Comparing the Compressive Stress-Strain Relationships and Strengths of Compacted Polymer Treated and Lime Treated Expansive CH Clay Soil Using Vipulanandan Model

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Abstract
In this study, the effects of a water soluble acrylamide polymer solution (PS) treatment was compared to the lime treatment on the stress-strain relationships and compressive strengths of an expansive CH soil (free swelling of 15%) obtained from the field in Houston, Texas was investigated. The 6% lime treated soil was cured for 7 days at 25°C and 100% relative humidity before testing. In treating the soil, polymer solution content was varied up to 20% (by dry soil weight) using three different mixes (polymer content) and the soil samples were cured for one day at 25°C and 100% relative humidity before testing. When the CH soil was treated with 10% polymer solution (PS), the compacted (ASTM 698 standard method) compressive strength increased from 126 kPa to 496 kPa. Polymer treatment also increased the compacted maximum dry density and reduced the optimum moisture content of the treated CH soil. Compressive stress-strain relationships of the expansive soil treated separately with lime and polymer solution have been modelled using the nonlinear Vipulanandan p-q stress-strain model. The stress-strain model parameters were sensitive to the polymer content and the type of treatment.

1. Introduction

Expansive soils are a worldwide problem as they cause extensive damage more than twice the combined average annual damage due to earthquakes, floods and hurricanes to the infrastructures (Estabragh et al. 2013). Expansive soils undergo large volumetric changes due to moisture fluctuations because of seasonal variations. The volumetric changes are caused by swelling and shrinkage movements in the high plasticity soils, which can lead to severe damage to structures, pipelines and roads. Most of the expansive soils include montmorillonite-rich clays, over consolidated clays and shale (Adem et al. 2015). Expansive soils undergo large amounts of heaving and shrinking due to seasonal moisture changes. These movements lead to cracking and buckling of the infrastructures built on the expansive soils (Miller 1997). Several traditional solid form and liquid form stabilizer materials have been used to stabilize subgrades to minimize the expansive and shrinkage of the clay soils (Onyejekwe et al. 2015; Vipulanandan and Mohammed 2014). The traditional stabilizers include ordinary Portland cement, lime and fly ash. Nontraditional stabilizers are polymers and enzyme types (Mohammed and Vipulanandan 2014). Many studies have been performed on the subject of soil stabilization using various additives, the most common methods of soil stabilization of clay soils supporting highway pavements are by adding cement, fly ash or lime (Al-Rawas et al. 2005; Mohammed and Vipulanandan 2015). To achieve effective soil stabilization based on the application, special attention has to be given to proper type and concentration of the stabilizer.

The use of water soluble polymers as a grouting material is a relatively recent technology, which began in the United States in the early 1950s. Water soluble polymers are used to change the physical characteristics (density, strength, permeability, compressibility) of the sandy soil and rock formation in which they are used. Water soluble polymers are widely used as grouting materials in a number of projects related to tunneling and sewer pipe joint sealing (Ozgurel et al. 2005; Vipulanandan et al. 2009). Water soluble grouts are generally a mixture of organic monomers, which can be polymerized at ambient temperature, with a controllable gelling time from a few seconds to several hours. Viscosity and density of the water soluble polymer solutions are close to those of water. Increased use of water soluble polymers in various applications will require better quantification of the gelling time and the maximum curing temperature for the polymers (Ozgurel et al. 2005). In a recent study the water soluble polymer was used for stabilization of sulfate contaminated CL clay soil and using only 1.5% of the polymer increased the compressive strength from 152 kPa to 1048 kPa (Mohammed and Vipulanandan (2014)). Vipulanandan and Mohammed (2014) have used water soluble polymer to also enhance the rheological properties of bentonite drilling mud.

Constitutive model

Vipulanandan p-q Stress-Strain Model

The stress-strain behavior of strain softening materials such as concrete, glass-fiber - reinforced polymer concrete, fine sands grouted with sodium silicate, sulfate contaminated clay soil and cement mortar have been predicted using the p-q model (Vipulanandan et al. 1990; Mebarkia et al. 1992; Mohammed and Vipulanandan 2015). Usluogullari et al. (2011) modeled the stress-strain behavior of Portland cement stabilized sand using the p-q model. Vipulanandan and Mohammed (2015 (a)) used the modified p-q model to predict the piezoresistive behavior of the smart cement modified with Iron oxide nanoparticles.

