Unconfined Compressive Strength of Clayey Soils Stabilized with Waterborne Polymer

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Abstract

Improvement and stabilization of soils are widely used as an alternative to substitute the lacking of suitable material on site. Soils may be stabilized to increase strength and durability or to prevent erosion and dust generation. The use of nontraditional chemical stabilizers in soil improvement is growing daily. A new stabilizing agent was developed to improve the mechanical performance and applicability of clayey soils. In this study a laboratory experiment is conducted to evaluate the effects of plasticity index and waterborne polymer on the Unconfined Compression Strength (UCS) of clayey soils. The laboratory tests include sieve analysis, hydrometer, Atterberg limits, modified compaction and unconfined compression tests. Three clayey soils with different plasticity indexes were mixed with various amounts of polymer (2, 3, 4 and 5%) and compacted at the optimum water content and maximum dry density. The unstabilized and stabilized samples were subjected to unconfined compression tests to determine their strength at different curing times. The results of the tests indicated that the waterborne polymer significantly improved the strength behavior of unsaturated clayey soils. Also, an increase in plasticity index causes a reduction in unconfined compression strength.

Keywords: *unconfined compressive strength, stabilization, waterborne polymer, clayey soils, curing time, plasticity index*

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1. Introduction

Soil stabilization is a collective term for any physical, chemical, or biological method, or any combination of such methods, which is employed to improve certain properties of a natural soil to make it adequately serve an intended engineering purpose over the service life of an engineering facility (Fang, 1991). The different uses of soil pose different requirements of mechanical strength and of resistance to environmental forces. Stabilization may be achieved by mechanically mixing the natural soil and a stabilizing material in order to form a homogeneous mixture or by adding a stabilizing material to an undisturbed soil deposit and letting it permeate through soil voids (Perloff, 1976). Chemical stabilization is the mixing of soil with one of, or a combination of admixtures of powder, slurry, or liquid for the general objectives of improving or controlling its volume stability, strength and stress-strain behavior, permeability, and durability. Traditional stabilization methods include the application of various combinations of lime, cement, fly ash, and bituminous materials. Extensive researches have been conducted on the use of traditional stabilizers (Alexander. *et al.*, 1972; Eades and Grim, 1960; Ferguson, Levorson, 1999; Ferguson, 1989; Little *et al.,* 2000; Prusinski *et al.,* 1999). The stabilization mechanisms for these traditional stabilizers are well documented, and the effectiveness of these traditional stabilizers has been demonstrated in many applications. Traditional stabilization techniques often require lengthy cure times and relatively large quantities of additives for significant strength improvement. Unfortunately, there is no step by step procedure for selecting nontraditional stabilizers (including polymers, enzymatic emulsions, lignosulfonates, tree-resin emulsions and etc.) and little research has been completed on these materials.

The use of soil stabilization has shown a major increase in geotechnical engineering applications such as construction of buildings, roads, railways, embankments, stabilization of slopes and improvement of soft ground. Improvement of certain desired properties like bearing capacity, shear strength and permeability characteristics of soil can be undertaken by a variety of improvement techniques. One of the techniques is to improve the soft soil with polymeric stabilizers. The major soil stabilization applications beneting from the advances in polymeric materials are chemical grouts, geotextiles, and geomembrane liners for ponds, waterways, and landlls. A synthesis of potential stabilizers identified by the US Army Corps of Engineers and contract researchers from 1946 to 1977 were developed (Oldham *et al.* 1977). The report identified acids, asphalt, cement, lime, resins, salts, silicates, and other products as potential stabilizers demonstrating varying

