Effects of Polymer Contents on the Index Properties of Expansive CH Clay Soil Using Vipulanandan Models

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Abstract

In this study, the effects of a water soluble acrylamide polymer solution (PS) treatment on the index properties of an expansive CH soil obtained from the field in Houston, Texas was investigated. In order to characterize the clay before and after polymer treatment X-ray diffraction (XRD) analyses and Thermogravimetric analyses (TGA) were used respectively. In addition to characterizing the behavior of expansive CH soil (free swelling of 15%), the effect of treating the soil with varying amounts of acrylamide polymer solution (PS) was investigated and the performance was compared to 6% lime treated soil 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 liquid limit (LL) and plasticity index (PI) (index properties) of the expansive CH soil decreased by 33% and 57% respectively. The behavior of the liquid limit and plasticity index of the expansive CH soil treated with different percentages of the polymer solutions have been quantified using the Vipulanandan property correlation model.

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. Expansive soils, both clays and silt with high clay content, 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 (Vipulanandan and Mohammed 2015 c). 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. For effective subgrade stabilization, a more rigorous soil classification which considers the soil mineralogy is needed for evaluating and assessing the use of certain type of chemical additives such as water soluble polymers for enhancing soil properties (Huang et al. 2012; Wang et al. 2012; Gilazghi et al. 2016). Cokca (2001) investigated the expansive CH soil stabilizing using low calcium and high calcium class C fly ash mixtures. The study also included comparison with treating the soil using lime and cement. The results showed that a soil treated with 20% fly ash had nearly the same stabilizing effect on the swelling potential as a soil treated with 8% lime. It was also found that the addition of the stabilizers changed the classification of the treated soil. This observed change was due to the additional silt size particles added from the fly ash and also was related to the chemical reaction that caused immediate flocculation of the clay particles. Bell (1996) studied the linear shrinkage of montmorillonite CH soil with different percentages of lime additive and showed that the shrinkage decreased with the addition of lime, but the decrease was not linear. The study also showed that the unconfined compression strength did not increase linearly with the addition of lime and excessive addition of lime actually reduced the strength. During this treatment, mineralogical and microstructural changes occurred, which lowered the plasticity and also enhanced the compressive strength and enable soil compaction to higher density. Arabani et al. (2007) observed that an increase in the lime content beyond 6% had negligible effect on the compressive strength of treated clay soils. Effects of soil stabilization with lime on the performance of various types of clay soils have been documented in the literature by several researchers in the past decades. Reaction of lime with alumino –silicate in clays, produced hydrated cementitious products that bonded to the soil particles and the results reported are for 7 and 28 days of curing (McCarthy et al. 2009). In these cases lime has been used in treating clays by varying the lime content up to 10%.

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.

According to the studies summarized in Table 1 and additional information in the literature most of the studies have used 6% of lime treated the expansive soil and the specimens were prepared and tested near the optimum moisture content (OMC %) (Harris et al. 2004; Knattab et al. 2007; Pedarla et al. 2011; Consoli et al. (2012)).

Constitutive models

Vipulanandan Property Correlation Model

In mathematics, hyperbolic functions are analogs of ordinary trigonometric or circular functions. During the past two decades, Vipulanandan has developed s special form of hyperbolic relation with three material parameters that will set the limits on the changes in the material properties due to additives and curing time, pile capacity, drilling fluid shear strength and material property correlations (Vipulanandan et al. 1993 and 2016). Usluogullari and Vipulanandan (2012) used the hyperbolic relationship to represent the variation of compressive strength, modulus and California Bearing Ratio (CBR) values with curing time for cemented sand. Mohammed and Vipulanandan

(2014) used the hyperbolic relationship to predicate the relation between the compressive and tensile strength of sulfate contaminated CL soils with and without polymer treatment. Vipulanandan and Mohammed (2014) used hyperbolic relationship to predict the maximum shear stress limit for the bentonite drilling mud modified with the polymer. Hyperbolic model was used to predict the rheological properties with the electrical resistivity of nanoclay modified bentonite drilling mud (Vipulanandan and Mohammed 2015 b).

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.

Objectives

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

(i) Characterize the expansive clay before and after treatment using XRD and TGA.

(ii) Compare and quantify the index properties of an expansive soil treated with different percentage of polymer solution (PS) content with lime treated soil.