Predicting the performance of treated expansive soil is important in selecting the most useful method for soil stabilization. Hence there is a need to develop methods to quantify the behavior of stabilized expansive soils.

2. Objectives

The overall objective was to quantify the changes in the stress-strain properties of a field expansive CH soil treated with different percentages of the polymer solution. The specific objectives are as follows:

(i) Test the compressive stress-strain relationships and strengths of expansive soil treated with different percentage of polymer solution (PS) content with lime treated soil.

(ii) Model and compare the behavior of polymer treated and lime treated clay soils.

3. Materials and methods

Materials

A series of laboratory tests were performed to evaluate the influence of acrylamide polymer solution (PS) content on the index properties, compaction, free swelling and compressive strength of expansive CH soil. The effect of various amounts of polymer solution treatment on the expansive CH soil was evaluated and compared with the lime treated soil. The polymer solution content was varied up to 20% by dry weight of soil.

Soil

In this study, field expansive clay soil sample was used. Soil was first dried in the oven at a temperature of 60°C, crushed, pulverized and sieved to get sizes finer than # 4 sieve. standard compaction, and unconfined compressive strength tests were performed according to the ASTM Standards. The test results are summarized in Table 1. The soil had 3% sand, 55% clay and 42% silt with a liquid limit of 80% and plasticity index of 45%.

Table 1. Summary of the Properties of the CH Soil

Property	Test Method	Value
Passing Sieve #200 (%)	ASTM D 6913	97

Clay (%)	ASTM D 6913	55
Silt (%)	ASTM D 6913	42
Sand (%)	ASTM D 6913	3
Specific Gravity	ASTM D 854	2.74
LL (%)	ASTM D 4318	80
PI (%)	ASTM D 4318	45
OMC (%) (Standard Compaction)	ASTM D 698	22
Maximum Dry Density (gm/cm^3)	ASTM D 698	1.42
Free Swelling, FS (%)	ASTM D 4546	15
Compressive Strength (kPa)	ASTM D 2166	126
USCS Classification	ASTM D 2487	CH

Polymer

The water soluble polymer used in this study was acrylamide. The polymer solution was prepared by mixing three different amounts of water soluble polymer contents 10%, 12% and 15% with 0.5% of catalyst (ethanol amine), 0.5% of activator (sodium persulfate) and water as summarized in Table 2. The polymer solution with 15% polymer content had a pH of 8 and the viscosity was 1.2 cP. Hence, if the 10% of polymer solution content (using 15% polymer mix) was used to treat the soil (based on dry weight of soil) the actual amount of polymer used to treat the soil was 1.5%.

Table 2. Composition of polymer solution (PS) mixes

Mix	Polymer (g)	Catalyst (g)	Activator (g)	Water (g)	Total (g)
1	10	0.5	0.5	89	100
2	12	0.5	0.5	87	100
3	15	0.5	0.5	84	100

Lime

In this study, hydrated lime was used to treat the soil. When quicklime reacts with water it transforms into hydrated lime as follows:

$$CaO + H_2O \longrightarrow Ca(OH)_2 + Heat \quad (1)$$

Hydrated lime ($Ca(OH)_2$) reacts with the clay particles and modifies the clay based on its mineralogy (Hassibi 2009).

Methods

Soil mixing

The CH field soil samples were first cut into small pieces using spatula and then mixed with the selected amount of polymer solution or lime using a table top mixer. Soil samples between 600 grams and 1000 grams were mixed in one mixing operation. Mixing was done for 2 to 5 minutes to get homogenous soil samples (visual observation).

Standard compaction test (ASTM D 698-12)

All the specimens were prepared by compacting with equivalent energy to achieve the maximum dry density at optimum moisture content as obtained from the standard proctor compaction test.