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degrees of success. The results of the investigation divided performance by soil type and demonstrated that product performance differed for varying soil types. It was also noted that the stabilization mechanisms for particular stabilizing agents, such as salts, were particularly suited for specific climates and environmental conditions. A polymer resin provided the greatest increase in the unconfined compression strength for the sand materials. Gopal *et al.* (1983) used Urea-Formaldehyde (UF) and its copolymers to stabilize dune sand. Specimens were prepared at different combinations of UF ratios, pH levels, and acid catalysts. The optimum UF ratio (ureas to formaldehyde) for their experiment was 1:2.25 by weight. They recommended using 9 percent resin and 0.3 percent acid catalyst for stabilizing dune sands. Also, an experimental study was conducted to determine the effects of stabilizing clay-silt soils with the combination of an epoxy resin (bisphenol A/epichlorohydrin) and a polyamide hardener (Ajayi-Majebi *et al.* 1995). It was observed that admixing up to 4 percent stabilizer into a clay-silt material produced large increases in the load-bearing capacity of the material in terms of its unsoaked California Bearing Ratio (CBR) for curing times as low as 3 hours. Palmer *et al.* (1995) investigated the strength and density modification of unpaved roads using lignin sulfonate (lignin), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$). Laboratory results indicated that lignin was the only product that increased specimen density and the unconfined compression strength of specimens subjected to 4 wet-dry cycles.

Also several researchers (Green *et al.*, 2000; Moustafa *et al.*, 2003; Santoni *et al.*, 2003; Naeini and Mahdavi, 2009) have discussed aqueous polymer applications while others (Daniels, 2003; Daniels and Inyang, 2004; Al-Khanbashi and Abdalla, 2006; Al-Khanbashi and El-Gamal, 2003) have provided useful data on polymer-soil interactions that determine the effectiveness of polymer solution in various applications. Al-Khanbashi and Abdalla (2006) studied the performance of three different emulsion systems as sand stabilizers through measurement of the hydraulic conductivity and compressive strength. Two methods of mixing and spraying for preparing specimens were chosen. The sprayed specimens of the three emulsions showed better hydraulic conductivity reduction compared with their mixing counterparts. However, the strength and the stiffness of the sprayed specimens were lower than those of the mixed specimens. Amu (2008) investigated the possibility of complementing poor lateritic soils with Palm Kernel Shells (PKS) and subsequent stabilization of the resulting composite mix with asphalt. The major finding revealed that the stabilized soils obtained inadequate strength for subgrade, sub-base and base courses in road construction.

In general, polymer emulsions can be used on most soils; however, certain products are more effective on specific soil types. When synthetic polymer emulsions applied at low application rates (sprayed-on or mixed-in) to the surface of the unbound roads, they perform well for dust suppression. They bond soil particles together and so reduce dust generation. At higher application rates (mixed-in), synthetic polymer emulsions can be used to stabilize soils (Kestler, 2009).

The aim of this research was to evaluate the influence of plasticity index and waterborne polymer on the engineering properties of clayey soils. The main benet of using waterborne polymer is that the dispersing medium is water, thus eliminating the negative environmental impact associated with chemicals found in some grouts and solutions used in stabilization.

2. Material

2.1 Soils

Soft clay specimens were collected locally from Abyek (located in Qazvin-Iran). Three fine-grained clayey samples (named: soil A, soil B and soil C) with different plasticity indices were used in this experimental study. Soil A is the as-sampled soft clay from Abyek, Soil B is the same soil with the addition of 10% bentonite by weight, and Soil C is the soft clay with the addition of 20% bentonite by weight. The grain-size distribution of the unaltered soil (sample A) is presented in Fig. 1. According to the properties, the soils lie above the A-line in the plasticity chart (Fig. 2), thus they are classified as high and low plasticity clay soil according to the Unified Soil Classification System (ASTM D422-63). The properties of the tested soils in term of atterberg limits, and particle size and compaction parameters are given in Table 1, and the chemical properties of used bentonite is given in Table 2.
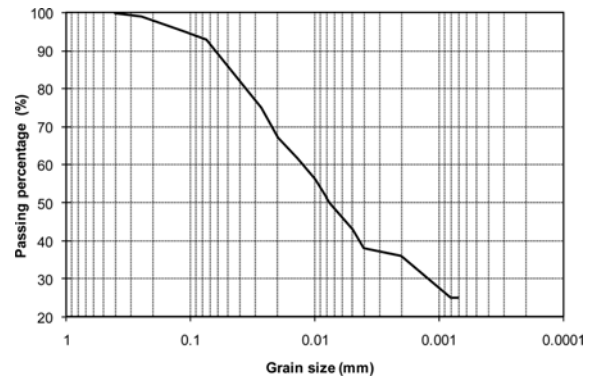

