of the sample.

The average unconfined compression strength of the samples made with the same additive type and percentage represents the strength of the soil with the respective additive. The unconfined compression strengths of the different additive types and percentages mixed with a specific soil type were presented graphically to compare the strength increase and to determine the most effective additive and percentage to stabilize the soil. A strength increase of 345 kPa from the raw soil to the treated soil is required for the chemical to be deemed an effective stabilizer. This is a somewhat arbitrary number set forth in ASTM D4609, and its appropriateness, along with the corresponding stiffness of the soil will be studied further to assist practicing engineers with pavement design.

Results

Table 2 provides the data from the tests performed.

Table 2: Control Soil Properties

Soil	AASHTO Classification	USCS Classification	% Clay	Liquid Limit %	Plastic Limit %	Shrinkage Limit %	Linear Shrinkage %	Total SSA m^2/g	Total Carbonates %
Devol	A-4 (0)	ML Silt with sand	7.1	26	NP	3	23	54	5.2
Anadarko County Soil	A-4 (0)	ML Silt with sand	14.9	NP	NP	4.5	2.1	37.1	7.3
Payne County Soil	A-4 (2)	CL Silty clay	31.4	24	14	9.5	9.1	43.2	8
Flower Pot	A-6 (18)	CL Lean clay	62.1	36.7	17.3	10.24	15	120	6.6
Ashport-Grainola Complex	A-6 (9)	CL Lean clay	27.5	31	17	10	13	50	8.2
Kirkland-Pawhuska Complex	A-6 (13)	CL Lean clay	28.6	37	21	10	20	57	8.6
Hollywood	A-7-6 (45)	CH Fat clay	61.5	71	32	18	10	220	4
Heiden	A-7-6 (19)	CH Fat clay	50.1	69.5	21.4	19.4	9.3	136	14.4

A-4 Soil Group

Based on the initial experiment results for the three A-4 soils tested (Devol, Anadarko County soil, and Payne County soil), Red Rock Fly Ash was a less effective stabilizer for all three soils (Figure 1) than the CKD (Figure 2). The current recommended additive content for CKD with A-4 soils is 10% according to ODOT's OHD L-50 standard (**Table 1**). All three soils easily achieve the required 345 kPa strength gain at this recommended value and adequate strength is achieved in the Devol soil at only 5%, while both the Anadarko Co. and Payne Co. soils reached at 8%. If the above results hold true with additional soil testing, the optimum CKD content could shift lower and save money in future projects.

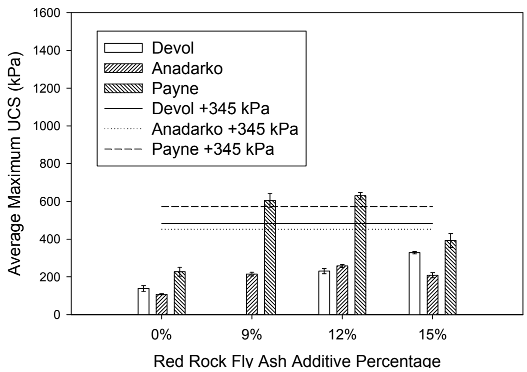

Figure 1 – Unconfined Compression Strengths for A-4 Soils with Red Rock FA

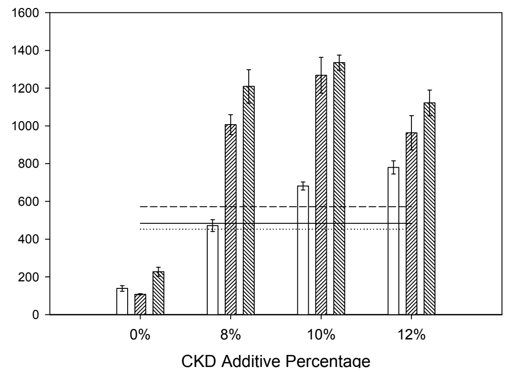

Figure 2 – Unconfined Compressive Strengths for A-4 Soils with CKD

ODOT currently uses 12% FA as the optimum additive content in A-4 soils. The FA stabilizer from Red Rock, Oklahoma, was not as effective at providing the needed strength gains as the CKD additive (Figure 2). Both the Devol and Payne Co. soils exhibited a strength gain of more than 345 kPa above the raw soil strength at 10% and 9% respectively, however, RR FA was not effective for the Anadarko Co. soil. This lack of stabilized soil strength increase would be problematic in the field and an understanding as to why Devol soil did not respond to the stabilizer in the same manner as other identically classified soils is being investigated. As mentioned during the CKD analysis above, for some soils, lowering the needed additive percentage could be beneficial economically, however, better soil parameter indicator(s) (other than LL and PI, which are currently used for classification) must be found to ensure adequate strength gains are met.

