CHARACTERIZING THE BEHAVIOR OF POLYMER AND LIME TREATED SULFATE CONTAMINATED CL SOIL

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Abstract

In this study, the effect of calcium sulfate content on the index properties, compacted soil properties and compressive strength of a CL soil obtained from the field was investigated. The calcium sulfate concentration in the soil was varied up to 4% (40,000 ppm) and the soil samples were cured for seven days at 25°C and 100% humidity before testing. With 4% sulfate contamination the liquid limit (LL) and plasticity index (PI) of the soil increased by 44% and 80% respectively. Maximum dry density decreased by 7% with 4% of calcium sulfate and also the optimum moisture content increased by 24% with 4% of calcium sulfate. With 4% calcium sulfate contamination the compressive strengths of the compacted soils decreased by 25% and 34% respectively and with polymer treatment these properties were substantially improved. Based on literature review, the sulfate contaminated soil was treated with 6% lime. During this study over 100 tests were performed to characterize the sulfate contaminated CL soil. Stress-strain relationships, index properties and compaction properties of the sulfate soil with and without lime and polymer treatment have been quantified using two nonlinear constitutive models. Also the model predications of index properties and compaction properties were compared with other published data in the literature. The variation of the compacted compressive strength with calcium sulfate concentrations for treated soils was quantified and the parameters were related to sulfate content in the soil and polymer content.

Keywords: Calcium sulfate, Index properties, Compaction, Polymer solution, Lime, Compressive strength.

Introduction

Natural sulfate rich soils are found in many parts of the world and are considered a challenge in engineering projects (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 problems occur when natural sulfate soils are stabilized with calcium-based chemicals such as lime and Portland cement (Hunter 1988; Mitchell and Dermatas 1990; Petry and Little 1992). Annual infrastructure related repair costs from sulfate heave damages are reported to be millions of dollars (Mitchell and Dermatas 1990; Petry and Little 1992; Kota et al. 1996). The majority of the sulfates heave distress problems have been reported in Texas, Nevada, Louisiana, Kansas, Oklahoma, and Colorado where lime, fly ash and cement have been traditionally used to stabilize natural soil subgrades rich with sulfates (Kota et al. 1996; Rollings et al. 1999). The increasing sulfate heave problems in construction projects, with and without lime treatment, calls for developing better treatment methods. These methods should mitigate the formation of ettringite minerals in sulfate soils and thereby decrease heave potentials of sulfate soils (Puppala 2004).

Arabani (2007) observed that any increase in lime content beyond 6 % had a negligible effect on the compressive strength of treated clay soil. However, an increase in lime content up to 6 percent resulted in a noticeable increase in compressive strength. In fact, it has been shown that with the additions of over 6% lime, the decreases in strength can be quite significant (Al-Rawi 1981). According to the studies summarized in Table 1 most of the specimens were prepared and tested near optimum moisture content (OMC %). Mainly 6% lime has been used to treat the clay soil (Table 1). The ettringite formation can be represented by the following relationship (Sivapullaiah 2002):

$$6Ca^{2+} + 2Al(OH)^{-}_{4} + 4(OH)^{-} + 3(SO_4)^{2-} + 26H_2O \longrightarrow Ca_6[Al(OH)_6]_{2}.(SO_4)_{3}.26H_2O \text{ ....(1)}$$

[Additive]+ [Clay] + [Contaminant] + [Water] ⟶ [Formation of Ettringite]

The formation of ettringite minerals in treated soils (Eqn. 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 same treated soils. If not addressed immediately, this heave will further deteriorate the structures to a condition where they need immediate and extensive rehabilitation (Mitchell and Dermatas 1990; Petry and Little 1992). Lime stabilization technique should be cautiously applied in sulphate enriched environment or clay soils containing sodium sulfate (Pillai et al. 2007). Hence alternative methods have to be developed.

Objectives

The overall objective was to quantify the changes in the properties of a field CL soil contaminated with varying percentage of calcium sulfate up to 4%. Also of interest was to investigate the treatment of sulfate contaminate soil with a polymer solution and lime. The specific objectives are as follows:

(i) Quantify the changes in the index properties and compaction properties of a CL soil with vary amount of calcium sulfate with and without treatment.

(ii) Compare the compressive strength behavior of polymer treated sulfate contaminated soil to lime treated soil.

(iii) Quantify the stress-strain relationships of clay soil contaminated with calcium sulfate up to 4%, and treated with a polymer solution and lime.

Materials and Methods

(a) Soil

Field clay soil sample was used in preparing the sulfate soil. Physical properties of the selected clay soil were determined from Atterberg limit tests, grain size distribution, hydrometer tests and standard proctor compaction tests according to ASTM standard. These results are summarized in Table 2.

(b) Hydrated Lime

Lime for ground improvement applications is typically used in the form of quicklime (CaO) or Hydrated lime ($Ca(OH)_2$). Quicklime (CaO) is manufactured by a chemical process transforming calcium carbonate (limestone – $CaCO_3$) into calcium oxide (CaO) (Hassibi 2009). When quicklime reacts with water it transforms into hydrated lime as follows:

$$CaO + H_2O \longrightarrow Ca(OH)_2 + \text{Heat} \quad \text{...................... (2)}$$

Hydrated limes ($Ca(OH)_2$) react with the clay particles and modify the clay based on its mineralogy. The soil stabilization with lime occurs through pozzolanic reaction causing a long-term strength gain. The calcium from the lime reacts with the aluminates and silicates from the clay producing stabilization along with hydration process.

(c) Polymer

Polymer solution was prepared by mixing 15% of water soluble acryamide 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 tread the soil (based on dry weight of soil) actual amount of polymer used was 1.5%.