Unconfined compression tests

The unconfined compression tests were conducted according to ASTM D 2166-16. The unconfined compressive strengths were determined from the stress–strain relationship. The natural CH soil was modified using different percentages of the polymer solutions and also the 6% of lime and all the treated soils were compacted at corresponding optimum moisture content. Cylindrical steel molds, 75 mm diameter and 150 mm height were used to prepare the specimens using the compaction energy in Eqn. (2). The soil samples were then extruded using a hydraulic jack. The soils modified using 6% lime were placed in moisture tight bags and placed in a 100% humidity room for curing for 7 days at room temperature. The soils treated with polymer solution were cured for 1 day at room temperature before performing the tests.
The test specimens were compacted in three layers with eighteen blows per layer. For the volume of the test mold the specific compaction energy (E) applied was determined as follows:

E = [(No. blows per layer) x (No of layers) x (Weight of hammer) x (Drop height)]/ Volume of Soil…. (2)
= (18 blows x 3 layers x 2.5 kg. x 0.304 m) / 6.76×10^{-4} m^3 = 60,706.2 kg-m/m^3

This compaction energy was comparable to that produced with the standard proctor equipment which provides about 60,706 kg-m/m^3. During the compression test the specimens were loaded to failure or tested until 10% strain.

4. Results and discussion

Compacted soil

Optimum moisture content (OMC %)

Optimum moisture content for the field CH soil decreased from 22% to 20%, 19% and 18.4% respectively, a 9%, 14% and 16% reduction respectively when the PS content in the soil was 10% using Mix 1, Mix 2 and Mix 3 as shown in Figure 1. Additional of 6% lime to the CH soil increased the (OMC) by 8% as shown in Figure 1. The lowest value of optimum moisture content was with 15% of the polymer solution content for all the polymer mixes used as shown in Figure 1.

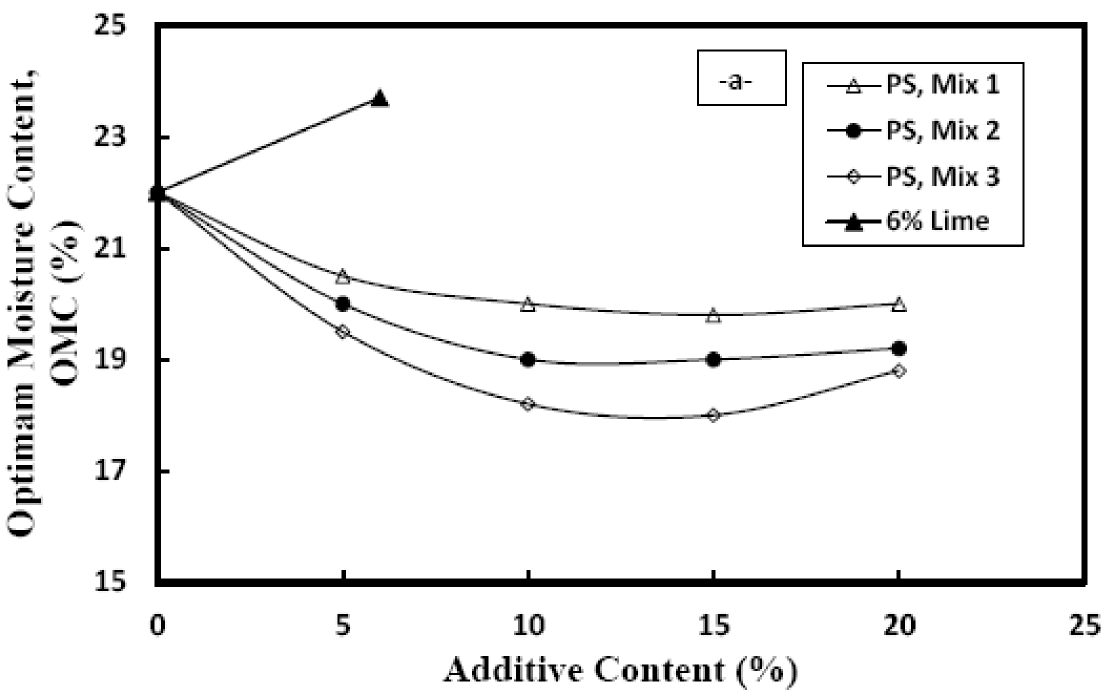

Figure 1. Variation of Optimum Moisture Contents with Polymer Solutions and Lime

Maximum dry density

Maximum dry density for the field CH soil increased from 1.42 gm/cm^3 to 1.48 gm/cm^3, 1.5 gm/cm^3 and 1.51 gm/cm^3 respectively, a 4%, 6% and 6% increase respectively when the PS content in the soil was 10% using Mix 1, Mix 2 and Mix 3 as shown in Figure 2. Additional of 6% lime to the CH soil increased the (OMC) by 1.5% as shown in Figure 2. The highest value of maximum dry density was with the 15% of the polymer solution content for all the polymer mixes used as shown in Figure 2.

