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ORIGINAL PAPER

Compressive and Tensile Behavior of Polymer Treated Sulfate Contaminated CL Soil

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Abstract In this study, the compressive and tensile behavior of polymer treated sulfate contaminated CL soil was investigated. Based on the information in the literature, a field soil was contaminated with up to 4 % (40,000 ppm) of calcium sulfate in this study. In addition to characterizing the behavior of sulfate contaminated CL soil, the effect of treating the soil with a polymer solution was investigated and the performance was compared to 6 % lime treated soil. In treating the soil, acrylamide polymer solution (15 g of polymer dissolved in 85 g of water) content was varied up to 15 % (by dry soil weight). Addition of 4 % calcium sulfate to the soil decreased the compressive and tensile strengths of the compacted soils by 22 and 33 % respectively with the formation of calcium silicate sulfate [ternesite $Ca_5(SiO_4)_2SO_4$)], magnesium silicate sulfate ($Mg_5(SiO_4)_2SO_4$) and calcium-magnesium silicate (merwinite $Ca_3Mg(SiO_4)_2$). With the polymer treatment the strength properties of sulfate contaminated CL soil was substantially improved. Polymer treated sulfate soils had higher compressive and tensile strengths and enhanced compressive stress–strain relationships compared to the lime treated soils. Also polymer treated soils gained strength more rapidly than lime treated soil. With 10 % of polymer solution treatment, the maximum unconfined compressive and splitting tensile strengths for 4 % of calcium sulfate soil were 625 kPa (91 psi) and 131 kPa (19 psi) respectively in 1 day of curing. Similar improvement in the compressive modulus was observed with polymer treated sulfate contaminated CL soil. The variation of the compacted compressive strength and tensile strength with calcium sulfate concentrations for the treated soils were quantified and the parameters were related to calcium sulfate content in the soil and polymer content. Compressive stress–strain relationships of the sulfate soil, with and without lime and polymer treatment, have been quantified using two nonlinear constitutive models. The constitutive model parameters were sensitive to the calcium sulfate content and the type of treatment.

Keywords Calcium sulfate · Polymer solution · Lime · Compressive strength · Splitting tensile strength · Models

1 Introduction

Natural sulfate rich soils are found in many parts of the world and are considered a challenge in engineering

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projects not only on the soil behavior but also the negative impact on the construction materials (Hunter 1988; Mitchell and Dermatas 1992; Petry and Little 1992; Kota et al. 1996; Rollings et al. 1999; Puppala et al. 2002). Sulfate-induced heave in stabilized soils was first reported by Sherwood (1962) and the problem received national attention only in the mid-1980s when Mitchell (1986) reported a case study based on his experience in Las Vegas, Nevada. There are different methods used for modifying the soils, which are categorized under soil treatment or stabilization methods (Holtz et al. 2011). Soil stabilization is commonly done with cement, lime, fly ash, bitumen, bentonite, and chemical grouts (Cernica 1995; Vipulanandan and Ata 2000; Vipulanandan and Ozgurel 2009). Effects of soil stabilization with cement, lime and polymer fibers on the performance of various types of soils have been documented in the literature by several researchers and few of the findings in the past two decades are summarized in Table 1. In these cases both lime and cement have been used in treating clays and sand by varying the stabilizer content up to 15 %, Also large variation in the compressive strengths of treated soils were observed. Arabani and Karami (2007) observed that for clayey sand with low plasticity any increase in lime content beyond 6 percent had a negligible effect on the compressive strength of treated soil. However, an increase in lime content up to 6 % resulted in a noticeable increase in compressive strength. Also 6 % lime content has been selected by other researchers such as Consoli et al. (2010) based on the increase in pH to about 12.4 to sustain the reactions to stabilize the soil.

Many investigations have identified the failure mechanisms in high sulfate soils (Harris et al. 2005). Based on the findings from some studies, four inorganic constituents have been identified as essential for sulfate-induced heave: water, calcium, aluminum, and sulfate. Current treatment methods of using lime or cement with sulfate soil sulfate is not effective because of ettringite formation as follows (Pillai et al. 2007):

$$\underset{\overset{\nwarrow}{\text{[Additive]+}}}{6Ca^{2+}} + \underset{\overset{\nwarrow}{\text{[Clay]}}}{2Al\,(OH)^{-}_{4}} + 4(OH)^{-} + \underset{\overset{\nwarrow}{\text{+ [Contaminant]}}}{3(SO_4)^{2-}} + \underset{\overset{\nwarrow}{\text{+ [Water]}}}{26H_2O} \longrightarrow Ca_6\,[Al\,(OH)_6]_2(SO_4)_3 26H_2O \ldots\ldots\ldots\ (1) \qquad (1)$$

The formation of ettringite in treated soils (Eq. 1) and its exposure to moisture variations from seasonal changes result in differential heaving, which in turn causes cracking of pavement structures built on the treated soils (Rajasekharan and Rao 2005; Pillai et al. 2007). If not addressed immediately, this heave will further deteriorate the structures to a condition where they need immediate and extensive rehabilitation. Hence alternative methods have to be developed to better stabilize the sulfate contaminated soils.