(d) Test Methods

Soil was first dried in an oven at a temperature of 60°C, crushed, sieved and pulverized to sizes finer than # 4 sieves. The pulverized soil was then mixed with different percentage of calcium sulfate and water. Soil samples were placed in moisture tight bags and cured for 7 days at room temperature before testing.

Atterberge limits, standard compaction tests and compressive strength were conducted on contaminated soil with different percentages (by weight) of calcium sulfate up to 4%. Sulfate soils were treated with 6% of lime and varying amount of polymer solutions.

The test specimens were prepared by compacting the soil in three layers with eighteen blows per layer. For the volume of the test mold the specific compaction energy applied was as follows:

$$\mathbf{E} = \frac{(\text{No.blows per layer}) * (\text{No. of layers}) * (\text{Weight of hammer}) * (\text{Height of drop of hammer})}{\text{Volume of mold}} \ldots (3)$$

$$\mathbf{E} = \frac{18 * 3 * 5.5\text{Ib} * 1\text{ft}}{0.024063\text{ft}^3} = 12342.6 \frac{\text{Ib.ft}}{\text{ft}^3}$$

This compaction energy was comparable to that produced with the proctor standard equipment which provides approximately 12370 ft-Ib/ft^3 (Rodriguez 2007). During the compression test the specimens were loaded to failure or until 10% strain.

Unconfined compression tests were conducted on the compacted soil according to ASTM D 2166. The unconfined compressive strengths were determined from the stress–strain relationships. 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 inches diameter and 6 inches height were used to prepare the specimens using the compaction energy in equation, Eqn (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.

Behavior Modeling

(i) Hyperbolic Model

Relationship between index properties, compaction properties, compaction properties and compressive strength of the soil with and without treatments of sulfate-contaminated soil was investigated. Based on the inspection of the test data following relationship is proposed.

$$Y - Y_o = \frac{X}{A + B * X} \quad \ldots\ldots\ldots (4)$$

Where:

Yo: is the soil property without contamination with calcium sulfate (natural CL soil).

A and B: are model parameters (Table 3).

X: is the calcium sulfate concentration.

Based on the experimental results the trends were either linear or nonlinear with the calcium sulfate content. As shown in fig. (1), relationship proposed in Eqn. (4) can be used to represent various linear and nonlinear trends based on the values of the parameters A and B. When parameters A and B are positive the relationship was hyperbolic. Linear relationship is represented by Eqn. (4) when B=0 and A will take any value. When parameters A and B are negative the inverse hyperbolic relationship is obtained Fig. (1).

(ii) p-q Model

Soils are modeled as linear elastic, linear plastic - perfectly plastic or strain hardening materials. In this study the soil with and without treatment, strain softening soil behavior was observed.

Based on experimental results and following the procedure proposed by Mebarkia and Vipulanandan (1992). The two parameter stress - strain relationship (Eqn. 5) was used to predict the stress- strain behavior of treated sulfate contaminated CL soil with different percentage of polymer solution. The model is defined as follows:

$$\sigma = \left(\frac{\frac{\varepsilon}{\varepsilon_c}}{q + (1-p-q)\left(\frac{\varepsilon}{\varepsilon_c}\right) + p * \left(\frac{\varepsilon}{\varepsilon_c}\right)^{\frac{p+q}{p}}} \right) * \sigma_c \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

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. Hence, parameters p and q in (Eqn.5) were determined based on the stress- strain behavior of sulfate soil treated with different percentages of polymer solution up to 15% (by dry weight) and the values and coefficient of determination (R^2) are summarized in Table (4). In the Fig. (7), 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.

The p and q values were obtained by comparing the descending portion of the standard curves Fig.(2).

$$p = Mp(S\%)^2 + Np(S\%) + Lp \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

$$q = Mq(S\%)^2 + Nq(S\%) + Lq \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

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 %) as follows was investigated:

Mp, Np and Lp $= K(P\%)^2 + T(P\%) + F$ .... (8)
Mq, Nq and Lq $= K(P\%)^2 + T(P\%) + F$ .... (9)

The parameters K, T, F and coefficient of determination (R^2) are summarized in Table 5.

Results and Analyses

(a) Liquid Limit (LL)

Additional of calcium sulfate to the natural CL soil increased the liquid limit and the change was nonlinear Fig.4 (a). When the calcium sulfate content in the soil was 4%, the liquid limit increased from 40% to 57%. The change in the LL with calcium sulfate concentration was represented using hyperbolic relationship (Eqn. (4)) and the parameters A and B are summarized in Table 3, and the coefficient of determination (R^2) for the relationship was 0.94. Total of 19 data were collected from various research studies and the liquid limit varied from 31 to 73% with a mean and standard deviation of 52.3% and 13.2 respectively. The collected data from the literature are compared to the model prediction and 47% of these data located above the model prediction (Fig.3(a)). Addition of 10% of polymer solution and 6% of lime to the sulfate soil with 4% of calcium sulfate decreased the liquid limit by 67% and 14% respectively. Nonlinear trends were observed between the LL and calcium sulfate concentration of sulfate soils modified using polymer solution and 6% of lime (by dry weight) (Fig.4 (a)).

(b) Plasticity Index (PI)

Plasticity index of natural CL soil increased from 19% to 34% by increasing calcium sulfate content to 4%. Total of 17 data were collected from various research studies and the plasticity index varied from 14 to 48% with a mean and standard deviation of 22.2% and 11.3 respectively. About 65% of the research data located below the model prediction (Fig.3 (b)). Plasticity index of the natural soil contaminated with 4% of calcium sulfate decreased by 66% and 25% when the sulfate soil modified using 10% of polymer solution and 6% of lime (by dry weight) respectively (Fig.4 (b)). In this study Total of 20 soil samples were tested. Hyperbolic relationship was observed between the plasticity index versus calcium sulfate concentration for treated and untreated sulfate soil (Fig.4 (b)). The parameters A and B for untreated sulfate soil and treated using 6% of lime and varying amount of polymer solution are summarized in Table 3 coefficient of determination (R^2) for the hyperbolic relationships for untreated and treated sulfate were > 0.95.