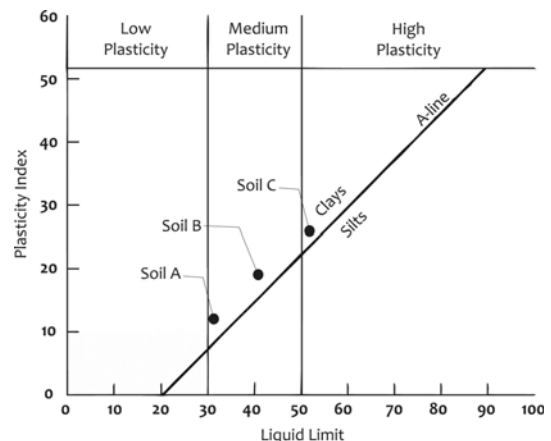Fig. 1. Grain Size Distribution of Unaltered Soil (Sample A)

Fig. 2. Plasticity Chart

Table 1. Engineering Properties of Collected Soils

Property	Soil A	Soil B	Soil C
Specific gravity	2.77	2.75	2.73
Mixed bentonite percentage	0%	10%	20%
Grain size			
Gravel (2-75 mm), (%)	0	0	0
Sand (0/075-2 mm), (%)	6	8	10
Silt (2-75 μm), (%)	58	52	47
Clay (<2 μm), (%)	36	40	43
Atterberg limits			
Liquid limits, (%)	31	41	52
Plastic limits, (%)	19	22	26
Plasticity index, (%)	12	19	26
Compaction parameters			
Optimum Moisture Content, (%)	12.0	13.3	14.4
Maximum dry unit weight, (g/cm^3)	1.92	1.87	1.84
Soil classification, (USCS)	CL	CL	CH
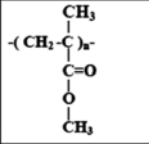
Table 2. Chemical Composition of Bentonite Used in this Study

Compound	Magnitude (%)
SiO_2	70.85
Al_2O_3	3.26
Fe_2O_3	0.07
TiO_2	0.05
CaO	2.81
MgO	7.00
Na_2O	0.07
K_2O	0.95
CO_2	0.44
P_2O_5	0.66
LiO	15.25

2.2 Acrylic Polymer

Liquid admixtures in clay have the advantage of easier access to clay particle surfaces than granular admixtures, particularly, if the liquids are water-soluble and do not produce excessively viscous solutions. Some aqueous polymer solutions meet this requirement. Synthetic polymer emulsions primarily consist of acrylic or acetate polymers that are specifically produced for soil stabilization, or are by-products from the adhesive or paint industries. In this study, a commercial product of Acrylic Polymer (product ID: AP225 – produced by Pars Polymer Khavaran (P.K.K.) Co. in Iran) was used, which is an emulsion synthetic elastic chemical substance that increases the bond with the substrate as an additive in optimum moisture, as well as the cohesion and the strength. This material consists of a tackifier/sealer that is a liquid polymer of methacrylates and acrylates. It is an aqueous acrylic emulsion which is blend of 40% solids by volume that is free from styrene, acetate, vinyl, ethoxylated surfactants or silicates. For soil stabilization applications, it is diluted with water in accordance with manufacturer's recommendations. Some important properties of the Acrylic Polymer used in this study are given in Table 3. The polymer used in this study has some advantages which justify its usage in geotechnical engin-

Table 3. Important Physicochemical Properties of the Acrylic Polymer

Physicochemical properties	
Name	Acrylic Polymer
Chemical formula	
Phase	Liquid
Polymer type	Cationic
Solvability in Water	Solution
Viscosity (cP)	280
Density(g/cm^3)	1.11
Colour	White

eering projects; it is inexpensive and available in Iran, the curing time for stabilized samples is relatively low, it has long-term durability, and it can be simply applied to soil.