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 amount 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. Atterberg limits, grain size distribution, hydrometer, standard compaction, free swelling 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% and hence it is important to understand the composition of the clay soil and XRD analyses was performed. Based on the test results and using the unified soil classification system (USCS) the soil was classified as a CH soil.

Table 1. Physical properties of 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
LL (%)	ASTM D 4318	80
PI (%)	ASTM D 4318	45
Free Swelling, FS (%)	ASTM D 4546	15
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 3. 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

XRD characterization

X-ray diffraction (XRD) was used to characterize the expansive CH soil. The XRD patterns were obtained using the Siemens D5000 powder x-ray diffraction machine. Specimens for XRD were prepared from air-dried soil. The soil sample (≈2 g) was placed in an acrylic sample holder which was about 3 mm deep. All samples were analyzed by using parallel beam optics with CuKα radiation at 40 kV and 30 mA. The sample was scanned for reflections (2θ) in the range 0^o to 80^o in a step size of 0.02° and a 2 sec count time per step (Vipulanandan and Mohammed 2016).

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).

Thermogravimetric analysis (TGA)

Thermogravimetric analysis curves, the percentage of weight loss with temperature (TGA) and its derivative (%weight change/^{o}C - DTG), were recorded using a Setaram TGA 500 apparatus at a heating rate of 10 °C/min for the sample of about 20 mg. The TGA and DTG curves were obtained for the field CH soil, treated expansive CH soil with 6% of lime after 7 days of curing and treated the soil with 10% polymer solution using Mix 3 after 1 day of curing. The test samples were loaded in a platinum pan (¾ full). This was followed by introducing nitrogen gas (N_2) into the TGA compartment for five minutes to purge the likely oxygen in the environment of the system. After the purging, the sample was heated in the N_2 atmosphere from room temperature to the maximum of 800^{O}C. The weight loss percentage and temperature relationships were obtained for the soil samples.

Particle size distribution (ASTM D6913 - 04)

Both sieve analysis and hydrometer analysis were used for the field soil to determine the particle size distribution (ASTM standard).

Atterberg limits (ASTM D 4318 - 10)

Both untreated and treated soils using varying amount of the polymer solutions and also 6% of lime were used to determine the liquid limit and plastic limit.

Free swelling test (FS %) (ASTM D 4546-14)

The optimum water contents for the natural expansive clay soil treated with 6% lime and different percentage of polymer solution up to 20% (by dry weight of the soil) were determined using standard proctor test in accordance with ASTM D 698-12. For the free swelling tests, cylindrical samples were prepared at optimum water content for the natural clay soil and clay soil treated lime and polymer solution. The swelling tests were carried out in the conventional oedometer apparatus for the natural soil and treated soils. The consolidation ring was pushed through the compacted soil samples at optimum moisture content, using standard proctor and the extra material was carefully trimmed in accordance with the ASTM Test Method D 2435-11 to match the height of the consolidation ring. The inside of the rings was lubricated with silicone grease to minimize side friction between the ring and the soil specimen. Extreme care was taken during specimen preparation to avoid any gap between the ring and the specimen. After 7 days of curing period at 100% humidity and 25^{o}C temperature for the soil sample modified using 6% lime and after 24 hours for the soil samples treated using polymer solution, the swelling tests were performed based on ASTM D 4546-14. Filter papers were placed on the top and bottom of the soil specimen to prevent finer particles from being forced into the pores of the porous stones placed on both sides of the specimen. After setting the swell measurement dial gage to zero, the specimens were inundated with water and were allowed to swell freely under (7 kPa) discharge load. Free swell measurements for first day were made at time intervals similar to that used for consolidation test. Each test was performed to run for at least 2 days. Free swell measurements for the first day were made at various time intervals similar to that used for consolidation test (ASTM D 4546-14). The percent free swell was expressed as:

$$FS\% = \left(\frac{\Delta H}{Ho}\right) * 100 \qquad (3)$$

where: ΔH is height of well due to saturation; H_o is the original height of specimen. Total of 14 tests were performed. Free swelling versus liquid limit of natural clay soils where compared with published data from literature.

Comparison of model predictions

In order to determine the accuracy of the model predictions, both root mean square error (RMSE) and coefficient of determination (R^2) for the model predictions as defined in Eqns. (4) and (5) were quantified.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{N}} \qquad (4)$$

$$R^2 = \left(\frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2} * \sqrt{\sum_i (y_i - \bar{y})^2}}\right)^2 \qquad (5)$$

where yi = actual test value; xi =calculated value from the model; $\bar{y}$ =mean of the actual test values; $\bar{x}$= mean of calculated values and N is the number of data points.

