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Effect of Liquid Polymer on Properties of Fine-Grained Soils

H. Soltani-Jigheh[1] and S.N. Tahaei Yaghoubi[2]
[1]*Associate Professor, Department of Civil Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran*
[2]*Department of Civil Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran*
E-mail: hsoltani@azaruniv.ac.ir

ABSTRACT: One of the most useful methods for improving engineering characteristics of soils is soil stabilization by chemical additives like cement, lime and polymer materials. Since polymeric additives are easier to handle, they have been used widely in geotechnical projects in recent years. The current practice is to evaluate the effect of CBR-Plus polymer on the physical and mechanical properties of fine-grained soils. For this purpose, CBR-Plus polymer was mixed with two high plasticity fine-grained soils and Atterberg limits, compaction and consolidated undrained (CU) triaxial tests were carried out on the compacted mixture in the laboratory. Interpretation of the results using scanning electron microscopy (SEM) images were carried out. Results show that CBR-Plus has insignificant effect on plasticity index and compaction characteristics of soils. Some amount of CBR-Plus additives lead to increase in shear strength of specimens. In fact, depending on the type of the soil, there is an optimum amount for this polymeric material in which the shear strength increases.

KEYWORDS: Fine-grained soils, CBR-Plus polymer, Triaxial test, Shear strength, SEM images

1. INTRODUCTION

Geotechnical engineers may encounter with problematic soils in civil engineering projects. For example, fine-grained soils, especially those consist of high percentage of clay particles, are commonly stiff in dry state, but they lose their stiffness when saturated with water. In addition, soft clays are characterized by low bearing capacity and high compressibility. In fact, low strength and low stiffness of soft clays may lead to bearing capacity failure and excessive settlement, and consequently cause severe damages to buildings and foundations (Sakr et al; 2009; Ziaie Moayed and Allahyari, 2012). On the other hand, it is not usually possible to obtain a construction site that will meet the design requirements without ground modification (Makusa, 2012).

Different researches have shown that the use of polymeric materials for stabilization is more comfortable and effective than the other chemical additives, so it has been considered widely in geotechnical projects in recent years (Yazdandoust and Yasrobi, 2008). For example, inorganic types of stabilizing agents, such as cement, lime, fly ash, and their mixtures, have been popularly applied to soil stabilization. These inorganic stabilizing agents are mainly used in non-ecological soil stabilization, such as foundations, roadbeds, embankments, and piles. Although they improve the engineering properties of soils such as strength and stiffness greatly, their higher stiffness and inorganic material will inhibit the plant growth. Therefore, the organic polymer soil stabilizers as a new stabilizing agent applied in soil ecological stabilization have received recent attention. STW is a new organic polymer soil stabilizer which causes the beneficial changes in the unconfined compressive strength (UCS), shear strength, water stability, and erosion resistance of clay slope topsoil and protecting the vegetation growth (Liu et al., 2011). In Australia, new polymeric-based additives have provided superior sustainability advantages for the construction and maintenance of low-volume roads (particularly unsealed roads) over traditional cement-blended additives. For example, PAM is an anionic additive which has mainly been used in wearing course of unsealed pavements in Australia. Results of unconfined compressive strength tests, performed on three types of pavement materials treated with PAM additive, confirmed an increase in dry density and unconfined compressive strength (Romel et al., 2015). The other example is a commercial polymer product, named β-1,3/1,6-glucan, which has been used to improve the strength of the Korean residual soil, hwangtoh. This polymer solutions with different concentrations were mixed with hwangtoh soil and cured under different temperatures. Results showed that this polymer significantly increased the compressive strength of the soil. Since the strength improvement was maximized under curing temperature of 60°C, a single economic/environmental analysis revealed that the β-1,3/1,6-glucan polymer treatment had advantages not only in strengthening the hwangtoh, but also in lowering its environmental impact while offering financial competitiveness over ordinary cement treatments (Chang and Cho, 2012).