(c) Compacted Soil

Optimum moisture content for the field CL soil increased from 17% to 21.1% when the calcium sulfate concentration increased from 0% to 4% (Fig.5 (a)). About 33% of total 17 data of (OMC %) versus calcium sulfate concentration from various research studies on the sulfate soils behavior with a mean and standard deviation of 20 and 4.5 respectively located below the model predication (Fig.5 (a)). Additional of 6% lime and 10% of polymer solution (by dry weight) to the sulfate soil with 4% of calcium sulfate decreased the (OMC %) by 6% and 20% respectively (Fig.6(a)). Nonlinear trends were observed between the (OMC %) versus calcium sulfate concentration for untreated and modified soils using 10% of polymer solution and 6% of lime (by dry weight) (Fig.6 (a)). The model parameters A and B for untreated sulfate soil and treated with 10% of polymer solution and 6% of lime and coefficient of determination (R^2> 0.9) are summarized in Table 3.

Dry density of natural CL soil decreased by 5% when the calcium sulfate concentration changed from 0 to 4 % (Fig.5 (b)). All of the total 16 data of maximum dry density versus calcium sulfate concentration from various research studies with a mean and standard deviation of 1.66 (gm/cm^3) and 0.11 respectively located above current results (Fig. 5 (b)). Maximum dry density of sulfate soil with 4% calcium sulfate concentration increased 8% and 2% by using 10% of polymer solution and 6% of lime respectively (Fig.6 (b)). Inverse hyperbolic relationships (parameters A and B in Table 3 are negative) are obtained between maximum dry density versus calcium sulfate concentration for untreated sulfate soil and treated using 10% of polymer solution and 6% of lime (by dry weight) (Fig.6 (b)).

(d) Compressive Strength

(i) Polymer Treatment

Increase in calcium sulfate content reduced the 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 Fig.(7). Compacted compressive strength of a field CL soil (calcium sulfate concentration=0%) improved from 22 psi (152 kPa) to 152 psi (1048 kPa) using 10% of polymer solution after one day of curing an improvement of over 500%. For 4% of sulfate contaminated CL soil treated with 10% of polymer solution the compressive strength increased by over 430% Fig. (7).

(ii) Lime Treatment

The compressive strength of field CL soil (calcium sulfate concentration=0%) improved from 22 psi to 42 psi (1psi=7kPa) using 6% of lime after 7 days of curing, an improvement of about 100%. 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.(7)).

Compressive Strength Model

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

$$\sigma_c = f(S, P) \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

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 shown in Fig. (8) was represented by the following relationship.

$$\sigma_c - \sigma_{c_o} = \frac{S\,(\%)}{D + E * S(\%)} \ldots\ldots\ldots\ldots \quad (11)$$

Where:

σ_c = compressive strength of soil (psi).

σ_{c_o}= initial compressive strength of untreated and treated soil without sulfate (calcium sulfate concentration, S=0%).

D, E = compressive strength hyperbolic constants.

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

$$D = -0.014\,(P\,\%)^2 + 0.03\,(P\,\%) - 0.03 \qquad R^2=0.99 \ldots\ldots\ldots\ldots \quad (12)$$

$$E = 0.002\,(P\,\%)^2 - 0.04\,(P\,\%) + 0.17 \qquad R^2=0.93 \ldots\ldots\ldots\ldots (13)$$

The variation of strength with calcium sulfate content was represented using the proposed model (Eqn. (11)) and the parameters are summarized in Table (6). 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 Fig.(8).

Conclusions

In this study the effect of sulfate content on a CL soil was investigated. Over 100 tests were performed during this study. Based on the laboratory tests and modeling analysis of compressive strength of treated CL soil contaminated with varying percentage of calcium sulfate up to 4% with vary polymer solution content up to 15% and 6 % of lime , the following conclusion can be advanced:

1. With 4% calcium sulfate contamination the compressive strength and tensile strength of the soil decreased by 25%.
2. Liquid limit of natural CL soil increased from 40% to 57% with the addition of 4% calcium sulfate. Adding 6% lime and 10% polymer to the 4% sulfate soil decreased the LL by 12% and 22% respectively.
3. Plasticity index of the CL soil increased by 79% with 4% calcium sulfate content. The plasticity index for 4% sulfate contaminated soil was reduced by 16% and 25% when treated with 6% lime and 10% polymer solution respectively.
4. Compressive stress- strain relationship was affected by sulfate content in the soil. Unconfined compressive strength of the CL decreased with increased sulfate content. Addition of 4% calcium sulfate to the soil decreased the strength by 25%. The unconfined compressive strength of 4% sulfate soils increased with 6% lime and 10% polymer solution treated soil by 29% and 430% respectively.
5. The hyperbolic model was effective in predicting the changes in the sulfate contaminated CL soil with and without treatment.
6. The p-q model predicated the stress - strain relationship of untreated and treated sulfate soil very well. Based on the q parameter, polymer treatment improved the linear behavior of the treated soil.

Reference

1. *Agus, M. (2002). "Utilization of uncontrolled burnt rice husk ash in soil improvement." Civil Engineering Dimension, Vol. 4, No. 2, pp.100-105.*
2. Al-Rawi, N.M. (1981). "The effect of curing temperature on lime stabilization". Proceedings of the 2nd Australian Conference on Engineering Materials, Sydney, pp. 611-662.
3. Al-Rawas, A., Hago, A.W. and Al-Sarmi, H. (2005). "Effect of lime, cement and Sarooj (artificial pozzolan) on the swelling potential of an expansive soil from Oman." Building and Environment, Vol. 40, No. 5, pp. 681–687.
4. Amy, B. and Miller, G. (2009). "Calcium-based stabilizer induced heave in Oklahoma sulfate bearing soils. " Final report – FHWA-OK-11-03, pp.1-9.
5. Arabani, M. and Veis, M. (2007)." Geomechanical properties of lime stabilized clayey sands "The Arabian Journal for Science and Engineering, Vol. 32, No. 1B, pp. 11-25.