1.1 Behavior Models

There is very limited information in the literature on the quantification of the effects of treatment and the behavior of treated soils. Consoli et al. (2010) quantified the relationship between unconfined compressive strength (q_u) and splitting tensile strength (q_t) of artificially cemented sand, as well as the strength ratio (q_t/q_u) relationship. Consoli et al. (2012) identified key parameters for the control of strength and stiffness of cemented soils by testing two soils with different grading and quantifying the influence of porosity/cement ratio on both initial shear modulus (G_o) and unconfined compressive strength (q_u). It was shown that the porosity/cement ratio is an important parameter to assess both the initial stiffness and the unconfined compressive strength of the soil–cement mixtures studied.

The stress–strain behavior of strain softening materials such as concrete, glass-fiber—reinforced polymer concrete, fine sands grouted with sodium silicate and cement mortar have been predicted using the p–q model and β models (Mebarkia and Vipulanandan 1992; Gonzalea and Vipulanandan 2007; Bencardino et al. 2008; Vipulanandan and Paul 1990; Vipulanandan and Garas 2008). Usluogullari and Vipulanandan (2011) modeled the stress–strain behavior of Portland cement stabilized sand using the p–q model. Also the variation of compressive strength, modulus, and CBR values with curing time for the cemented sand were represented using hyperbolic relationships.

Table 1 Literature review on soil stabilization with strength models

Reference	Soil type	Tests	Sample preparation	Stabilizer type	Stabilizer (%)	Curing time (Days)	Temperature, humidity	USC (psi)	Splitting tensile (psi)	Remarks
Das and Dass (1995)	Silica sand, Poorly grade	Splitting Tensile, UCS	Standard compaction test	Cement	4 and 8	14	Not specified	160–390	Not available	Linear UCS- Cement content relationship was observed
Bell (1996)	Clay soil	UCS, CBR	Standard compaction test	Lime	2, 4, 8 and 10	1, 3, 7, 14 and 21	35 °C	70–400	Not available	No relationship was observed
Puppala et al. (2006)	Sulfate soil	Stiffness property, Shear Modulus	Standard compaction test	Lime	4	0, 1, 2, 4, 8 h, and 1, 2, 3, 4, 5, 7 days	23 ± 2 °C, 95 %	10–511	Not available	Relatively large variation in strength. No relationship was observed
Kumar et al. (2007)	CH	Splitting Tensile, UCS	Standard compaction test	Polyester Fiber	0.5, 1, 1.5 and 2	7 and 28	Not specified	20–500	4–8	Linear relationship was obtained between Split tensile strength and UCS with fiber content
Consoli et al. (2010)	Non plastic sand	Splitting Tensile, UCS	Standard compaction test	Portland cement (III)	1, 2, 3, 5, 7, 9 and 12	6	23 ± 2 °C, 95 %	10–510	10–50	Nonlinear relationship between UCS and tensile strength with porosity % was developed
Usluogullari and Vipulanandan (2011)	Sand, Poorly grade	UCS and CBR	3 layers static with a cylindrical tamper (25 mm diameter 1 kg) 30 blows	Portland cement	1.5, 3 and 6	1, 3 and 7	Room condition	9–200	Not specified	Linear relationship was observed between CBR and UCS values
Malekzadeh and Bilsel (2012)	CH	Splitting Tensile, UCS	Standard compaction test	Polypropylene Fiber	0, 0.5, 0.75 and 1	1	Room condition	40–60	30–80	Linear relationship was obtained between Split Tensile strength and fiber content
Current study	CL	Splitting Tensile, UCS	Standard compaction test (3 layers with 18 blows)	Lime Polymer solution	0, 6 0, 5, 10 and 15 %	7 1	25 °C, 100 %	17–42 17–152	5–16 5–23	Hyperbolic relationship was observed between Tensile and compressive strength
Remarks	Different soil types were used	UCS is the popular test to characterize the strength behavior	Mainly standard compaction test was used	Different type of stabilizer were used	Up to 15 % of stabilizer were used	Curing time was up to 28 days	Mainly 25 °C temperature was used	UCS varied from 10 to 511 psi	Splitting tensile varied from 4 to 80 psi	Compressive and tensile strength properties have been studied

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

2 Objective

The overall objective of this study was to investigate and quantify the compressive stress–strain relationship and tensile strength of polymer treated CL soil contaminated with varying amounts of calcium sulfate. The specific objectives are as follows:

1. Compare the compressive and tensile behavior of polymer treated sulfate contaminated soil with lime treated soil.
2. Quantify the stress–strain relationship of clay soil contaminated with calcium sulfate up to 4 %, and treated with polymer solution and lime.
3. Correlate the compressive and tensile strength of polymer treated sulfate contaminated soil.

3 Materials and Methods

A series of laboratory tests were undertaken to evaluate the influence of polymer solution on the tensile and compressive strength of sulfate contaminated CL soil with up to 4 % of calcium sulfate (dry weight). Initially the compressive and tensile behavior of sulfate contaminated CL soil with different percentage of calcium sulfate up to 4 % was characterized. Also, the effect of polymer solution treatment on the tension and compression strength behavior of sulfate contaminated CL soil was evaluated and compared with the lime stabilized soil. The polymer solution content was varied up to 15 % by dry weight of soil. The Brazilian test or indirect tension test was done to determine the tensile strength of soils (Arabani and Karami 2007).

3.1 Soil

Field clay soil sample was used in preparing the sulfate soil. Atterberg limits, grain size distribution, hydrometer, standard compaction, spilt tension and unconfined compressive strength tests were performed according to ASTM Standards. The test results are summarized in Table 2. The soil had 20 % clay and 35 % silt with a liquid limit of 23 % and plasticity index of 9. Based on the test results and using the unified soil classification system (USCS) the soil was classified as a CL soil (Tables 3, 4).