4. Results and Discussion

XRD analysis

Based on the XRD analyses, the field clay soil had four peaks corresponding to calcium silicate ($CaSiO_3$) (2θ peaks at 36.23°, 60.02° and 76.01°), aluminum silicate (Al_2SiO_5) (2θ peaks at 26.65°, 40.05° and 42.55°), sodium montmorillonite ($(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$) (2θ peaks at 6.05°, and 55.03°) and quartz (SiO_2) (2θ peaks at 21.0°, 50.02° and 68.10°) as shown in Fig. 1 (Nadeau et al. 1984). The CH clay soil with 55% clay content had sodium montmorillonite in it and that contributed to the higher index properties.

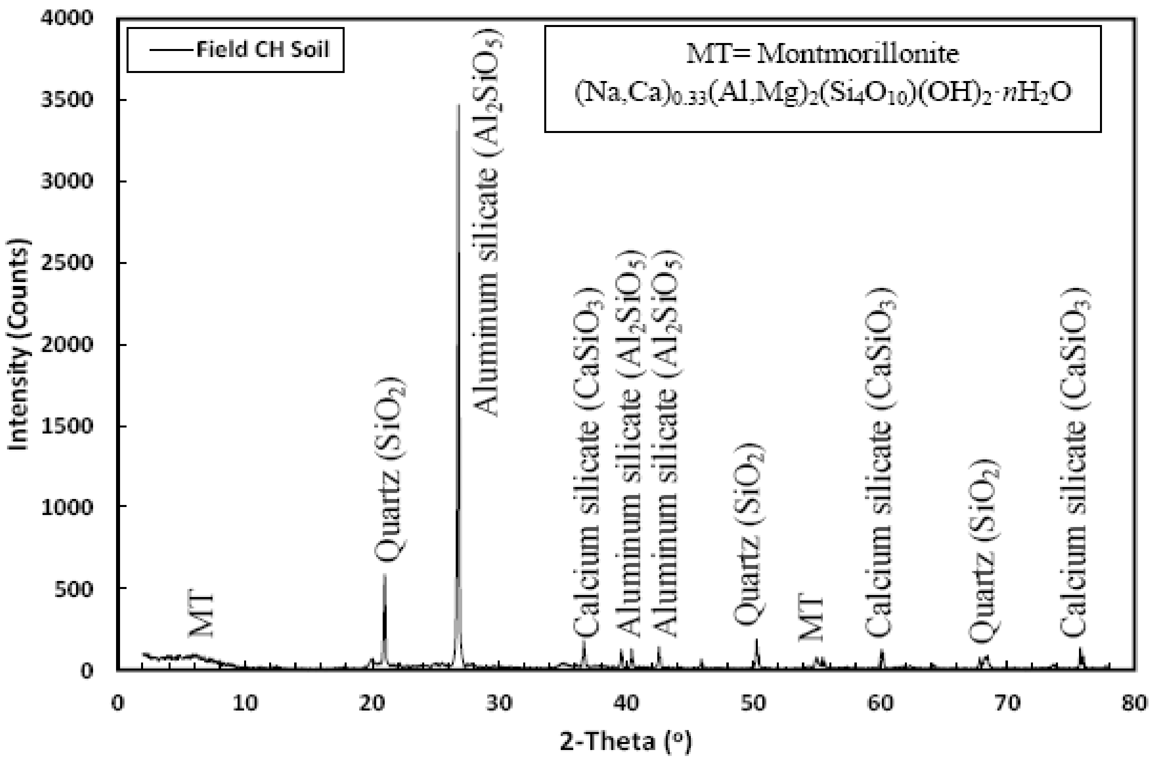

Figure 1 XRD Analyses of the Clay Soil

TGA analysis

Using the thermogravimetric analysis (TGA) the weight loss at rate of weight change with temperature were obtained for the field expansive soil and treated soil with 10 % of polymer solution (15% polymer mix) using Mix 3 and 6% of lime separately after 1 day and 7 days of curing respectively. Weight loss in treated and untreated expansive soil were analyzed in four temperature ranges as summarized in Table 2. The weight loss below 120°C is mainly due to free water (water not linked to the exchangeable cation and water between clay particles) and between 120°C and 400°C it is linked to the exchangeable cation (Hunter 1988). The weight loss between 400°C and 600°C is due to the dehydration of the clay minerals such as aluminum silicate and between 600°C and 800°C the dehydration of calcium silicate as shown in Figure 2 (Hunter 1988). The heating rate used in these tests was 10°C/min and the weight loss at 105°C is considered to represent the free water. The total weight loss for the field CH soil between 25°C to 120°C was 6.4% and it was 1.3% when the temperature changed from 120°C to 400°C as summarized in Table 5. The weight loss for the CH soil increased by 15% when the temperature changed between 400°C to 600°C. The total weight loss for the field CH soil at 800°C was 12.9 % as summarized in Table 3.