6. Aravind, P., Chittoori, S. and Puppala, A. J. (2011).” Influence of mineralogy and plasticity index on the stabilization effectiveness of expansive clays”. Transportation Research Record, Journal of the Transportation Research Board, Washington, DC, pp. 91-99.
7. Arvind, K., Walia, B and Bajaj, A. (2007).” Influence of fly ash, lime, and polyester fibers on compaction and strength properties of expansive soil.” Journal of Materials in Civil Engineering, ASCE, pp.242-248.
8. Bell, G. (1996). “Lime stabilization of clay minerals and soils.” Engineering Geology. Vol. 42, pp. 223-237.
9. Chakkrit, S. (2008)." Novel stabilization methods for sulfate and non-sulfate soils" Doctor of Philosophy, University of Texas at Arlington, pp.1-294.
10. Hassibi, M. (1999). "An overview of lime slaking and factors that affect the process" (Paper presented at the 3rd International Sorbalit Symposium, New Orleans, LA, November 3-5, Vol.19.
11. Harris, P., Tom, S. and Stephen, S. (2004)” Hydrated lime stabilization of sulfate-bearing soils in Texas.” Texas Department of Transportation, FHWA/TX-04/0-4240-2, pp.1-36.
12. Hunter, D. (1988). ‘‘Lime-induced heave in sulfate-bearing clay soils.’’ Journal Geotech. Engineering, Vol.114, No.2, pp.150–167.
13. Kota, P., Hazlett, D. and Perri, L. (1996). ‘‘Sulfate-bearing soils: problems with calcium based stabilizers.” Transportation Research Record 1546, Transportation Research Board, Washington, D.C, pp. 62-69.
14. Little, D., Syam, N. and Herbert, B. (2010).” Addressing Sulfate-Induced Heave in Lime Treated Soils.” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, pp. 110-118.
15. Luan, M., Jia, C. and Yu, Y. (2006). “Swell potential and strength of expansive soils modified by Surfactant.” Geotechnical and Geoenvironmental Engineering, ISBN7, pp. 5611-2813.
16. McCarthy, J. , Csetenyi, J., Sachdeva, A. and Dhir, K. (2012)” Identifying the role of fly ash properties for minimizing sulfate-heave in lime-stabilized soils ” Fuel 92, pp. 27–36.
17. Mebarkia, S., and Vipulanandan, C. (1992). “Compressive Behavior of Glass-fiber-reinforced Polymer Concrete.” J. Mater. Civ. Eng.,Vol. 4, No.1,pp.91–105.
18. Michael, M., Laszlo, C. Jones, M. and Sachdeva, A. (2011).” Clay-lime stabilization: characterizing fly ash effects in minimizing the risk of sulfate heave.” World of Coal Ash (WOCA) Conference, Denever, Co., USA, pp.1-15.
19. Mitchell, K. and Dermatas, D. (1992). “Clay Soil Heave Caused by Lime-Sulfate Reactions. Innovations in Uses for Lime.” ASTM STP 1135, American Society for Testing and Materials (ASTM), Philadelphia, PA, pp. 41-64.
20. Petry, M. and Little, D. (1992). ‘‘Update on sulfate-induced heaven treated clays; problematic sulfate levels.’’ Transportation Research Record 1362, National Research Council, Washington, D.C, pp.51–55.
21. Pillai, A., Abraham, B. and Sridharan A., (2007)." Determination of Sulphate Content in Marine Clays." Research and Applications (IJERA), Vol. 1, No. 3, pp.1012-1016.
22. Puppala, A. J., Viyanant, C., Kruzic, and Perrin, L. (2002). ‘‘Evaluation of a modified sulfate determination method for cohesive soils.’’ Geotechnical Test Journal, Vol.25, No.1, pp.85–94.

23. Puppala, A. J., Julie, A., Laureano, R. and Suppakit, C.(2004) "Studies on sulfate-resistant cement stabilization methods to address sulfate-induced soil heave." Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol.130, pp.1-12.
24. Puppala, A. J., Rupesh, K., Raja, S. and Laureano, R. (2006). “Small-strain shear moduli of chemically stabilized sulfate-bearing cohesive soils.” Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol.132, No.3, pp.322-336.
25. Rodríguez, A., (2007)." Engineering Behavior Of Soft Clays Treated with Circulating Fluidized Bed Combustion Fly Ash." Master Thesis, University of Puerto Rico, pp.1-148.
26. Rollings, R., Burkes, J., and Rollings, M. (1999). ‘‘Sulfate attack on cement-stabilized sand.’’ Geotechnical and Geoenvironmintal. Engineering, Vol. 125, No.5, pp.364–372.
27. Sivapullaiah, P., Sridharan, A. and Ramesh, H.N. (2000).” Strength behavior of lime treated soils in the presence of Sulphate.” Canadian Geotechnical Journal, Vol.37, pp.1-10.