Mechanical Properties

Stress- strain relationships for the untreated and treated expansive soils are shown in Figure 3. CH soils treated with all three polymer mixes with 10% polymer solution content were used for the compression test, with the increase in polymer content the compressive strength and the initial modulus of the treated compacted soils increased as shown in Figure 3.

Stress-strain behavior modeling

Soils are generally modeled as linear elastic, linear elastic - perfectly plastic or as strain hardening materials. In this study the soil, with and without treatment, exhibitored strain softening behavior as shown in Figure 3.

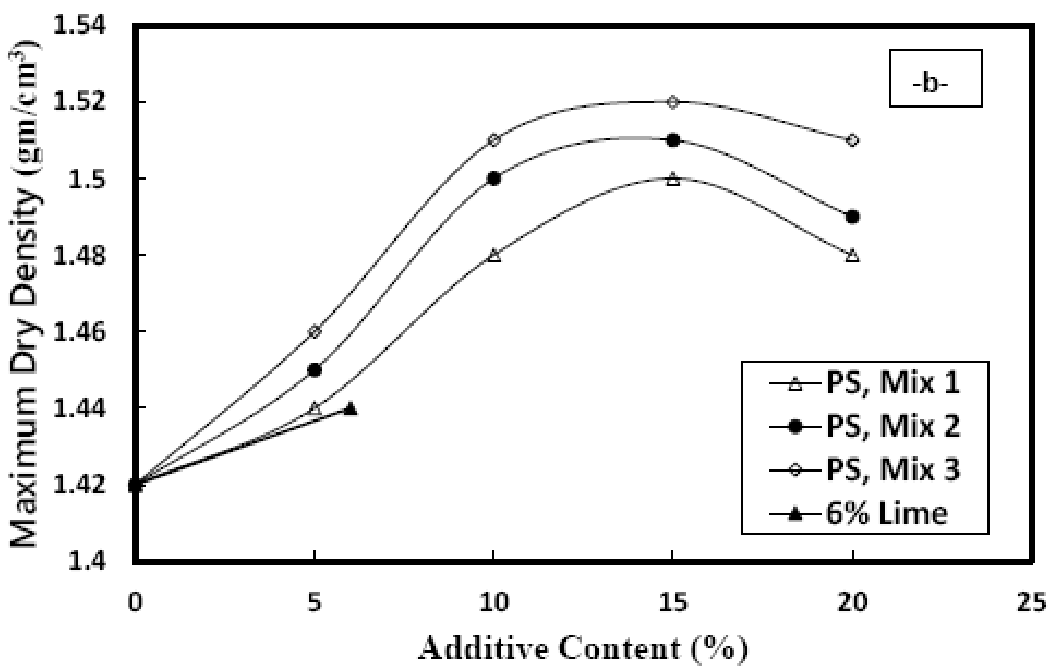

Figure 2. Variation of Optimum Moisture Contents with Polymer Solutions and Lime

Vipulanandan p-q Stress-Strain Model

Based on experimental results, Vipulanandan p-q stress-strain model proposed by Vipulanandan and Paul (1990), was used to predict the stress- strain behavior of treated expansive CH soil with different percentages of polymer solutions and 6% lime. The model is defined as follows:

$$\sigma = \left(\frac{\frac{\varepsilon}{\varepsilon_c}}{q + (1 - p - q)(\frac{\varepsilon}{\varepsilon_c}) + p * (\frac{\varepsilon}{\varepsilon_c})^{\frac{p+q}{p}}} \right) * \sigma_c \qquad (3)$$