For lime treated CH soil, two weight loss peaks where observed between 25°C to 120°C and between 550°C to 700°C. Addition of 6% lime to CH soil decreased the weight loss from 6.4% to 1.3%, a 80% reduction for the temperature range of 25°C to 120°C and the total weight loss of CH soil treated with 6% lime was also decreased by 23% at 800°C as summarized in Table 3 and shown in Figure 2. Treated CH soil using 10% of polymer solution (15% polymer content mix) using Mix 3 reduced the weight loss from 6.4% to 0.33%, a 99% reduction in the temperature range of 25°C to 120°C, where polymer treatment substantially reduced the dehydration of the free water. Also the polymer treatment reduced the total weight loss in the natural clay soil by 64% at 800°C as summarized in Table 3. This indicates that the polymer solution coated the soil particles and prevented the weight loss in the expansive CH soil.

Table 3 TGA results on lime and polymer treated CH soils

Sample	Temperature Range and Weight Loss (%)				
	(25-120) ºC	(120-400) ºC	(400-600) ºC	(600-800) ºC	Total (%)
Field CH Soil	6.4	1.3	1.5	3.7	12.9
CH soil treated with 6 % lime after 7 days of curing	1.3	2.9	0.88	5	10
CH soil treated with 10 % polymer solution (1.5 % polymer content) using mix 3 after 1 day of curing	0.33	0.46	0.27	3.6	4.66

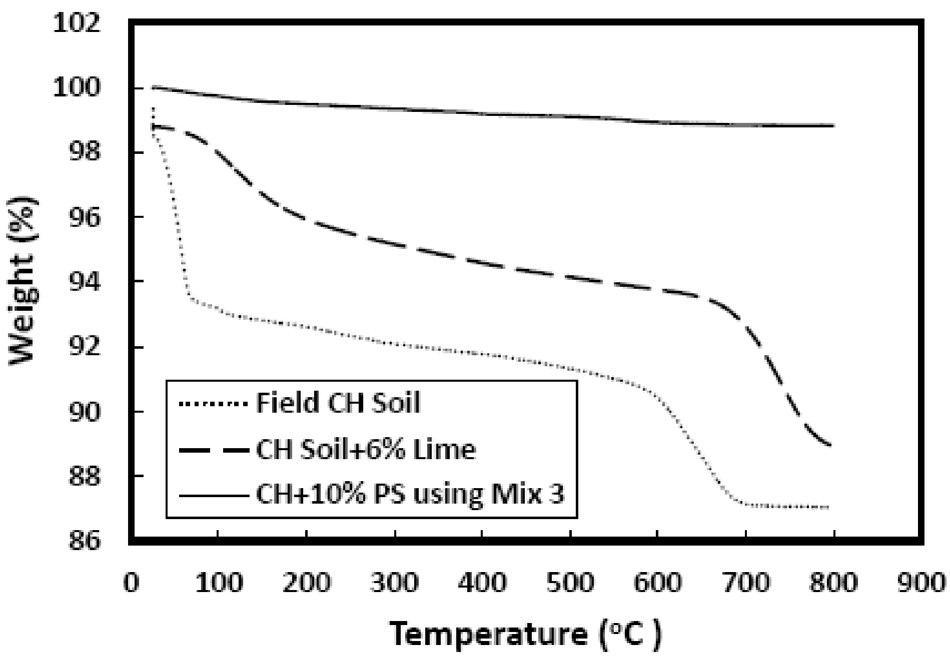

Figure 2 TGA Analyses of the Clay Soil with and without 10% Polymer and 6% Lime

Modeling

Based on the inspection of the test data Vipulanandan property correlation model (3 parameters model) is proposed to predict the changes in the treated soil properties (Vipulanandan et. 1993 and 2016). The relationship is as follows:

$$Y - Y_o = \frac{PS}{A + (B * PS)} \tag{6}$$

where:
Y: is the soil property with varying polymer solution content.
Y_o: is the untreated soil property (natural CH soil).
A and B: are model parameters (Table 6).