Table 1 Summary of Clay Soil Stabilization Studies

Reference	Soil Type	Stabilizer	Application	% of Stabilizer (by Dry Weight)	Curing Time (days)	Curing Temperature, Humidity	Water Content for Study
Sivapullaiah et al. (2002)	CL	Lime	Sulfate soil	6	7 & 30	not specified	*OMC
Agus (2002)	CH	Lime	Expansive clay	2,4,6&10	0	not specified	OMC
Harris et al. (2004)	Clay	Lime	Sulfate soil	6	1	25°C	OMC
Al-Rawas (2005)	MH	Lime	Expansive clay	3,6,9	0	not specified	OMC
Luan (2006)	CH	Lime	Expansive clay	6&8	7	25°C	OMC
Puppala et al. (2006)	Clay	Lime	Sulfate soil	4	not specified	(25-40)°C	OMC
Aravind et al. (2011)	CH,CL	Lime	Expansive clay	6&8	2	40°C	OMC
Remarks	Clay soils	Mainly lime was used	Expansive and sulfate soils	Mainly 6% of lime	Up to 30 days	Up to 40°C and 100% Humidity	Mainly OMC was used

**OMC: Optimum Moisture Content – (Standard Compaction)*

Table 2. Test Methods and Physical Properties of CL Soil

Property	Test Method	Value
Passing Sieve #200 (%)	ASTM D 6913	64
Specific gravity	ASTM D 854	2.66
LL (%)	ASTM D 4318	40
PI (%)	ASTM D 4318	19
OMC (%)(Standard Compaction)	ASTM D 698	16.5
Max. Dry Density (gm/cm^3)	ASTM D 698	1.52
Sand (%)	ASTM D 6913	36
Silt (%)	ASTM D 6913	45
Clay (%)	ASTM D 6913	19

Table 3. Model Parameters for Treated and Untreated Soil Contaminated with Calcium

Treatmen		Soil Property (Y)	Figure	Yo	A	B	R^2
Untreated		LL	4(a)	40	0.04	0.05	0.94
		PI	4(b)	19	0.04	0.06	0.92
		OMC (%)	6(a)	17	0.21	0.2	0.95
		γ_{dmax}.(gm/cm^3)	6(b)	1.52	-6.45	-9.18	0.92
		Compressive Strength (psi)	7	22	-0.03	-0.18	0.95
Polymer Solution	5%	LL	4(a)	23	-0.18	-0.45	0.99
		PI	4(b)	13.6	-1.08	-0.08	0.99
		OMC (%)	6(a)	15.3	-0.3	-0.3	0.99
		γ_{dmax}.(gm/cm^3)	6(b)	1.6	28.7	5.33	0.97
		Compressive Strength (psi)	7	89.2	0.075	0	0.94
	10%	LL	4(a)	11	-0.2	-0.09	0.99
		PI	4(b)	10	-0.6	-0.13	0.99
		OMC (%)	6(a)	12.2	-0.2	-0.18	0.99
		γ_{dmax}.(gm/cm^3)	6(b)	1.62	24.44	8.12	0.94
		Compressive Strength (psi)	7	152	0.1	0	0.95
	15%	LL	4(a)	14.3	-0.4	-0.075	0.99
		PI	4(b)	7.6	-0.85	-0.04	0.99
		OMC (%)	6(a)	12	-0.35	-0.3	0.99
		γ_{dmax}.(gm/cm^3)	6(b)	1.61	14.2	5.5	0.99
		Compressive Strength (psi)	7	86.5	0.065	0	0.95
6% Lime		LL	4(a)	37	-0.28	-0.005	0.96
		PI	4(b)	15.7	-0.14	-0.05	0.98
		OMC (%)	6(a)	17.6	-0.27	-0.0155	0.99
		γ_{dmax}.(gm/cm^3)	6(b)	1.54	13.3	10.74	0.98
		Compressive Strength (psi)	7	41.5	0.24	0	0.96

Table 4. Stress- Strain Model Parameters for Sulfate Soil Treated Using Polymer Solution (P%)

S%	P %	Lime (%)	p-q Model		
			p	q	R^2
0	-	-	0.35	0.56	0.97
2	-	-	0.50	0.43	0.96
3	-	-	0.50	0.44	0.95
4	-	-	0.25	0.67	0.95
0	-	6	0.52	0.43	0.93
2	-	6	0.24	0.75	0.97
3	-	6	0.35	0.50	0.90
4	-	6	0.24	0.75	0.99
0	10	-	0.20	0.76	0.95
2	10	-	0.23	0.75	0.95
3	10	-	0.13	0.85	0.93
4	10	-	0.20	0.59	0.96

Table 5. Coefficients of Variation

	M				N				L			
Parameter	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

Table 6. Compressive Strength Model Parameters for Sulfate Soil Treated Using Polymer Solution (P %)

Soil Type	Compressive Strength, σ_c Eqn.(11)			
	σ_{co}	D	E	R^2
Untreated	22.0	-0.03	0.18	0.95
6% Lime	41.5	0.24	0	0.96
5% P	89.2	0.075	0	0.94
10% P	152.0	0.1	0	0.95
15% P	86.5	0.065	0	0.95