Latifi et al. (2016a) observed that adding 6% (as an optimum amount) of the liquid polymer to the laterite soil increased the unconfined compressive strength of soil noticeably, after 7 days curing period. Based on the FESEM results, they found that the stabilization process modified the porous network of the laterite soil.

Cameron et al. (2016) used hydrophobic dry powder polymers mixed with lime to improve road base quickly with relatively low cost. They demonstrated that the resilient modulus can be almost doubled with the addition of dry powder polymers and permanent strain was reduced at least 60% at the end of second stage of repeated loading. Moreover, specimens treated with dry powder polymers exhibited excellent stability through the third stage of loading, while the untreated specimens were unstable. Another observation indicated that addition of water and liquid polymer have great improvement effect on the UCS of clayey soil. This study demonstrated that the liquid stabilizer can be successfully utilized to provide acceptable strength, durability and mitigated swelling (Rezaeimalek et al., 2017).

Moreover, the combination of an expanding polyurethane polymer with ballast for structural support of the rail tracks in practice showed that this in-situ technique has the potential to mitigate impacts of ballast fouling, enhance rail freight capacity, and improve track-substructure maintenance efficiency. Easy injection and the negligible curing period for Polyurethane-Stabilized Ballsat (PSB) makes it an attractive option for railway maintenance, especially for time-sensitive maintenance activities, such as intersections and bridge approaches (Keene et al., 2014).

The important factor in soil stabilization with polymers is the permanent effect of these additives on soils. In other words, addition of polymeric materials to soils results in strong bonds between the particles which in turn causes the improvement of soil engineering characteristics. Some researchers have shown that stabilization of soils with polymers causes significant reduction in plasticity properties and swelling potential, especially in fine-grained cohesive soils (Yazdandoust and Yasrobi, 2008).

Since the surface charges on fine-grained soils are negative (anions), they attract cations and the positively charged side of water molecules from surrounding water. Consequently, a thin film or layer of water, called adsorbed water, is bonded to the mineral surfaces. This layer of water is known as the diffuse double layer, which influences the way a soil behaves (Budhu, 2011). The obvious solution to overcome most problems of these soils is to reduce the adsorbed layer of water surrounding the soil particles. If powerful positive molecules can be supplied, the negative charge of the clay minerals can be satisfied or balanced out (Ziaie Moayed and Allahyari, 2012; Soil Stabilization and Dust Control, 2015).

The objective of this research is to study how CBR-Plus additive affects engineering characteristics of fine-grained soils. Therefore, CBR-Plus solution with different concentrations was added to two fine-grained soils and then their physical and mechanical characteristics were evaluated by conducting Atterberg limits, compaction and consolidated undrained triaxial compression tests. Finally, the results of these tests were implemented and an interpretation was offered on the results based on SEM images.

2. MATERIALS DESCRIPTION AND SAMPLES PREPARATION

Two natural fine-grained soils were selected for investigation purposes, namely Tabriz yellow marl (TYM) and Sayin (S) soils. TYM soil was collected from foothills in east of Tabriz city and S soil was taken from Sarab-Ardebil roadway, in Iran. Both of the soils have low bearing capacity and generally need to be stabilized. Particle-size analysis was performed on both fine-grained soils according to ASTM D422 (2007) (Figure 1). As can be seen, the largest component of the soils are passing No. 4 sieve. The liquid limit (LL) and plasticity index (PI) of TYM soil are 66% and 25%, respectively (ASTM D4318, 2010) and according to unified soil classification system falls within the MH group (ASTM D2478, 2006). The LL and PI of S soil is 58% and 32%, respectively and categorized within the CH group. Specific gravity of TYM and S soils are 2.68 and 2.66, respectively.