Table 2 Test methods and physical properties of soil

Property	Test method	Value
Passing sieve #200 (%)	ASTM D 6913	55
Sand %	ASTM D 6913	45
Silt %	ASTM D 6913	35
Clay %	ASTM D 6913	20
Specific gravity	ASTM D 854	2.67
LL %	ASTM D 4318	23
PI %	ASTM D 4318	9
OMC % (standard compaction)	ASTM D 698	10
Max. dry density (gm/cm^3)	ASTM D 698	1.88
Soil type	ASTM D 2487	CL

3.2 Polymer

Polymer solution was prepared by mixing 15 % of water soluble acrylamide polymer with 0.5 % of catalyst, 0.5 % of activator and 84 % of water. Hence the polymer solution had 15 % polymer dissolved in it. The pH of the polymer solution was 10. Hence, if 10 % of polymer solution content was used to treat the soil (based on dry weight of soil) actual amount of polymer used was 1.5 %.

3.3 Lime

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

$$\mathrm{CaO} + \mathrm{H_2O} \rightarrow \mathrm{Ca(OH)_2} + \mathrm{Heat}. \tag{2}$$

Hydrated lime ($Ca(OH)_2$) reacts with the clay particles and modifies the clay based on its mineralogy (Hassibi 1999).

3.4 Test Methods

Soil was first dried in the oven at a temperature of 60 °C followed by pulverizing and sieving to select

Table 3 Constitutive model parameters and the coefficients of variation

Parameter	M				N				L			
	K	T	F	R^2	K	T	F	R^2	K	T	F	R^2
p	−0.002	0.035	−0.12	0.99	0.004	−0.107	0.44	0.95	0.003	−0.062	0.57	0.90
q	0.001	−0.023	0.06	0.96	−0.004	0.08	−0.2	0.92	0.003	−0.062	0.57	0.88
β	0.02	−0.23	0.15	0.94	−0.6	0.87	1.66	0.91	0.02	−0.13	2.62	0.99

Table 4 Stress–strain model parameters for sulfate soil treated with polymer solution (P %)

S %	P %	Lime (%)	p–q model			β model	
			p	q	R^2	β	R^2
0	0	0	0.35	0.56	0.97	2.5	0.96
2	0	0	0.50	0.43	0.96	1.75	0.97
3	0	0	0.50	0.44	0.95	1.75	0.98
4	0	0	0.25	0.67	0.95	4	0.96
0	0	6	0.52	0.43	0.93	1.75	0.90
2	0	6	0.24	0.75	0.97	3.25	0.94
3	0	6	0.35	0.50	0.90	3	0.94
4	0	6	0.24	0.75	0.99	3.5	0.96
0	5	0	0.28	0.52	0.95	2.7	0.98
2	5	0	0.35	0.64	0.98	3.25	0.97
3	5	0	0.50	0.44	0.96	2.7	0.98
4	5	0	0.40	0.54	0.97	2.25	0.96
0	10	0	0.20	0.76	0.95	3.5	0.98
2	10	0	0.23	0.75	0.95	4.5	0.96
3	10	0	0.13	0.85	0.93	5	0.96
4	10	0	0.20	0.59	0.96	2.75	0.96
0	15	0	0.28	0.52	0.97	6	0.96
2	15	0	0.35	0.60	0.98	2.25	0.96
3	15	0	0.20	0.77	0.95	3	0.97
4	15	0	0.5	0.42	0.96	2.5	0.96

the soil finer than # 4 sieves. The pulverized soil was then mixed with different percentage of calcium sulfate and water. Sulfate contaminated soil samples were placed in moisture tight bags and cured for 7 days at room temperature before treating and testing the soil. The testing program was investigated the stress–strain relationship and split tensile test response of polymer solution according with ASTM D 2166 and ASTM C 496 respectively. A total of 40 samples were used in this study, twenty samples for each compression test and split tensile test for sulfate contaminated CL soil treated with vary percentages of polymer solution and 6 % of lime was used.

3.4.1 XRD Characterization

X-ray diffraction (XRD) was used to characterize the soil and the reaction products with 4 % calcium sulfate. The XRD patterns were obtained using the Siemens D5000 powder X-ray diffraction machine. Specimens for XRD were prepared from air-dried soils with and without contamination. The soil sample ($\approx$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. All samples were scanned for reflections (2θ) in the range 0° to 70° at a step size of 0.02° and a 2 s count time per step.

3.4.2 Standard Compaction Test

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 (ASTM D 698-91).

3.4.3 Unconfined Compression Tests

The unconfined compression tests were conducted according to ASTM D 2166. The unconfined compressive strengths were determined from the stress–strain curves. The natural CL soil contaminated with different percentage of calcium sulfate up to 4 % and the sulfate soils were modified using different percentage of polymer solution and 6 % lime were all compacted at corresponding optimum moisture content. Cylindrical steel molds, 3 in. diameter and 6 in. height were used to prepare the specimens using the compaction energy in equation, Eq. (3). The soil samples were then extruded using a hydraulic jack. The sulfate contaminated soil specimens (lime treated and untreated) were placed in moisture tight bags and placed in a 100 % humidity room for curing for 7 days at room temperature. Sulfate soil samples 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:

$$\begin{aligned}\mathrm{E} &= \big[\big(\text{No. blows per layer}\big) \times \big(\text{No. of layers}\big) \\ &\quad \times (\text{Weight of hammer}) \times (\text{Drop height})\big]/ \\ &\quad \text{Volume of Soil} \\ &= 18\ \text{blows} \times 3\ \text{layers} \times 5.5\ \text{lb} \times 1\ \text{ft}/ \\ &\quad 0.024063\ \text{ft}^3 = 12342.6\ \text{lb-ft}/\text{ft}^3. \end{aligned} \tag{3}$$

This compaction energy was comparable to that produced with the standard proctor equipment which provides about 12,370 ft-lb/ft^3 (ASTM D 698).