3. Laboratory Studies

This experimental work has been done to investigate the influence of plasticity index, curing time and percentage of aqueous polymer on the unconfined compression strength of unsaturated clayey soils. Use of the unconfined compressive strength test for soil stabilizers is a quick and simple test and provides a convenient basis for comparison between stabilizer types. For this purpose three clayey soils with different plasticity indices were used and various percentages of aqueous polymers were added to soils in order to investigate the strength parameters of stabilized samples. The clayey soils were dried before using in the mixtures. First, the required amounts of polymer as a percentage of optimum water content were blended and then added to dry soils. The pure amounts of aqueous polymer were chosen as 2%, 3%, 4% and 5% by total weight of the amount of water needed to achieve the optimum water content. These amounts of polymer were then diluted in water and mixed with the soil samples. As the soils tended to lump together, considerable care and time were spent to get a homogeneous distribution of the mixture. Then all the specimens were compacted at their respective maximum dry density in their optimum moisture content, corresponding to the values obtained in the modified proctor compaction Tests (ASTM D-1557). The cylindrical specimens (diameter=50 mm, height=100 mm) were stored in the curing room at the temperature of ranging 21º to 25º and then tested at 2, 4, 6, 8 and 14 days of curing times. In order to determine the unconfined compression strength parameters of unstabilized and stabilized samples, a series of unconfined compression tests at the rate of 1.2 mm/min were carried out according to ASTM D2166. The axial strain and axial normal compressive stress are given by the following relations:

$$\sigma = P/A \tag{1}$$

$$\varepsilon = \Delta L / L_0 \qquad (2)$$
$$A = A_0 / (1 - \varepsilon) \qquad (3)$$

where A is the corresponding cross-sectional area [mm^2], A_0 is the initial cross-sectional area of the specimen [mm^2], L_0 is the initial length of the test specimen [mm], P is the corresponding force [kN], ΔL is the length change of specimen [mm], σ is the compressive stress [kPa], ε is the axial strain for the given load.

4. Results and Discussion

4.1 Effect of Curing Time on the UCS

To observe the effect of curing time on the UCS, three clayey soils with different plasticity indexes were mixed with different percentages of acrylic polymer and tested at 2, 4, 6, 8 and 14 days of curing time. The results of unconfined compressive strength on stabilized and unstabilized soils at different curing times are presented in Fig. 3 and Table 4. Note that q_u is the UCS of the samples and q_0 is the UCS of untreated and uncured soil samples which were acquired separately for samples A, B and C.
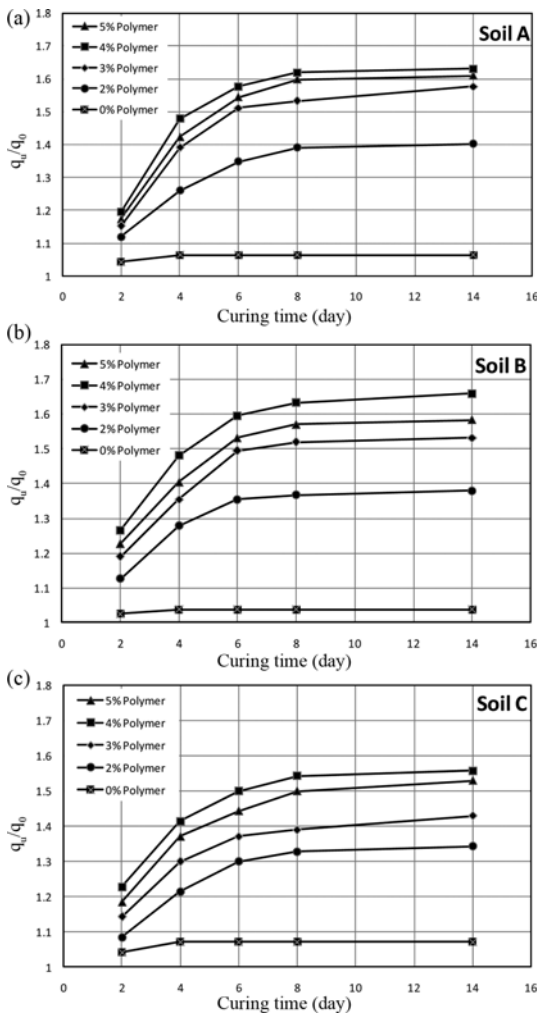