A-6 Soil Group

In this group, three different soils were tested: Flower Pot, the Ashport-Grainola complex, and the Kirkland-Pawhuska complex. As noted earlier, these soils were tested with CKD, Red Rock FA, Muskogee FA, and hydrated lime. While fly ash is the recommended stabilizer for A-6 soils, the UCS tests involving FA are still in progress and are not shown here. Since a mix design is currently required for A-6 soils stabilized with CKD, additive amounts similar to those used with the A-4 soils were chosen to determine when the required strength gain was met. When mixed with CKD as the stabilizing agent, all three soils surpassed the necessary 345 kPa strength increase (Figure 3), and therefore, it seems that CKD should be included in the table as a recommended additive for A-6 soils. Flower Pot soil met the necessary strength gain at 8% CKD, Ashport-Grainola met the strength gain at 7% CKD, and the Kirkland-Pawhuska met the strength gain requirement at 9% CKD. Cement kiln dust is not listed as a recommended additive for A-6 soils, but if other stabilizers are not available, knowing the optimum additive content for CKD could prove very useful.

While hydrated lime can help soils gain strength with lower additive percentages than CKD or FA, it is a more expensive stabilizer since it is not a byproduct of any industrial process (such as producing cement or burning coal).

According to the ODOT standard, the optimum additive content for hydrated lime with an A-6 soil is 4%. Ignoring the economics of the stabilizer, hydrated lime was effective at increasing the strength of the tested soils to at least 345 kPa above their raw strengths. As shown in Figure 4, both the Ashport-Grainola and Kirkland-Pawhuska complexes reached the necessary strength gains at 2% lime, while Flower Pot did not reach the strength gain until 3% lime. These results are lower than the recommended amount, and, if confirmed with additional testing, could save money in future construction costs.

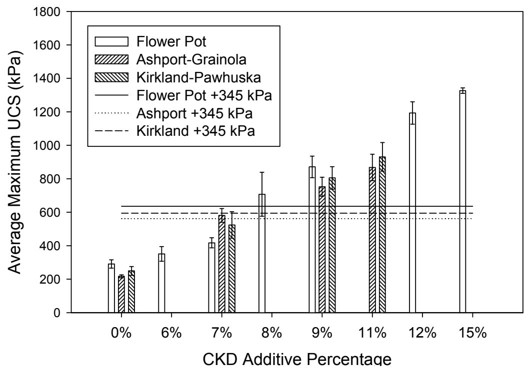

Figure 3– Unconfined Compressive Strengths for A-6 Soils with CKD

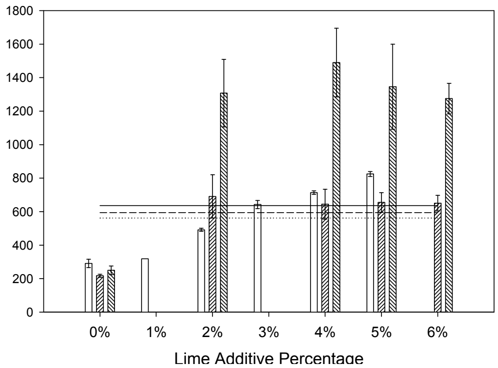

Figure 4- Unconfined Compressive Strengths for A-6 Soils with Lime

A-7-6 Soil Group

Two soils were located and tested to represent the A-7-6 classification: Hollywood and Heiden. According to the ODOT standard, the optimum additive content for hydrated lime with an A-7-6 soil is 5%, with an increase to 6% if the LL is over 50. There are no other recommended additives besides lime for A-7-6 soils. When tested with hydrated lime as a stabilizing agent, the Heiden soil reached the 345 kPa increase over the raw soil strength at 2% and Hollywood at 3%. If a consistent trend is found that proves these strength gains are accurate, ODOT could potentially save a significant amount of money by using lower percentages of lime.