During the compression test the specimens were loaded to failure or until 10 % strain.

3.4.4 *Split Tensile Strength Tests*

For performing the split tensile test, 75 mm (3 in) diameter and 150 mm (6 in) height cylindrical specimens were prepared at optimum moisture content in the same manner as in case of unconfined compression tests. After curing, the cured specimens were placed horizontally between the two bearing plates of the compression testing machine adjusted for a machine displacement rate of 1.0 mm/min. The split tensile strength (σ_t) was obtained using the following relationship.

$$\sigma_t = \frac{2\mathrm{P}}{\Pi LD} \tag{4}$$

where P = failure load; L = thickness or length of specimen; and D = diameter of the specimen.

4 Results and Discussion

Based on the XRD analyses, the field soil had three peaks corresponding to calcium silicate ($CaSiO_3$), magnesium silicate (Mg_2SiO_4) and Quartz (SiO_2). With the addition of 4 % calcium sulfate, three sets of new peaks corresponding to calcium silicate sulfate (ternesite ($Ca_5(SiO_4)_2SO_4$), magnesium silicate sulfate ($Mg_5(SiO_4)_2SO_4$) and calcium magnesium silicate (merwinite $Ca_3Mg(SiO_4)_2$) were observed. Hence some of the changes observed in the contaminated soil behavior could have been due to the changes in the soil mineralogy.

4.1 Polymer Treatment

4.1.1 *Unconfined Compressive Strength (UCS)*

Increase in calcium sulfate content reduced the unconfined compressive strength of compacted soil. The compressive strength decreased from 22 psi (152 kPa) with no calcium sulfate to 17 psi (117 kPa) with 4 % calcium sulfate. The change in the strength could be attributed to the changes in the soil mineralogy due to the addition of 4 % calcium sulfate. Compacted compressive strength of a field CL soil (calcium sulfate concentration = 0 %) improved from 22 psi (152 kPa) to 152 psi (1,048 kPa) using 10 % of polymer solution after 1 day of curing. While 4 % of sulfate contaminated CL soil treated with 10 % of polymer solution the compressive strength increased by 433 % (Fig. 1).

4.1.2 *Compressive Modulus*

The compressive modulus decreased by 13 % when the calcium sulfate concentration increased from 0 to 4 % and could be attributed to the changes in the soil mineralogy. Compacted compressive modulus of a field CL soil with 0 % of calcium sulfate increased from 2.5 MPa (357 psi) to 39 MPa (5,577 psi) using 10 % of polymer solution after 1 day of curing. While 4 % of sulfate contaminated CL soil treated with 10 %

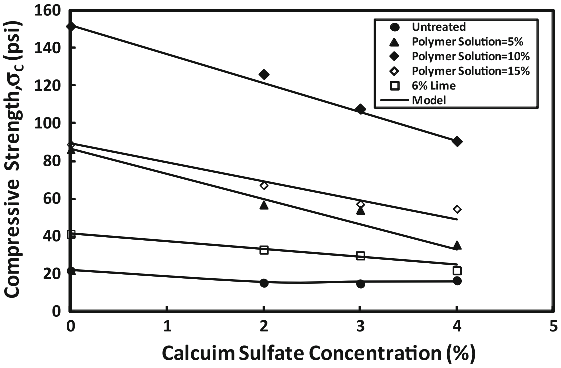

Fig. 1 Variation of compressive strength of CL soil with calcium sulfate concentration

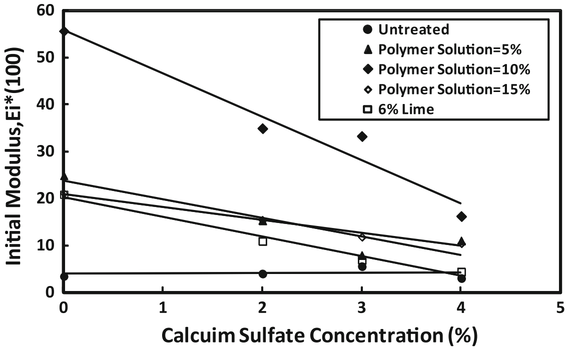

Fig. 2 Variation of initial compressive modulus of CL soil with calcium sulfate concentration

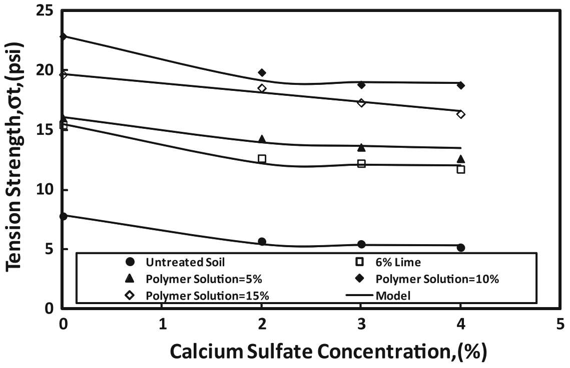

Fig. 3 Variation of tensile strength of CL soil with calcium sulfate concentration

of polymer solution the compressive modulus increased by 422 % (Fig. 2).