σ = compressive stress.
σ_c, ε_c =compressive strength and corresponding strain.
p, q= material parameters.
Parameter q was defined as the ratio of secant modulus at peak stress to initial tangent modulus. Parameter p was obtained by minimizing the error in the predicated stress - strain relationship. Hence, parameters p and q in (Eqn. 3) were determined based on the stress- strain behavior of expansive soil treated with 6% of lime and different percentage of polymer content and the values and coefficient of determination (R^2) and root mean square error (RMSE) are summarized in Table 4. As summarized in Table 3 the parameters p and q were influenced by the polymer content in the three mixes investigated in this study. .
Parameter p: For untreated soils the parameter p was 0.04. Soil treated with 6% lime increased the p parameter from 0.04 to 0.07 and treating the CH soils with 10% of polymer solutions using Mix 1, Mix 2 and Mix 3 increased the p parameter from 0.04 to 0.18, 0.32 and 0.12 respectively as summarized in Table 6. Hence the model parameter p was sensitive to the type of treatment.
Parameter q: Parameter q represents the nonlinear behavior of the material up to peak stress. For the polymer treated expansive CH soil the parameter q was in the range of 0.47 to 0.89 based on the type of the polymer mix as summarized in Table 6. Treating the CH soil with 6% lime decreased the q parameter from 0.63 to 0.55. Hence the model parameter q was sensitive to the type of treatment.

Table 3. Stress- Strain Model Parameters for lime and polymer treated expansive CH soils

Additive (%)	p-q Model Parameter (Eqn. 3)						
	σ_c (kPa)	ε_c (%)	Modulus of Elasticity E_i (kPa)	p	q	RMSE (kPa)	R^2
0	126	6.1	2206	0.04	0.63	1.90	0.99
6% Lime	174	4.5	3447	0.07	0.55	5.40	0.99
10% Mix 1	303	4	10342	0.18	0.68	5.61	0.99
10% Mix 2	403	4.1	12066	0.32	0.89	2.81	0.99
10% Mix 3	496	5.6	14479	0.12	0.47	4.32	0.99

Compressive Strength

Total of 14 unconfined compression tests were performed in this study. Compressive strength of the CH soil used in the current study increased from 126 kPa to 303 kPa, 403 kPa and 496 kPa when the expansive soil was treated with 10% of polymer solution using Mix 1, Mix 2 and Mix 3 respectively after one day of curing as shown in Figure 4. Additional of 6% of lime to the expansive soil increased the 7 days cured compressive strength from 126 kPa to 174 kPa as shown in Figure 4. The variation of compressive strength with the polymer solution content for Mix 1, Mix 2 and Mix 3 are shown in Figure 4. The highest value of compressive strength was with 15% of the polymer solution content as shown in Figure 4.

5. Conclusions

In this study the effects acrylamide polymer solution on the behavior of expansive soil was investigated. Over 70 tests were performed during this study. Based on the experimental and model study following conclusions are advanced:

1. Polymer treated expansive soil decreased the optimum moisture content and increased the maximum dry density of the expansive soils. The addition of lime increased the maximum dry density and optimum moisture content of the compacted expansive soil.
2. The compressive strength of the CH soil used in the current study increased from 126 kPa to 303 kPa, 403 kPa and 496 kPa, a 142%, 220% and 300% increase when the expansive soil was treated with 10% of polymer solution content using the three different mixes after one day of curing. Addition of 6% of lime to the expansive soil increased the 7 days cured compressive strength from 126 kPa to 174 kPa a 39% increase. Vipulanandan p-q compressive stress-strain model was used to predict the behavior of lime and polymer treated expansive soils. The model parameters were sensitive to the type of treatment.
3. Vipulanandan p-q stress-strain model predicted the compressive stress-strain relations of CH soil with and without polymer and lime treatment very well. The model parameters were sensitive to the type of treatment.