Fig. 3. Effect of Curing Time on Normalized UCS of: (a) Soil A, (b) Soil B, (c) Soil C

Table 4. The Results of (UCS) on Polymer Stabilized Soils (kPa)

Soil type	polymer (%)	Curing time					
		0 day	2 day	4 day	6 day	8 day	14 day
Soil A	0%	9.2	9.6	9.8	9.8	9.8	9.8
	2%		10.3	11.6	12.4	12.8	12.9
	3%		10.6	12.8	13.9	14.4	14.5
	4%		11.0	13.6	14.5	14.9	14.9
	5%		10.8	13.1	14.2	14.7	14.7
Soil B	0%	7.9	8.1	8.2	8.2	8.2	8.2
	2%		8.9	10.1	10.7	10.8	10.9
	3%		9.4	10.7	11.8	12.0	12.1
	4%		10.0	11.7	12.6	12.9	12.9
	5%		9.7	11.1	12.1	12.4	12.4
Soil C	0%	7.0	7.3	7.5	7.5	7.5	7.5
	2%		7.6	8.5	9.1	9.3	9.4
	3%		8.0	9.1	9.6	9.8	9.8
	4%		8.6	9.9	10.5	10.8	10.8
	5%		8.3	9.6	10.1	10.5	10.6

As Fig. 3 shows, the unconfined compressive strength of stabilized soils in relation to curing time for all of the polymer contents increases more rapidly within the first 8 days and then becomes almost constant up to 14 days. Therefore, optimum curing time of 8 days has been recommended for all three soil samples. The polymer-stabilized soil properties improved with curing time. Curing for the polymer emulsions occurs by break-ing of the emulsion and subsequent water loss by evaporation. The breaking of the emulsion occurs when the individual emul-sion droplets suspended in the water phase coalesce. This occurs as the emulsion particles wet the surface of the soil particle and the polymer is deposited on the surface. The amount of polymer deposited on the surface of the soil particle depends on the concentration of the polymer added and the degree of mixing with the soil (Santoni *et al.* 2003).

4.2 Effect of Polymer Content on the UCS and Stress-strain Behaviour

As shown in Fig. 4, the addition of polymer played an impor-tant role in development of the UCS of polymer mixed soils. It is observed that the value of the UCS increased, when the amount of polymer percentage increased. Similar trend has been ob-served in all of the soil samples. Also, it is observed that as the percentage of polymer increased up to 4%, the value of UCS increased in soil A, soil B and soil C but with a further increase in percentage of polymer up to 5% the value of the UCS slightly decreased. This is because of the adsorption mechanism of polymer emulsion that more likely to bond to the clay content (fine particle size) than to the sand or silt particles. As it is mentioned in Table 3, the used polymer categorized as cationic polymer. Thus the molecules of polymer easily can form an elec-trostatic bond with clay particles. Their retention on clay which is mostly through sorption of polymer molecules can occur on both internal and external pore surfaces or microscopic interlayer spaces that cause more cohesion of particles of clay and an in-crease in value of UCS. Adsorption leads to change in conforma-
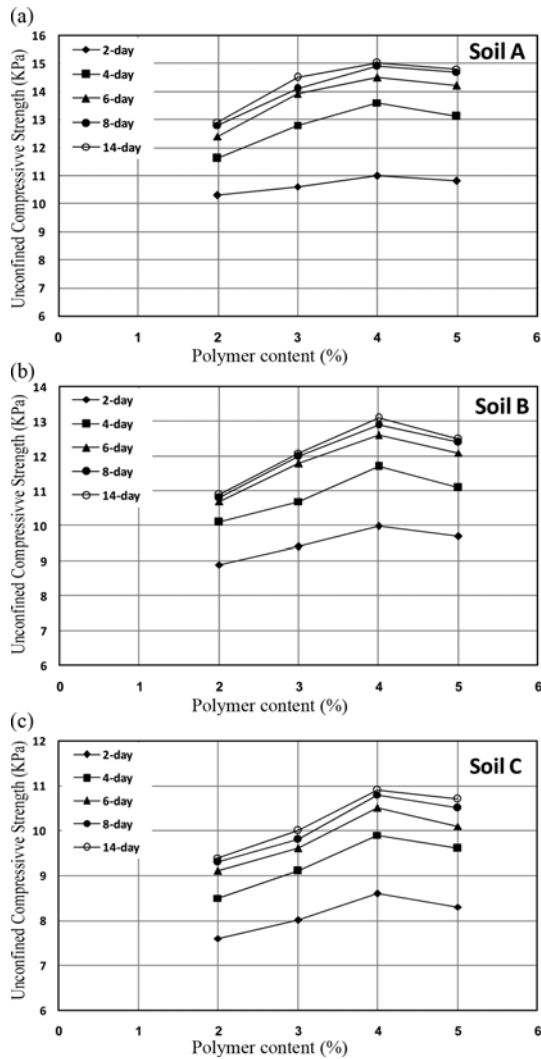
Fig. 4. Effect of Polymer Percentage on UCS of: (a) Soil A, (b) Soil B, (c) Soil C