4.1.3 *Tensile Strength*

The tensile strength of the soil samples decreased by 33 % when the calcium sulfate concentration was increased from 0 to 4 % and could be attributed to the changes in the soil mineralogy. Also the tensile strength of the CL soil contaminated with 4 % of calcium sulfate increased by 260 % when the soil was modified using 10 % of polymer solution (Fig. 3). The ratio of tensile strength to compressive strength for uncontaminated and contaminated soil with 4 % of calcium sulfate was 0.35 and 0.3 respectively. While these ratios decreased to 0.15 and 0.21 respectively when the soils treated with 10 % polymer solution.

4.2 Lime Treatment

4.2.1 *Compressive Strength*

The unconfined compressive strength of sulfate contaminated CL soil with different concentration of calcium sulfate up to 4 % varied from to 22 to 17 psi (152–117 kPa, Fig. 1). The compressive strength of field CL soil (calcium sulfate concentration = 0 %) improved from 22 to 42 psi (1 psi = 7 kPa) using 6 % of lime after 7 days of curing. Also the compressive strength of 4 % calcium sulfate contaminated CL soil treated with 6 % lime was improved by 29 % after 7 days of curing (Fig. 1). The effects of polymer solution content and lime on the stress–strain behavior of calcium sulfate contaminated CL soils are shown in Fig. 6.

4.2.2 *Compressive Modulus*

The compressive modulus decreased from 357 psi (1 psi = 7 kPa) to 312 psi when the calcium sulfate concentration increased from 0 to 4 %. The compacted compressive modulus of a field CL soil with 0 % of calcium sulfate increased by 88 % using 6 % of lime after 7 days of curing. While 4 % of sulfate contaminated CL soil treated with 6 % of lime the compressive modulus decreased by 47 % compared to treated uncontaminated soil as shown in Fig. 2.

4.2.3 *Tensile Strength*

Based on test results, it appears that the tensile strength for samples decreased by 33 % when the calcium sulfate content changed from 0 to 4 %. Tensile strength increased by over 80 % when the soil was treated using 6 % of lime Fig. 3. The ratio of tensile strength to compressive strength for uncontaminated and contaminated soil with 4 % of calcium sulfate increased by 6 and 77 % when the soil was treated with 6 % lime.

5 Property Correlations

In order to better understand the effects of calcium sulfate content and polymer or lime content on the CL soil, it was important to quantify the property with the composition of the soil and type of treatment.

Table 5 Compressive and tensile strength model parameters for sulfate soil treated with polymer solution (P %)

Soil type	Tensile strength, σ_t Eq. (4)				Compressive strength, σ_c Eq. (9)			
	σ_{to}	A	B	R^2	σ_{co}	H	E	R^2
Untreated	7.56	−0.065	0.4	0.98	22.0	−0.03	0.178	0.95
6 % lime	15.2	0.06	0.3	0.94	41.5	0.24	0	0.96
5 % P	16.0	0.35	0.31	0.85	89.2	0.075	0	0.94
10 % P	22.5	1.3	0	0.96	152.0	0.1	0	0.95
15 % P	19.8	0.06	0.24	0.95	86.5	0.065	0	0.98

5.1 Tensile Strength

The variation of tensile strength with calcium sulfate content was represented using the proposed model (Eq. 5) and the parameters and coefficient of determination (R^2) are summarized in Table 5.

$$\sigma_t - \sigma_{to} = \frac{S(\%)}{A + BS(\%)} \tag{5}$$

$$A = -0.015(P\%)^2 + 0.23(P\%) + 0.01 \quad R^2 = 0.88 \tag{6}$$

$$B = -0.004(P\%)^2 - 0.075(P\%) + 0.41 \quad R^2 = 0.87 \tag{7}$$

where σ_t = tensile strength; σ_{to} = initial tensile strength (calcium sulfate concentration, S = 0 %), A, B = tensile strength hyperbolic constants.

The highest value of tensile strength was with 10 % of the polymer solution content for all level of sulfate content (Fig. 4a).

5.2 Compressive Strength

Results indicated that compressive strength could be represented as a function of calcium sulfate concentration and percentage of polymer solution as follows:

$$\sigma_c = f(S,\ P) \tag{8}$$

where σ_c = unconfined compressive strength of soil (psi), f = function of calcium sulfate concentration and polymer solution content, S = calcium sulfate concentration (%), P = polymer solution (%).

The compressive strength (σ_c) variation with calcium sulfate concentration is shown in Fig. 1 and was represented by the following relationship.

$$\sigma_c - \sigma_{co} = \frac{S(\%)}{H + ES(\%)} \tag{9}$$

where σ_c = compressive strength of soil (psi), σ_{co} = initial compressive strength of untreated and treated soil without sulfate (calcium sulfate concentration, S = 0 %), H, E = compressive strength hyperbolic constants.