In order to provide more chemical stabilization options, especially when economics and green engineering are important to a project, RR FA was used to stabilize the A-7-6 soils to determine if adequate strength gains were met (Figure **6**). As was seen with the lime addition, the strength of the Heiden soil achieved the strength gain prior to the Hollywood soil. The Heiden soil reached the required 345 kPa increase at 5% RR FA, and the Hollywood soil reached the 345 kPa strength increase at an additive content of 9% Red Rock Fly Ash. As ODOT does not currently recommend the use of fly ash as a stabilizer for A-7-6 soils, there is no current design standard to compare these percentages to.

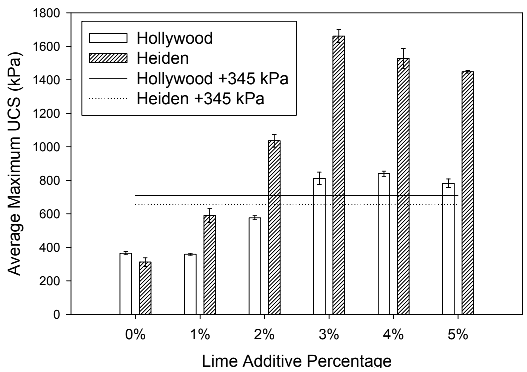

Figure 5- Unconfined Compressive Strengths for A-7-6 Soils with Lime

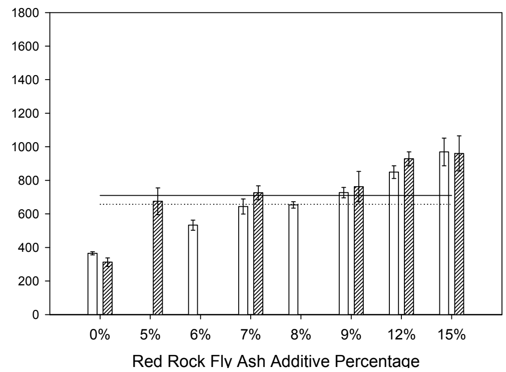

Figure 6 - Unconfined Compressive Strengths for A-7-6 Soils with RR FA

Conclusions

The use of unconfined compression tests to measure strength gain of stabilized soils is the first step in completely characterizing the behavior of stabilized sub-bases. In order to make a more reliable method for determining the type and amount of an additive to add to a certain soil, we must also look at the stiffness of the soil so as to ensure the longevity of pavement placed over these sub-grades. We must also determine alternative soil parameters that better predict stabilized soil behavior because based on the aforementioned results, the commonly used Atterberg Limits do not always provide adequate information about soil behavior when stabilizing and strengthening problematic soils within the soil classifications A-4 to A-7-6. In several instances, such as the A-6 soils with hydrated lime and the A-4 soils with fly ash, the recommended additive amount was several percentage points higher than what was determined to be needed to achieve the requisite unconfined compression strength increase of 345 kPa, and in some cases, such as with the A-7-6 soil, no amount of stabilizer was adequate in strengthening the soil. Therefore, it is imperative for engineers to determine an adequate, easily measurable soil parameter or several parameters that will better indicate soil behavior after stabilization. Specific Surface Area (SSA) and Cation Exchange Capacity (CEC), are two of the parameters being investigated. The surface area will be tested according to Cerato and Lutenegger (2002).

After comparing the initial properties of each soil type with the resulting strength gains from the different additives, it seems that the SSA of the soil is one of the most important parameters in determining the amount of a chemical additive to use in stabilization. All the tested soils with surface areas less than approximately 150 m^2/g reached the necessary strength gain with at least one stabilizer, but the one soil with a surface area higher than 150 m^2/g (Hollywood at 220 m^2/g) never reached the 345 kPa strength gain with any of the additives at any of the tested percentages and the Anadarko County soil did not reach the needed strength gain with fly ash. This is a promising correlation and SSA plus other fundamental soil properties should be further investigated in light of these findings to determine if they can be used in conjunction with the AASHTO classification system to better advise engineers on what type and amount of stabilizer to use on roadway projects. This improved design protocol will save not only time and money in the sub-grade and pavement design phase, but time and money during the lifecycle of the roadway from lowered maintenance costs because of a stronger sub-base and pavement.

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