tion in the polymer, which in solution tends to exist as a random coil, uncoils and spreads out at the solid/solution interface.

The size of polymer molecule in an aqueous solution is highly dependent on its conformation which in turn, depends largely on solution concentration, ionic concentration, pH, etc. Conformation is the extent to which a polymer molecule coils up or stretches out in solution. If it coils tightly, it will assume a smaller size; and if it stretches out, it will occupy a larger space of variable shape. With increasing polymer up to 4% the polymer molecules are separated from one another and behave like free coils but with increasing concentration, 5%, the polymer coils began to overlap and segments of molecules begin to entangle and their bonding effects on clay particles diminishes. In addition, with regard to the adsorption mechanism of the polymer emulsion, there is an important relation between the polymer content and the clay content. In other words, the increase in clay content dilutes the polymer phase.

By observing stress-strain plots of tests, one can conclude that, the gradient of stress-strain curves increased with an increase in
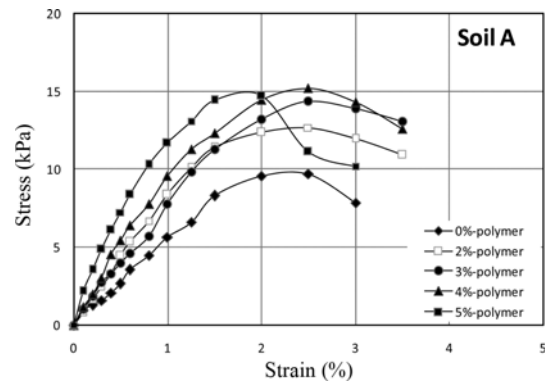

Fig. 5. Effect of Polymer Content on the Stiffness of the Soil A

polymer content. This means with an increase in polymer content, the treated soils show a greater strength at the same strain level. In other words, increasing polymer content leads to an increase in the stiffness of soil samples. This is shown in Fig. 5. Also, similar trends were observed for the soil B and soil C.

4.3 Effect of Plasticity Index on the UCS

Figure 6 shows the effect of plasticity index of soils on unconfined compressive strength for different contents of polymer after 8-days of curing time. As shown in Fig. 6 the unconfined compressive strength of soils decreases from soil A to C which is due to the increasing plasticity index of soils from soil A to C. An increase in plasticity index causes a reduction in unconfined compressive strength. Again, referring to the fact that the polymer emulsion tends to bond to the clay mineral phase (bentonite), an increase in the bentonite content (i.e., plasticity index) results in a decrease in the availability of the polymer for the rest of the soil matrix. It should be noted that a similar trend has been observed for all other curing times.