PS: is the polymer solution content (%).
The three model parameters are Y_o, A and B.

Particle size distribution

Based on the sieve and hydrometer analysis on field soil, the percentage passing sieve # 200 (75 µm), sand, silt and clay fractions in the natural clay soil were 97%, 3%, 42% and 55% respectively as summarized in Table 1.

Liquid limit (LL)

Additional of polymer solutions (PS) in varying amounts to the natural CH soil decreased the liquid limit and the change was nonlinear as shown in Fig. 3 (a). When the PS content in the soil was 10% using Mix 1, Mix 2 and Mix 3, the liquid limit decreased from 80% to 73%, 62% and 54% respectively, a percentage reduction of 9%, 22% and 34% respectively as shown in Fig. 3. The change in the LL with polymer solution (PS) was represented using the relationship Eqn. (6) and the parameters A, B and Yo are summarized in Table 5, and the coefficient of determination (R^2) for the relationship was 0.99 and root mean square error (RMSE) ranged between 0.28% and 0.36% based on the polymer content. Addition of 6% of lime to the CH soil decreased the liquid limit by only 8% as shown in Figure 3. Hence the polymer solution treatment showed greater reduction in the LL than lime treatment.

Plasticity index (PI)

When the PS content in the soil was 10% using Mix 1, Mix 2 and Mix 3, the PI decreased from 45% to 34%, 28% and 19% respectively, a 24%, 38% and 58% reduction respectively as shown in Fig. 3 (b). In this study, total of 34 soil samples were tested. The relationship (inverse hyperbolic) in the Eqn. (6) was used to relate plasticity index to polymer solution content for treated soil as shown in Figure 4. The parameters A, B and Yo for treated CH soil using different percent of polymer solution are summarized in Table 5. The coefficients of determination (R^2) was 0.99 and root mean square error (RMSE) for the hyperbolic relationships ranged between 0.20% and 0.71% based on the polymer content. The addition of 6% of lime to the CH soil decreased the PI by 10% as shown in Figure 4. Hence the polymer solution treatment showed greater reduction in PI than lime treatment.