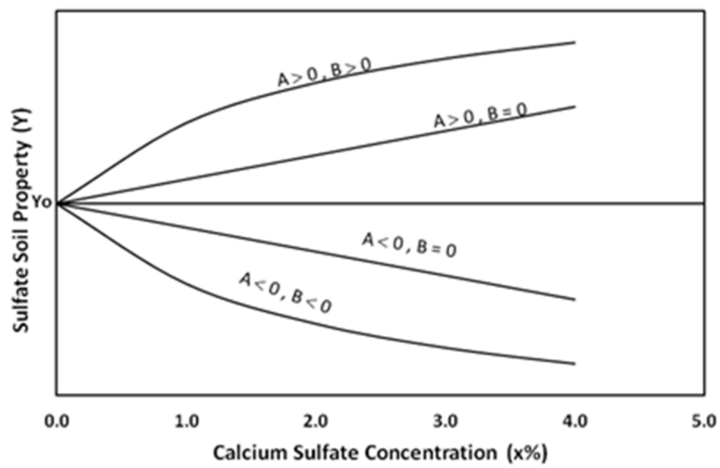

Figure 1. Modeling the Linear and Non Linear Responses of Treated Sulfate Soils

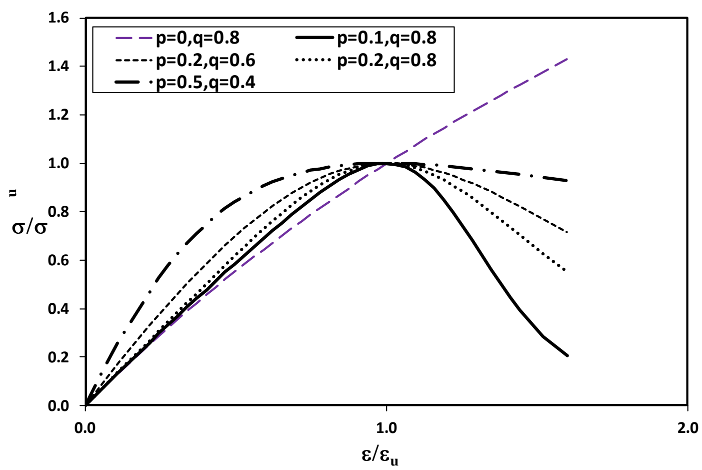

Figure 2. Compressive Stress- Strain Relationship using (p-q) Model

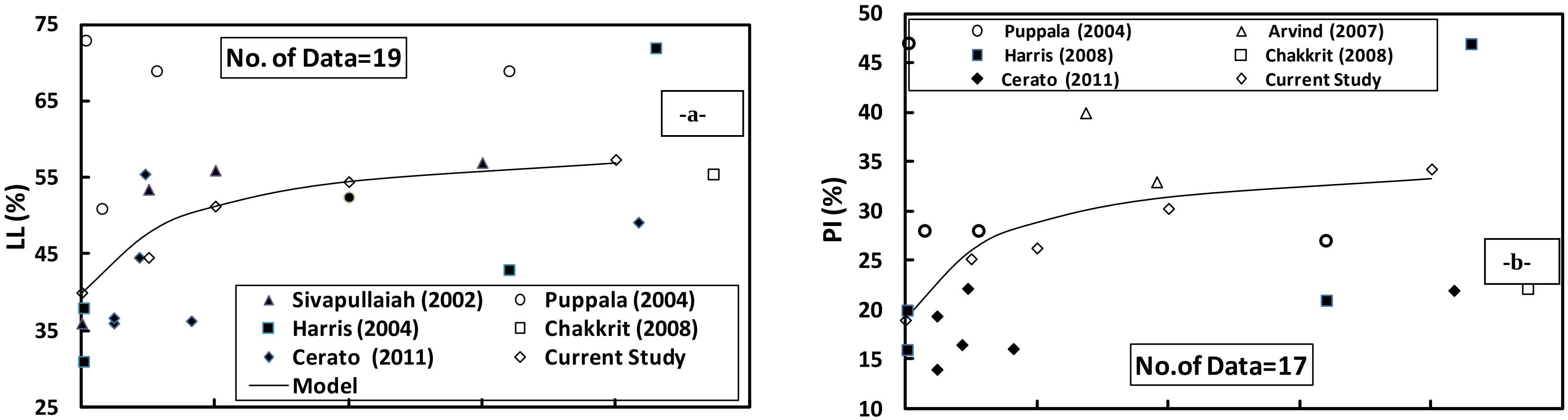

Figure 3. Variations of Index Properties with Calcium Sulfate Content (a) Liquid Limit (b) Plasticity Index

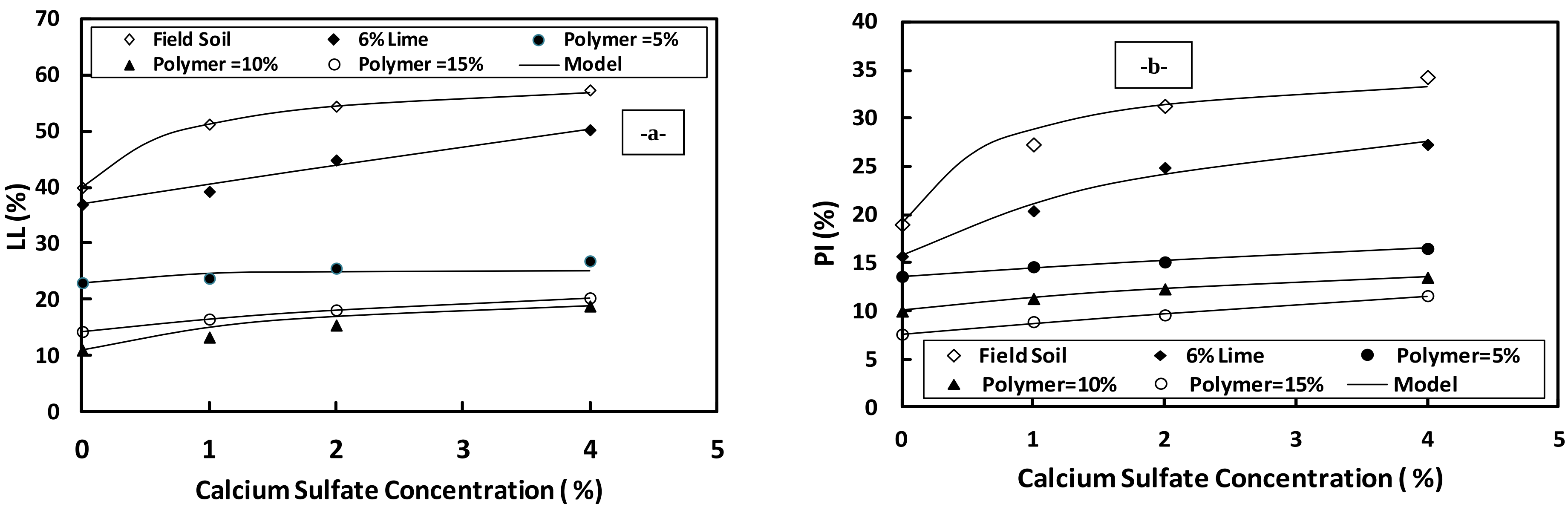

Figure 4. Variations of Index Properties of Treated Calcium Sulfate Soil With 6% of Lime and Polymer Solution (a) Liquid Limit (b) Plasticity Index