Plasticity index plays an important role in the stress-strain behaviour of the soil samples. The stress-strain curves for soil samples mixed with 2% polymer are shown in Fig. 7. Observing stress-strain plots of the tests showed that as the plasticity index increases, it makes the soil yield at a higher strain as shown in
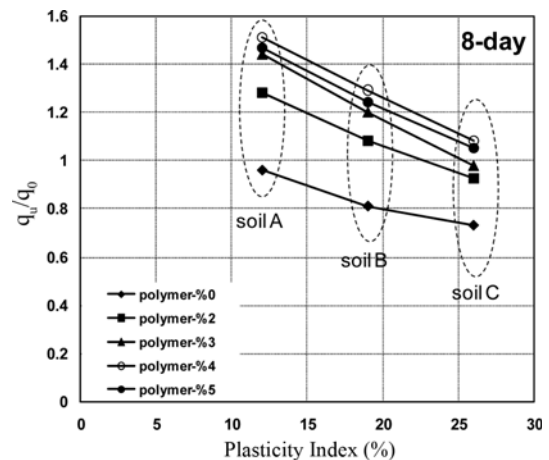

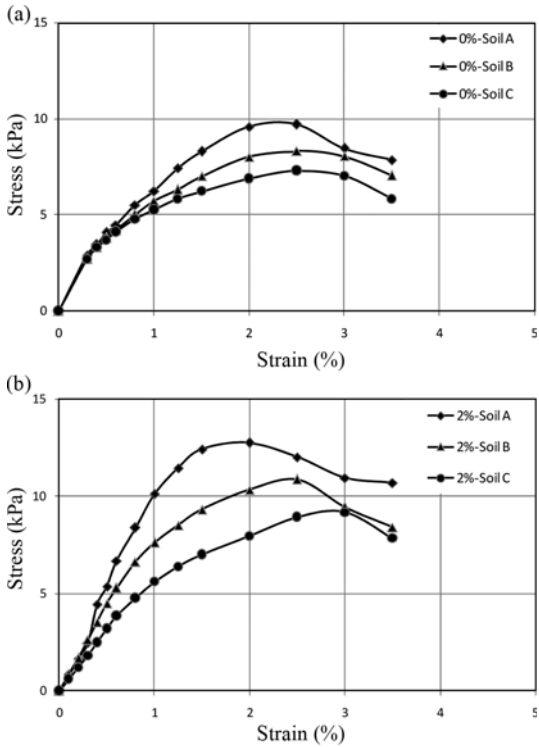Fig. 6. Effect of Plasticity Index on UCS of Soils

Fig. 7. Effect of Plasticity Index on Stress-strain Behaviour of Soil Samples: (a) Samples with 0% Polymer, (b) Samples with 2% Polymer Content

Fig. 7. Also, samples with higher plasticity indexes show softer stress-strain behaviour, reduced stiffness and smaller peak strength. Therefore the higher plasticity index could change the stress-strain behaviour of soil samples from a brittle to relatively ductile manner.

4.4 Statistical Evaluation of Test Results

To quantitatively evaluate the effect of polymer content and curing time on the unconfined compressive strength of the studied soil, a multiple regression analysis was applied to obtain the following relationships among UCS, polymer content (P) and time (t) values, with Eqs. (4), (5) and (6) for soils A, B and C, respectively:

$$UCS(kN/m^2) = 8.7911 + 0.8078 \times P(\%) + 0.2078 \times t(days) \quad (4)$$
$$UCS(kN/m^2) = 7.55 + 0.7381 \times P(\%) + 0.1503 \times t(days) \quad (5)$$
$$UCS(kN/m^2) = 6.8248 + 0.5195 \times P(\%) + 0.1190 \times t(days) \quad (6)$$