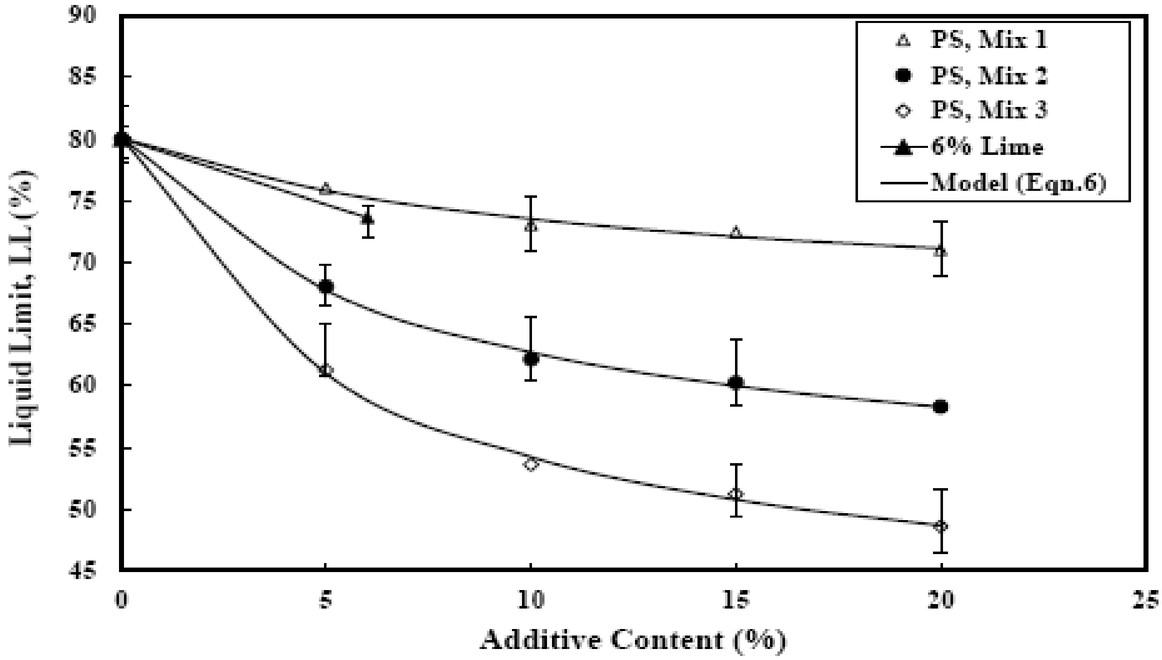

Figure 3 Comparing the Liquid Limit Changes with Varying Amounts of Polymer and 6% Lime

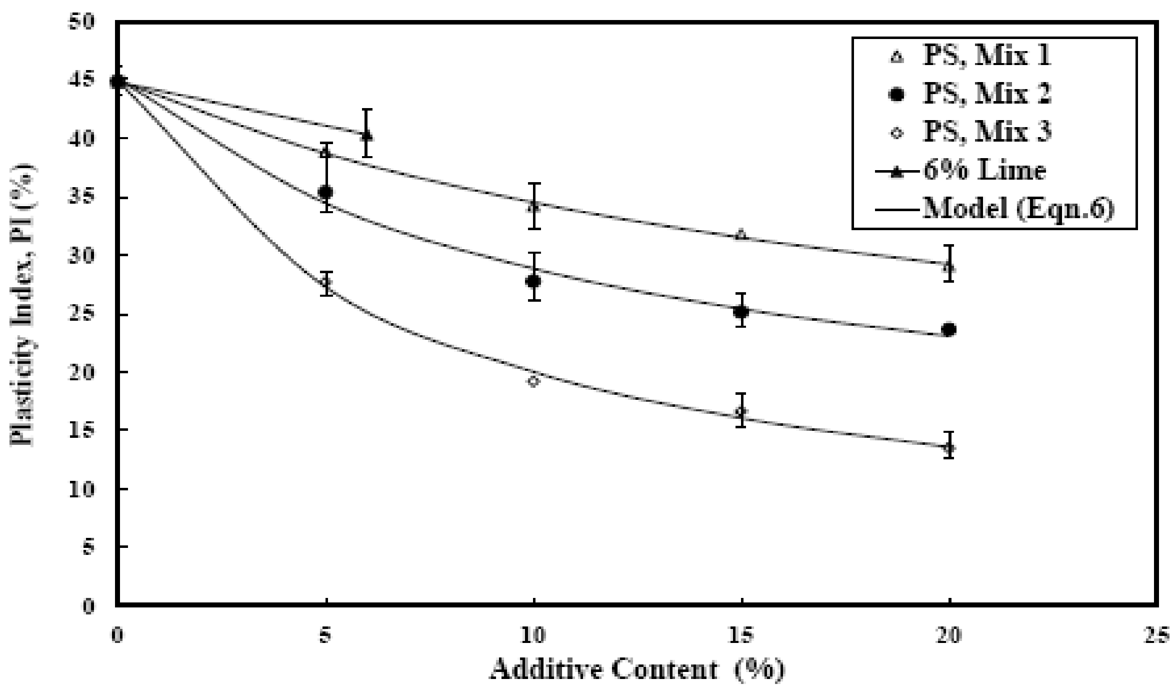

Figure 4 Comparing the Plasticity Index Changes with Varying Amounts of Polymer and 6% Lime

Table 3 Model parameters for expansive CH soil treated with different mixes of polymer solutions

Polymer Solution (PS)	Y	Yo	A	B	RMSE (%)	R^2
Mix 1	LL	80	0.07	0.82	0.28	0.99
	PI	45	0.03	0.65	0.20	0.99
	FS (%)	15	0.13	0.56	0.05	0.99
Mix 2	LL	80	0.03	0.23	0.31	0.99
	PI	45	0.02	0.16	0.48	0.99
	FS%	15	0.09	0.43	0.12	0.99
Mix 3	LL	80	0.03	0.13	0.36	0.99
	PI	45	0.03	0.32	0.71	0.99
	FS (%)	15	0.09	0.33	0.11	0.99

Free swelling (FS)

Total of 14 soil samples were tested in this study. Percent of free swelling with time for the CH soil treated with different percentage of polymer solution are shown in Fig. 5. The free swelling of natural CH soil decreased to 9.5%, 7.5% and 6% respectively a 40%, 57% and 68% reduction when the soil was treated with 20% of polymer solution content using Mix 1, Mix 2 and Mix 3 respectively after one day of curing as shown in Fig. 5. The free swelling of the CH soil decreased to 11%, a 30% reduction when the soil treated using 6% lime after 7 days of curing as shown in Figure 5.