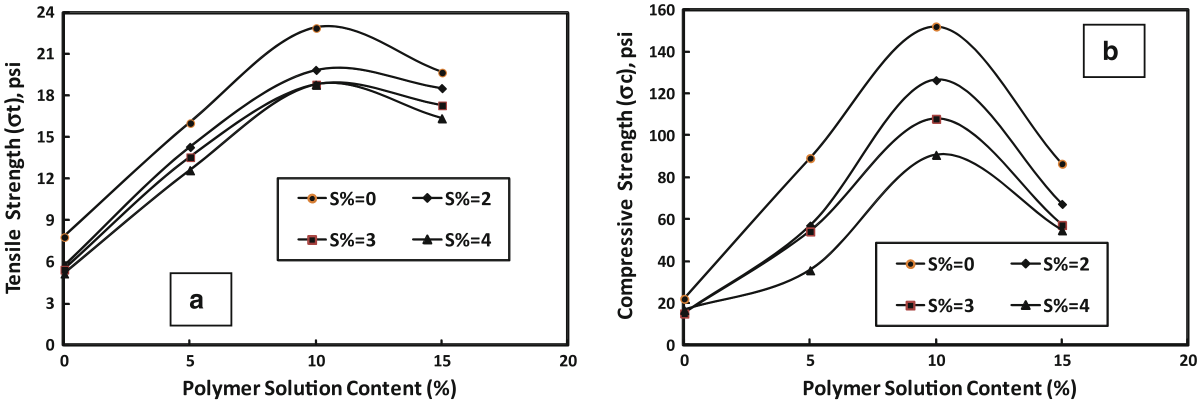

Fig. 4 Variation of strength with polymer solution content. **a** Tensile strength and **b** compressive strength

Variation of parameter H and E values with polymer solution content were investigated.

$$H = -0.014(P\%)^2 + 0.03(P\%) - 0.03 \quad R^2 = 0.99 \tag{10}$$

$$E = 0.002(P\%)^2 + 0.04(P\%) + 0.17 \quad R^2 = 0.93. \tag{11}$$

The variation of strength with calcium sulfate content was represented using the proposed model (Eq. 9) and the parameters are summarized in Table 5. The hyperbolic relationships was used to represent change in compressive strength with calcium sulfate concentration for untreated sulfate soil and treated using 6 % of lime and different percentage of polymer solution as shown in Fig. 1. The highest compressive strength was obtained with soils treated with 10 % of the polymer solution content at all level of sulfate content as shown in Fig. 4b.

5.3 Compressive Modulus

The initial modulus was almost constant when the sulfate content for the field soil increased from 0 to 4 %. The highest initial modulus was obtained when the sulfate soil with 4 % calcium sulfate was treated using 10 % of polymer solution content as shown in Fig. 2. The highest compressive strength was obtained with soils treated with 10 % of the polymer solution content at all level of sulfate content as shown in Fig. 2.

5.4 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 Fig. 6.

5.4.1 p–q Model

Based on experimental results, model proposed by Mebarkia and Vipulanandan (1992), was used to predict the stress–strain behavior of treated sulfate contaminated CL soil with different percentage of polymer solution (Eq. 12). The model is defined as follows:

$$\sigma = \left(\frac{\frac{\varepsilon}{\varepsilon_c}}{q + (1-p-q)\left(\frac{\varepsilon}{\varepsilon_c}\right) + p\left(\frac{\varepsilon}{\varepsilon_c}\right)^{(p+q)/p}} \right) \sigma_c \tag{12}$$

where σ = compressive strength, 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. Effect of parameters p and q on the shape of the stress-strain relationship are shown in Fig. 5a. Hence, parameters p and q in (Eq. 12) were determined based on the stress–strain behavior of sulfate soil treated with 10 % of polymer solution (by dry weight) and the values and coefficient of determination (R^2) are summarized in Table 4. In Fig. 6, the predicted values of compressive strength for sulfate contaminated CL soil treated with different percentage of polymer solution are compared to the 6 % lime treated soil. The polymer treated soils were much stronger and stiffer than lime treated soils. As summarized in Table 4 the parameters p and q influence by sulfate content and the method of

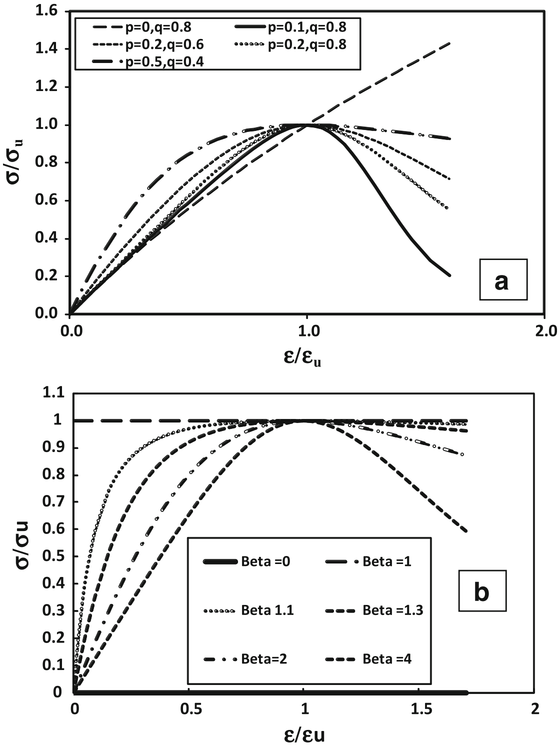

Fig. 5 Compressive stress–strain relationships. **a** p–q model and **b** β model