The relationships between measured and predicted strength parameters (obtained from Eqs. (4) to (6)) as well as the 95% confidence intervals are shown in Fig. 8. The correlations between measured and predicted values are 85%, 87% and 88% for soil A, B and C respectively. As it was mentioned before, the UCS of the treated samples decreases when the polymer content is over 4%. Therefore, the Eqs. (4), (5) and (6) are assigned for polymer contents up to 4%.
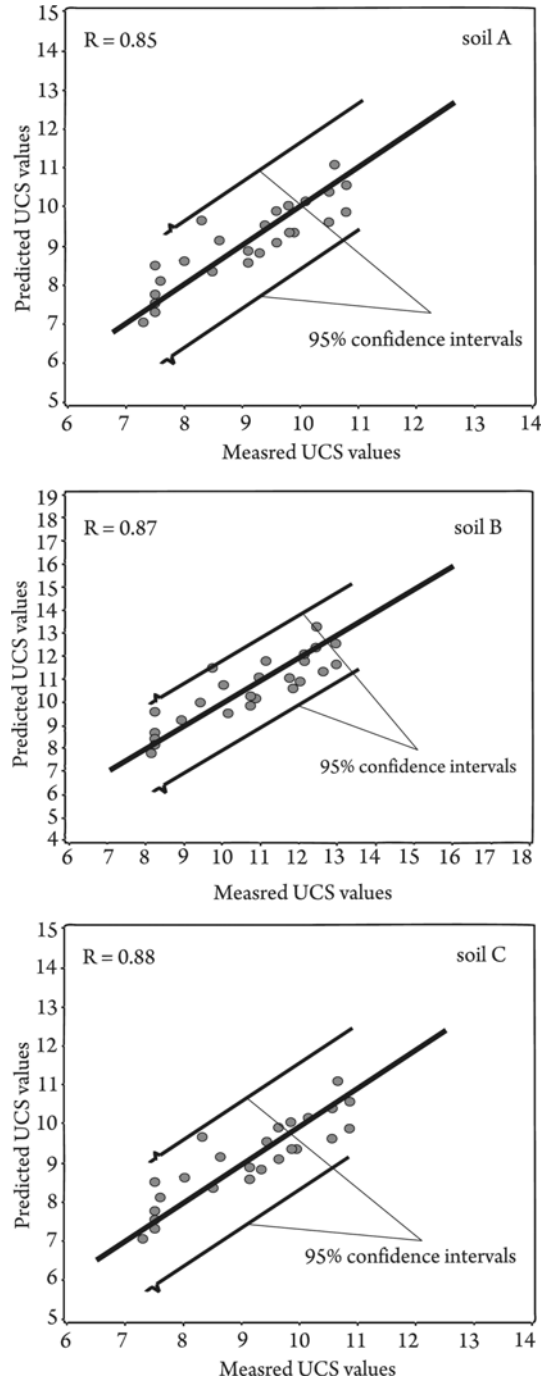

Fig. 8. Measured and Predicted Values of UCS Soils

5. Conclusions

This study was undertaken to investigate the influence of plasticity index and aqueous polymer percentage and curing time on the unconfined compressive strength of stabilized and unstabilized unsaturated clayey soils. The results of the study are presented in following conclusions:

1. The unconfined compressive strength significantly increases with curing time. The UCS values increase more rapidly within the 8 days and then become almost constant up to 14 days.

2. The maximum UCS increases with increasing polymer content. Soils stabilized with 4% polymer have higher unconfined compressive strength than other percentages. Stabilized samples with 5% polymer have lower strength than 4% polymer. Also it should be noted that increasing polymer content lead to higher stiffness of soil samples.

3. Plasticity index has an important effect on the UCS. An increase in plasticity index causes a reduction in unconfined compressive strength. It is due to decrease in dry density and increase in optimum water content. Also, stress-strain plots of the tests showed that as the plasticity index increases, the soil yields at a higher strain. Therefore the higher plasticity index could change the stress-strain behaviour of soil samples from a brittle to ductile manner.

4. Soil stabilization with aqueous polymer improves the strength behavior of unsaturated clayey soils and can be potentially useful in time and cost savings because of its low curing time.

5. From the point of view in mechanics and applicability in roadways, adding 4% polymer with an 8 day curing time gives an economic and reasonable scheme.

Acknowledgements

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