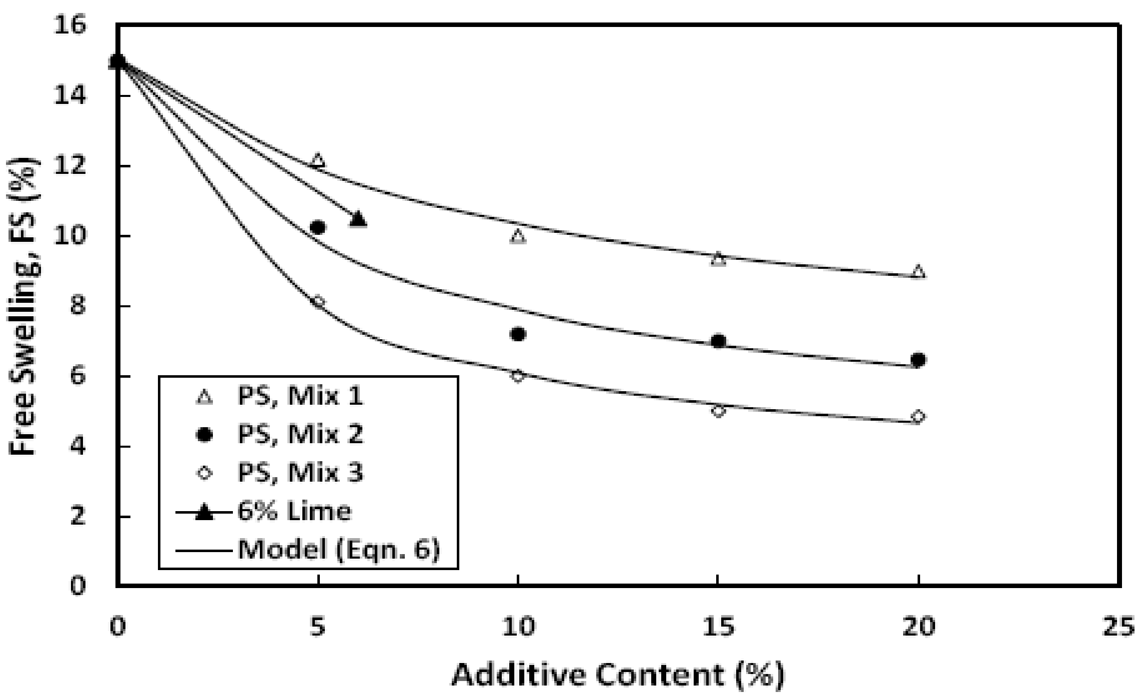

Figure 5 Comparing the Free Swelling Changes with Varying Amounts of Polymer and 6% Lime

Conclusions

In this study the effects acrylamide polymer solution on the behavior of expansive soil was investigated. Over 50 tests were performed during this study. Based on the experimental and model study following conclusions are advanced:

1. TGA analyses showed greater weight loss up to 800°C in expansive soil and lime treated soil compared to polymer treated soil. Polymer treatment reduced the weight loss of expansive CH soil by 64%. Lime treatment reduced the weight loss of expansive CH soil by only 22%.
2. Liquid limit of natural CH soil decreased from 80% to 49%, a 40% reduction with the addition of 20% polymer solution content of Mix 3 (15% polymer content), which represented 3% polymer. Adding 6% lime to the CH soil decreased the LL by 8%.
3. Plasticity index of natural CH soil decreased from 45% to 13.5%, a 70% reduction with the addition of 20% polymer solution content of Mix 3 (15% polymer content). Adding 6% lime to the CH soil decreased the LL by 10%.
4. After 2 days of swelling measurement, the addition of polymer solution decreased the free swelling percent from 40% to 68% after one day of curing based on the amount of polymer content. Addition of 6% lime decreased the free swelling percent by 30% after 7 days of curing.
5. The Vipulanandan property correlation relationship was used to predict the changes in the index properties and free swelling of the treated expansive soils with the different percent of the polymer solution.

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