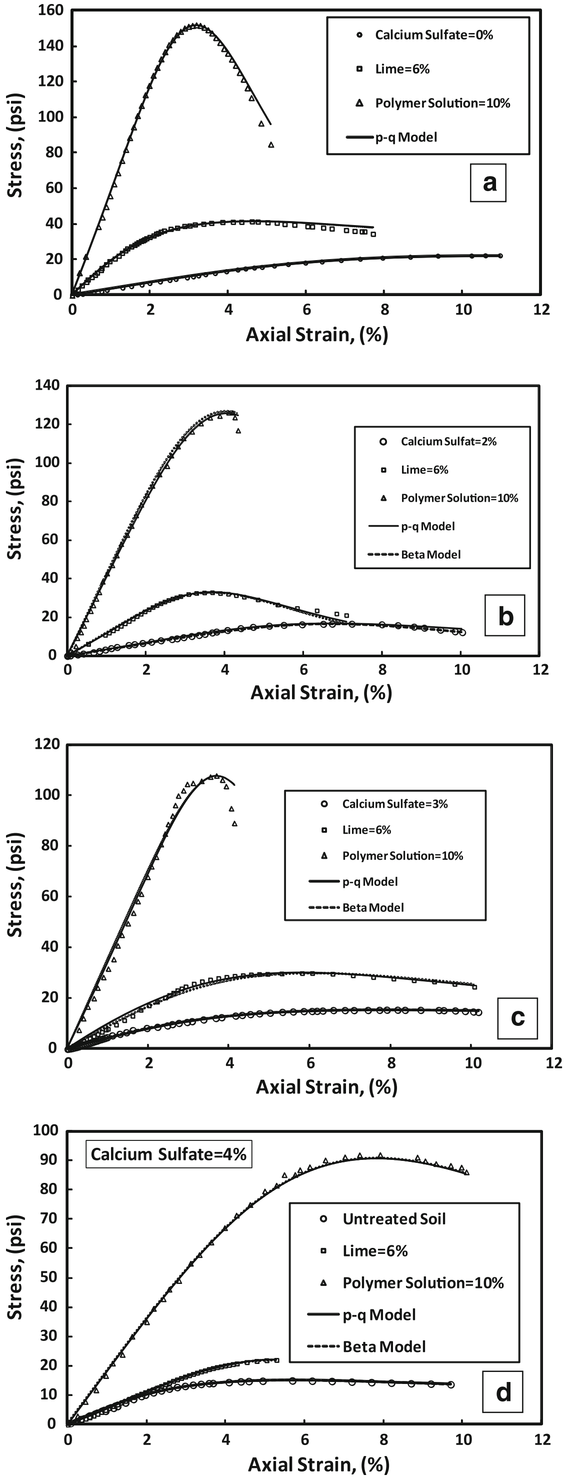

Fig. 6 Comparison of model predictions and experimental stress–strain relationship for sulfate (S) contaminated CL soil treated with 6 % of lime and 10 % of polymer solution: **a** S = 0 %, **b** S = 2 %, **c** S = 3 % and **d** S = 4 %

treatment. Hence the following relationships are proposed to relate the sulfate content and polymer content to the parameters p and q as follows:

$$p = Mp(S\%)^2 + Np(S\%) + Lp \quad (13)$$

$$q = Mq(S\%)^2 + Nq(S\%) + Lq \quad (14)$$

where Mp, Np, Lp, Mq, Nq and Lq = p–q model parameters.

Variation of Mp, Np, Lp, Mq, Nq and Lq values with polymer solution content (P %) are represent as follows:

$$Mp,\ Np,\ Lp = K(P\%)^2 + T(P\%) + F \quad (15)$$

$$Mq,\ Nq,\ Lq = K(P\%)^2 + T(P\%) + F \quad (16)$$

where parameters K, T, F and coefficient of determination (R^2) are summarized in Table 3.

Parameter q Parameter q represents the nonlinear behavior of the material up to peak stress. For calcium sulfate contaminated CL soil the parameter q was in the range of 0.43 to 0.67 (Table 4). Treating the CL soil with 10 % polymer solution increased the q parameter to be in the range of 0.59 to 0.76 (Table 4) indicating that the material behavior is more linear with polymer treatment. For lime treated soils, parameter q varied from 0.43 to 0.75, covering a larger range than 10 % polymer treated soil.

Parameter p For untreated soils the parameter p varied from 0.25 to 0.5. Soil treated with 10 % polymer solution content the parameter p varied from 0.13 to 0.23. Hence the descending part of the strain softening stress–strain relationship for the polymer treated soils were steeper compared to the untreated soils. For lime treated soils the parameter p range was 024 to 0.52, similar to the untreated soils (Fig. 6).

5.4.2 β Method

Ezeldin and Balaguru (1992) proposed an analytical equation (Eq. 17) to generate the stress–strain curve for normal strength of steel fiber reinforced concrete based on the equation proposed by Carreira and Chu (1985) for uniaxial compression of plain concrete. This equation involves a material parameter β, which is the slope of the inflection point at the descending branch of the shear stress relationship.

$$\sigma = \left(\frac{\beta\left(\frac{\varepsilon}{\varepsilon_c}\right)}{\beta - 1 + \left(\frac{\varepsilon}{\varepsilon_c}\right)^{\beta}} \right) \sigma_c \tag{17}$$

where σ = compressive strength, σ_c, ε_c = compressive strength and corresponding strain, β = material parameter. Effect of parameter β on the stress-strain relationships are shown in Fig. 5b.