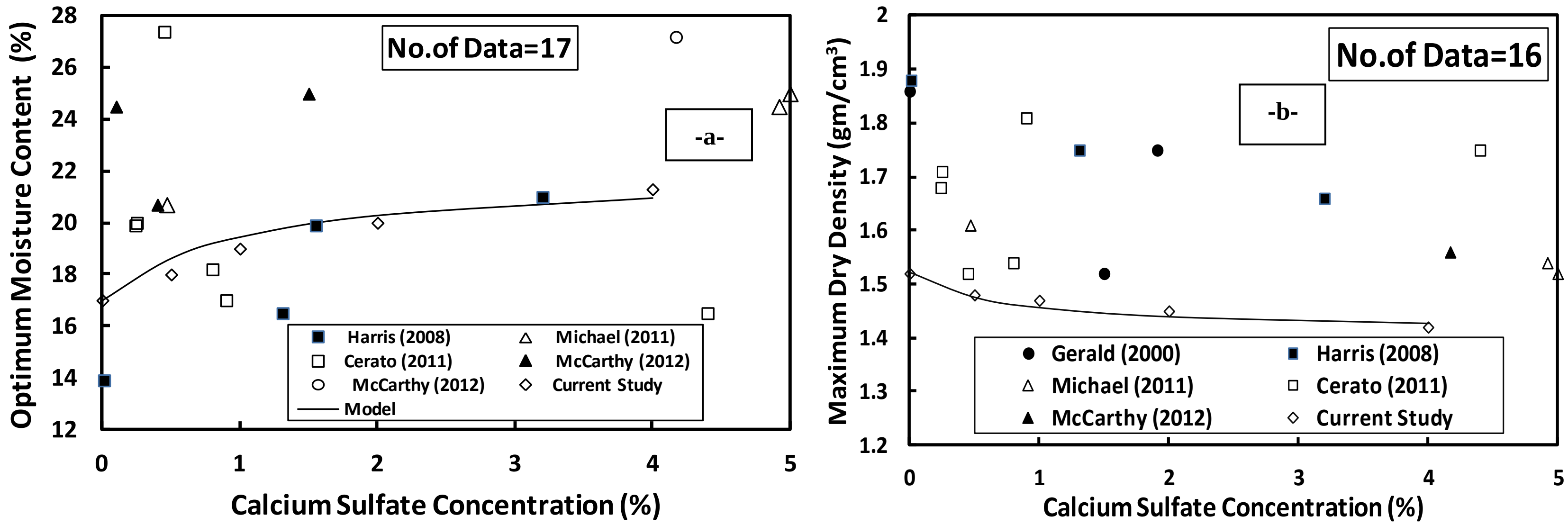

Figure 5. Variations of Compacted Soil Properties with Calcium Sulfate Content (a) Optimum Moisture Content (OMC) (b) Maximum Dry Density

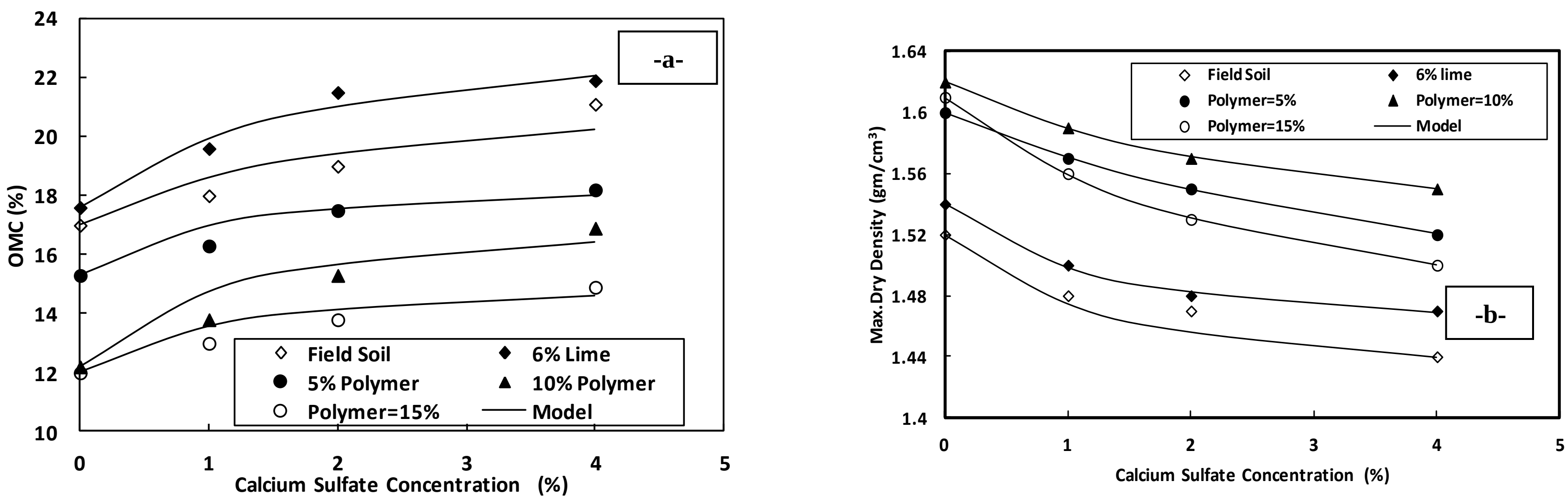

Figure 6. Variations of Index Properties of Treated Calcium Sulfate Soil With 6% of Lime and Polymer Solution (a) Optimum Moisture Content (OMC) (b) Maximum Dry Density