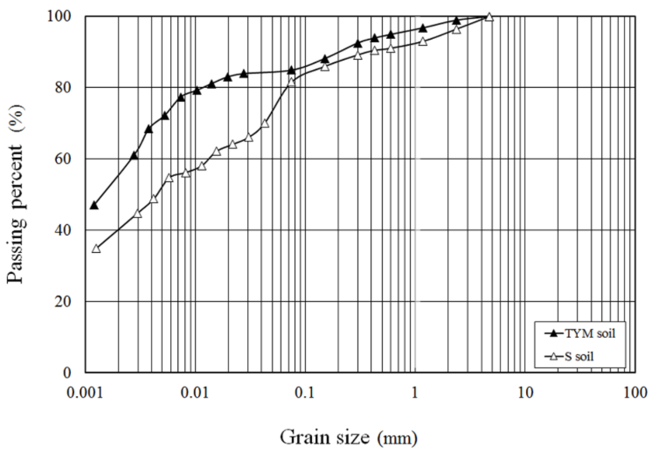

Figure 1 Particle-size distributions of tested soils

In this study, CBR-Plus liquid polymer with specific gravity of 1.001 gr/cm^3 was used as a soil stabilizer. This stablizer with 4$^+$ charge, which is manufactured exclusively in South Africa, forms an extremely thin oily layer on the surface of soil particles and easily neutralizes negative charges on the surface of clay particles. In fact, it reduces ion mobility and ion exchange and simultaneously makes the materials hydrophobic by eliminating the adsorption of water. As a result, unpaved roads treated with CBR-Plus turn from mud surfaces into roads that are trafficable in wet weather. However, non-cohesive materials, such as sand, can be treated only when they were mixed with a suitable clayey material (Ziaie Moayed and Allahyari, 2012; Soil Stabilization and Dust Control, 2015).

CBR-Plus material is totally water soluble with no solid residue, non-flammable, non-corrosive, non-toxic and safe, non-hazardous, environment and user friendly, safe for streams and vegetation, and safe for transport by air, land or sea. The main physical properties of CBR-Plus polymer are given in Table 1 (Ziaie Moayed and Allahyari, 2012; CBR-Plus material safety data sheet, 2012).

Table 1 Physical and Mechanical Properties of CBR-Plus Polymer

Character	Description
Appearance	Chocolate brown viscous fluid
Odour	Sulphurous odour
Physical state	Viscous fluid
Freezing point (º C)	< -10
Boiling point (º C)	100
Vapor pressure (mm Hg)	20
Evaporation rate	As for water
pH	0.9
Percent soluble (@ 20 º C)	100

Since CBR-Plus is a highly concentrated liquid, which 100 litres will treat between 10,000 to 20,000 square meters of soil to a depth of 15 cm when diluted with water, transport costs for the product to remote sites worldwide is low (Soil Stabilization and Dust Control, 2015). Therefore, diluted solution was prepared by adding 20 cc CBR-Plus to 980 cc water, which was called 2% CBR-Plus solution. After preparing the solution, it was added in 5 cc, 10 cc, 20 cc, 40 cc, 75 cc, 150 cc, and 225 cc amounts for each 1000 gr soil and then distilled water was added to the samples as necessary. Then, the samples were cured in laboratory environment during 7 days.

3. CONDUCTED TESTS

3.1 Atterberg Limits Tests

Atterberg tests were performed on natural and stabilized specimens to investigate the effect of CBR-Plus on plasticity properties of used soils (ASTM D4318, 2010).

3. 2 Compaction Tests

To determine the optimum water contents and maximum dry unit weights of natural and stabilized soils, standard Proctor tests were carried out on specimens (ASTM D698, 2008).