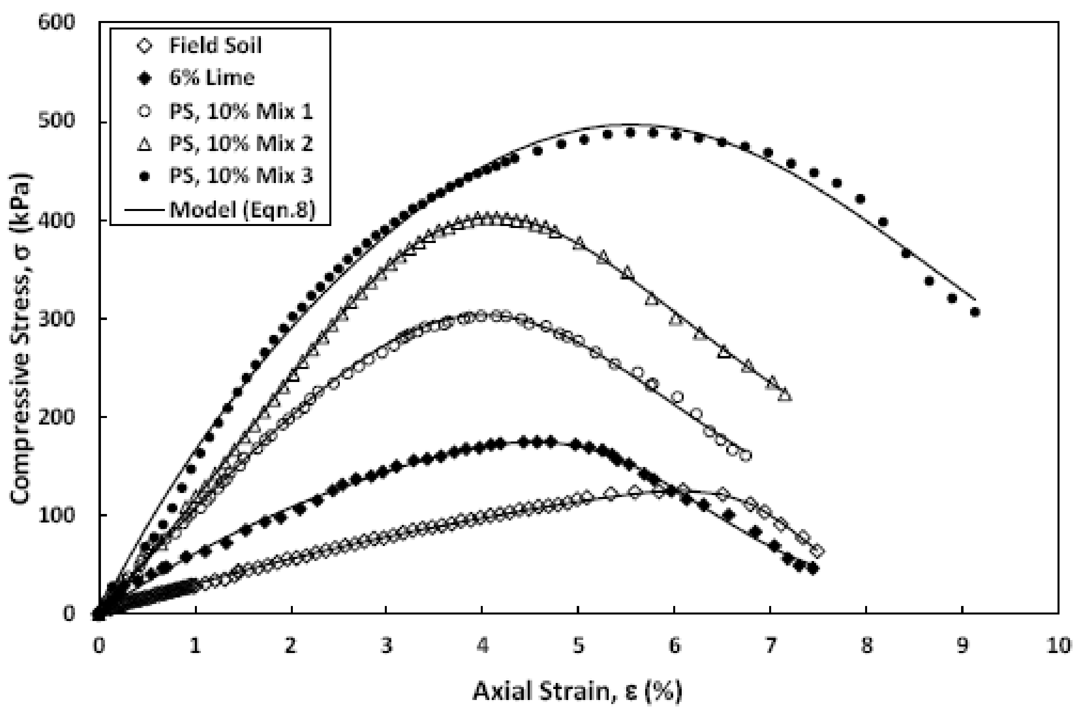

Figure 3. Measured and Predicted Stress-Strain Relationships for the CH Soil Treated with Polymer Solutions and Lime

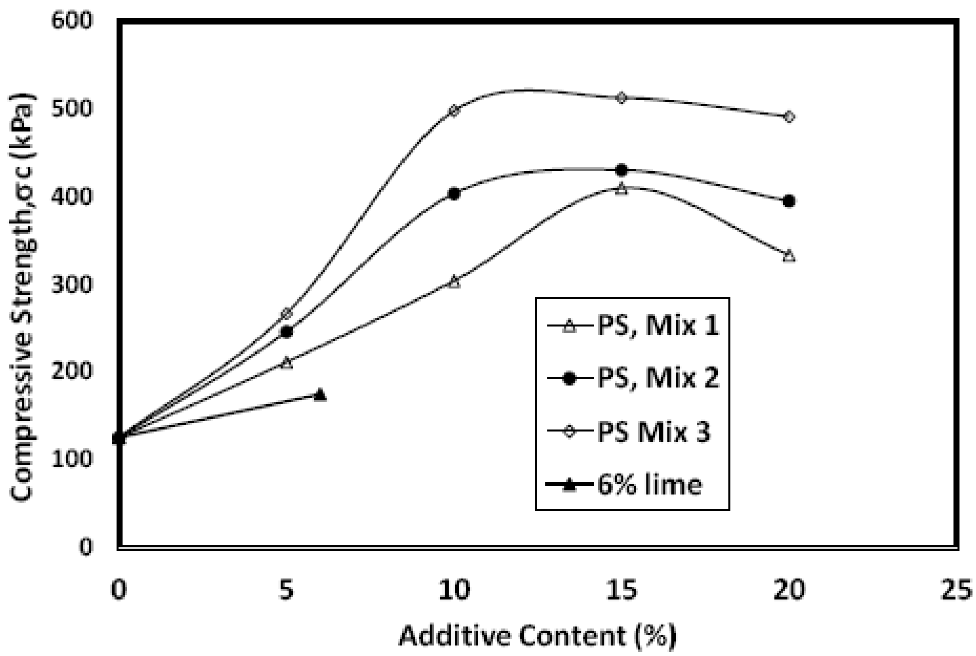

Figure 4. Variation of Compressive Strength for the CH Soil Treated with Polymer Solutions and Lime

6. Acknowledgement

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