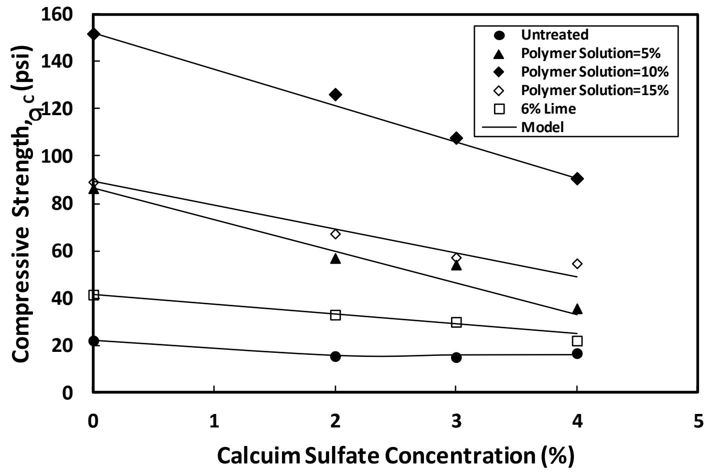

Figure 7. Relationship between Compressive Strength with Calcium Sulfate Concentration

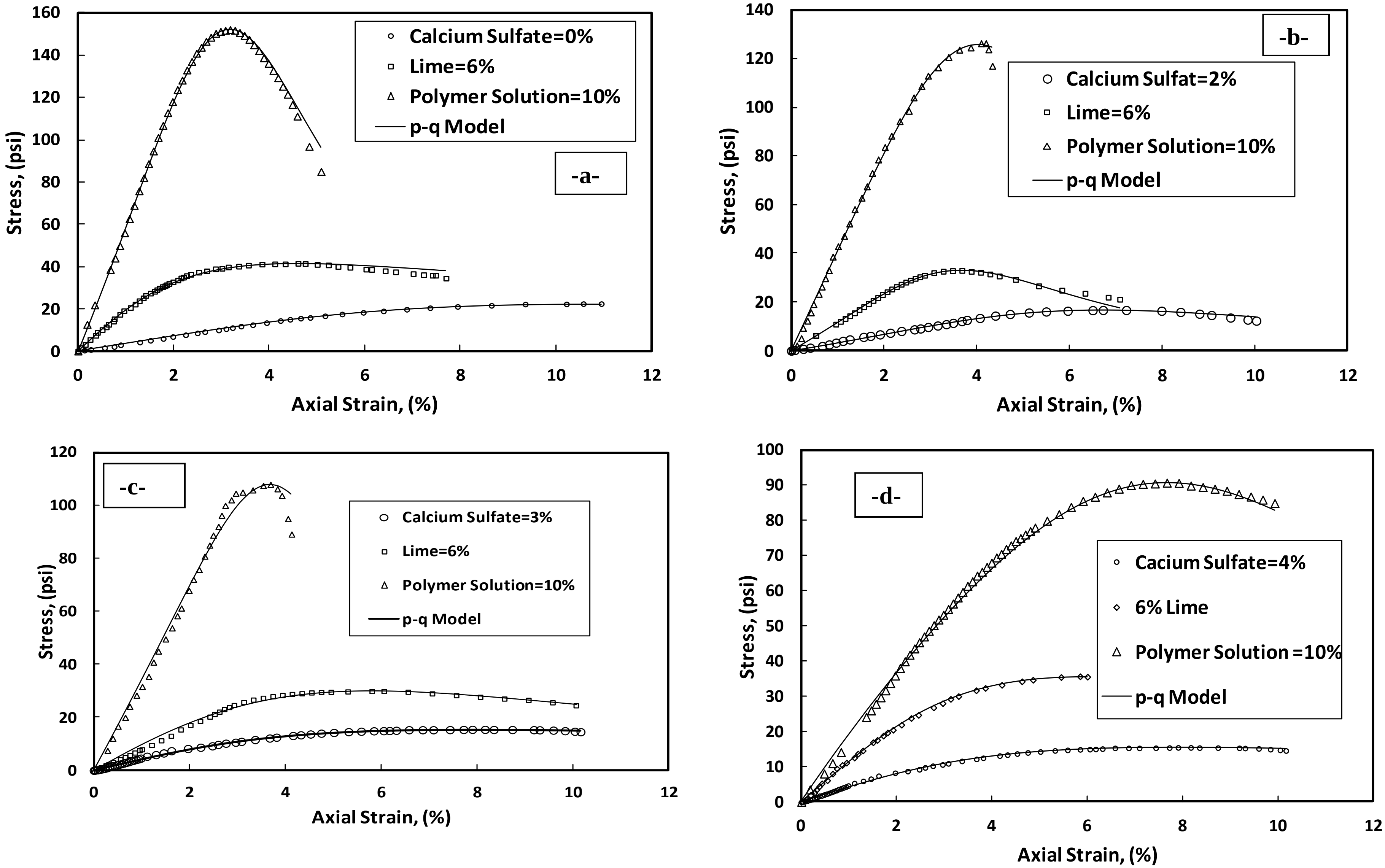

Figure 8. Comparison of Models Prediction and Experimental Stress - Strain Relationship for Sulfate Contaminated CL Soil Treated With 6% of Lime and 10% of Polymer Solution :(a) Calcium Sulfate =0% (b) Calcium Sulfate =2% (c) Calcium Sulfate =3% (d) Calcium Sulfate =4%