Stress–strain relationship for sulfate soil modified using polymer solution and lime and the model predication are shown in Fig. 6.

From Eq. (12), if (p + q = 1) then the relationship is as follows. Then:

$$\sigma = \left(\frac{\frac{\varepsilon}{\varepsilon_c}}{q + p\left(\frac{\varepsilon}{\varepsilon_c}\right)^{\frac{1}{p}}} \right) \sigma_c \tag{18}$$

if ($p = 1/\beta$) then Eq. (18) is represented as follows:

$$\sigma = \left(\frac{\frac{\varepsilon}{\varepsilon_c}}{\left(1 - \frac{1}{\beta}\right) + \frac{1}{\beta}\left(\frac{\varepsilon}{\varepsilon_c}\right)^{\beta}} \right) \sigma_c = \left(\frac{\beta\left(\frac{\varepsilon}{\varepsilon_c}\right)}{\beta - 1 + \left(\frac{\varepsilon}{\varepsilon_c}\right)^{\beta}} \right) \sigma_c \tag{19}$$

Hence β-method (Eq. 17) is a special case of the p–q model (Eq. 12).

The relation between parameter β and the calcium sulfate concentration is as follows:

$$\beta = M_\beta (S\%)^2 + N_\beta (S\%) + L_\beta \tag{20}$$

where M_β, N_β, L_β = β-model parameters that depend on the polymer content.

Based on the test results, the relations of parameter β with percentage of polymer solution are as follows:

$$M_\beta,\ N_\beta,\ L_\beta = K(P\%)^2 + T(P\%) + F \tag{21}$$

The parameters K, T, F and coefficient of determination (R^2) are summarized in Table 3.

Parameter β For untreated contaminated soil parameter β varied from 1.75 to 4. With 10 % of polymer solution treatment the parameter β varied from 2.75 to 5 indicating faster descending after the peak stress. For the lime treated soil the parameter b range was 1.75 to 3.5, similar to untreated soil.

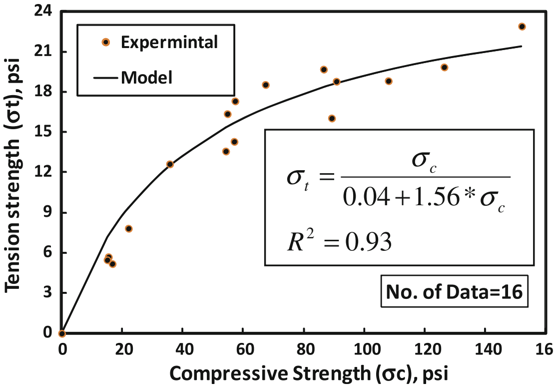

Fig. 7 Relationship between tensile strength and compressive strength of polymer treated sulfate contaminated soil

6 Correlation between Compressive and Tensile Strengths

Polymer solution stabilized sulfate soil samples were subjected to indirect tensile test, also known as the Brazilian test. Hence in this study, compressive strength (σ_c) was related to tensile strength (σ_t). Based on the test results of the variation of tensile strength with the compressive strength (Fig. 7) was represented as the following non-linear hyperbolic relationship.

$$\sigma_t = \frac{\sigma_c}{0.04 + 1.56\sigma_c} \quad R^2 = 0.93 \tag{22}$$

$$\sigma_t \geq 0.1\sigma_c \quad \text{For Concrete} \tag{23}$$

Hence the tensile strength of sulfate contaminated CL soil, with and without treatment was higher than the 10 % of compressive strength, which relationship is generally used for cement concrete (Eq. 23).

7 Conclusions

In this study, the effectiveness of polymer treatment of sulfate contaminated soil was compared to lime treated CL soil. XRD analyses showed that the major constituents of the soil were calcium silicate ($CaSiO_3$), magnesium silicate (Mg_2SiO_4) and Quartz (SiO_2). Based on the laboratory tests and modeling the compressive and tensile behavior of treated sulfate contaminated CL soil, the following conclusions are advanced:

1. The compressive strength and tensile strength of CL soil decreased with increased sulfate content. With 4 % calcium sulfate contamination the compressive strength and tensile strength of the soil decreased by 22 and 33 % respectively. With the addition of 4 % calcium sulfate, changes in soil mineralogy was observed and the new constituents were calcium silicate sulfate (ternesite ($Ca_5(SiO_4)_2SO_4$), magnesium silicate sulfate ($Mg_5(SiO_4)_2SO_4$) and calcium magnesium silicate (merwinite $Ca_3Mg(SiO_4)_2$). Hence some of the changes observed in the contaminated soil behavior could have been due to the changes in the soil mineralogy.
2. Polymer solution treatment substantially improved the compressive and tensile behavior of the sulfate contaminated CL soil. Hyperbolic relationship was used to predict the changes in the compressive and tensile strengths of the treated contaminated sulfate soils with different percentages of polymer solution.
3. Polymer solution treatment showed much higher enhancement in the strengths and modulus of sulfate contaminated soils compared to the lime treatment. Also the polymer solution treatment enhanced the sulfate contaminated soil properties much more rapidly compared to the lime treated soils. Adding the low viscous polymer solution to the soil would have coated the soil particles and when gelled in place would have formed the polymer network with soil embedded in it resulting in enhanced soil properties.
4. Nonlinear stress–strain models were used to predicate the behavior of polymer and lime treated sulfate contaminated soils. The model parameters were sensitive to the type of treatment.

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