3. 3 Triaxial Compression Tests

Effect of CBR-Plus stabilizer on mechanical behaviour of the soils was investigated by performing a number of consolidated undrained (CU) triaxial compression tests on the specimens with cylindrical with 50 mm in diameter and 100 mm in height. Since the objective of this study is to use CBR-Plus stabilized fine-grained soils in the subgrade of the pavement systems, so for better simulation, all of the triaxial test specimens were compacted in special mold with 98% of corresponding maximum dry unit weight and optimum water content after curing time. Each specimen was compacted in four layers in the mould by tamping each layer until the accumulative mass of the soil placed in the mold to a known volume and the surface of each layer was scratched for better connectivity with next layer (ASTM D4767, 2004). After preparation, the specimens were mounted in triaxial chamber and distilled water was allowed to pass through the specimens at least 72 hours. Since almost complete saturation before cell and back pressure application was intended, water was allowed to be distilled through the samples for 72 hours. In fact, low permeability of the soils was the reason for choosing this time. Then, gradual cell and back pressures were implemented to the specimens until full saturation was obtained. After saturation, all of the specimens were consolidated under isotropic effective stress (σ'_c) of 200 kPa. In addition, some of the specimens were consolidated under σ'_c = 300 kPa. It should be noted that consolidation effective stresses are usualy chosen based on the stress condition in practice. In other hand, this additive is commonly used to stabilize subgrade and subbase layers in roads without base and surface layers, which are compacted in project site with high stresses. Therefore, consolidation effective stresses were selected 200 and 300 kPa.

Finally, they were loaded with applying axial load in the form of strain-controlled (ASTM D4767, 2004) with uniform speed of 0.04 mm/min (i.e., 0.04%/min) (Bishop and Henkel, 1969). Table 2 lists specifications of all conducted tests on the specimens.

Table 2 Some Characteristics of Specimens and Conducted Tests

Soil	Dilution (cc)	Conducted tests			
		Atterberg	Compaction	Triaxial with σ'_c 200 kPa	Triaxial with σ'_c 300 kPa
TYM	0	×	×	×	×
TYM	10	×	-	×	×
TYM	40	×	-	×	×
TYM	75	×	×	×	×
TYM	150	×	×	×	×
TYM	225	×	×	×	×
S	0	×	×	×	-
S	5	×	-	×	-
S	10	×	-	-	-
S	20	×	-	×	-
S	40	×	-	×	-
S	75	×	×	×	-
S	150	×	×	×	-
S	225	×	×	×	-

3.4 Repeatability Tests

Generally, in all experimental studies, the accuracy of results is most important. In this study, repeatability tests of Atterberg and compaction were performed on some of the specimens. Also, for determination of effect of test method (sample preparation, saturation, consolidation, and loading) on triaxial compression test results, repeatability tests were performed on some specimens consolidated under σ'_c of 200 kPa. In addition, the effect of curing time on mechanical behaviour of the TYM specimen stabilized with 225 cc dilution consolidated under σ'_c = 200 kPa was investigated. The specimen was cured during 7 and 15 days and tested. In the basis of obtained results, the relative difference in all of the tests was acceptable.

3.5 Scanning Electron Microscopy (SEM)

Microstructure of soil mainly plays an important role in controlling the deformational response to external stresses, resistance to shearing forces, electrochemical interactions between the particles and between the particles and adjacent liquid or gas phase (Lin and Cerato, 2014). Scanning electron microscopy images give a spatial distribution and a total summary of the specimen status. In order to investigate the microstructure of natural and stabilized soils and to interpret the test results, SEM images were taken at a magnification ratio of 2500 X.

4. TEST RESULTS

4.1 Atterberg Limits

Effect of CBR-Plus dilution on the liquid limit (LL), plastic limit (PL), and plasticity index (PI) values of the soils are presented in Figure 2. Figure 2(a) illustrates that addition of dilution up to 40 cc decreases the LL of the TYM but thereafter increases this parameter. In S soil, only addition of 40 cc decreases the LL and the other amounts of dilution increase this parameter. However, dilution contents greater than 75 cc have insignificant effect on LL values of both studied soils.

Plastic limit of TYM soil decreases with an increase in CBR-Plus content up to 40 cc and then it increases to 41.0%, so that by adding 225 cc dilution, the amount of PL exceeds the associated value of the natural soil (Figure 2(b)). In S soil, CBR-Plus addition leads to increase in PL.

Variations of PI with different CBR-Plus contents (Figure 2(c)) illustrate that, excluding the TYM specimens containing 10 cc and 40 cc dilution, addition of this polymeric material decreases the PI of the both soils to some extent. In general, addition of CBR-Plus more than 150 cc has no significant effect on Atterberg limits of the studied soils.

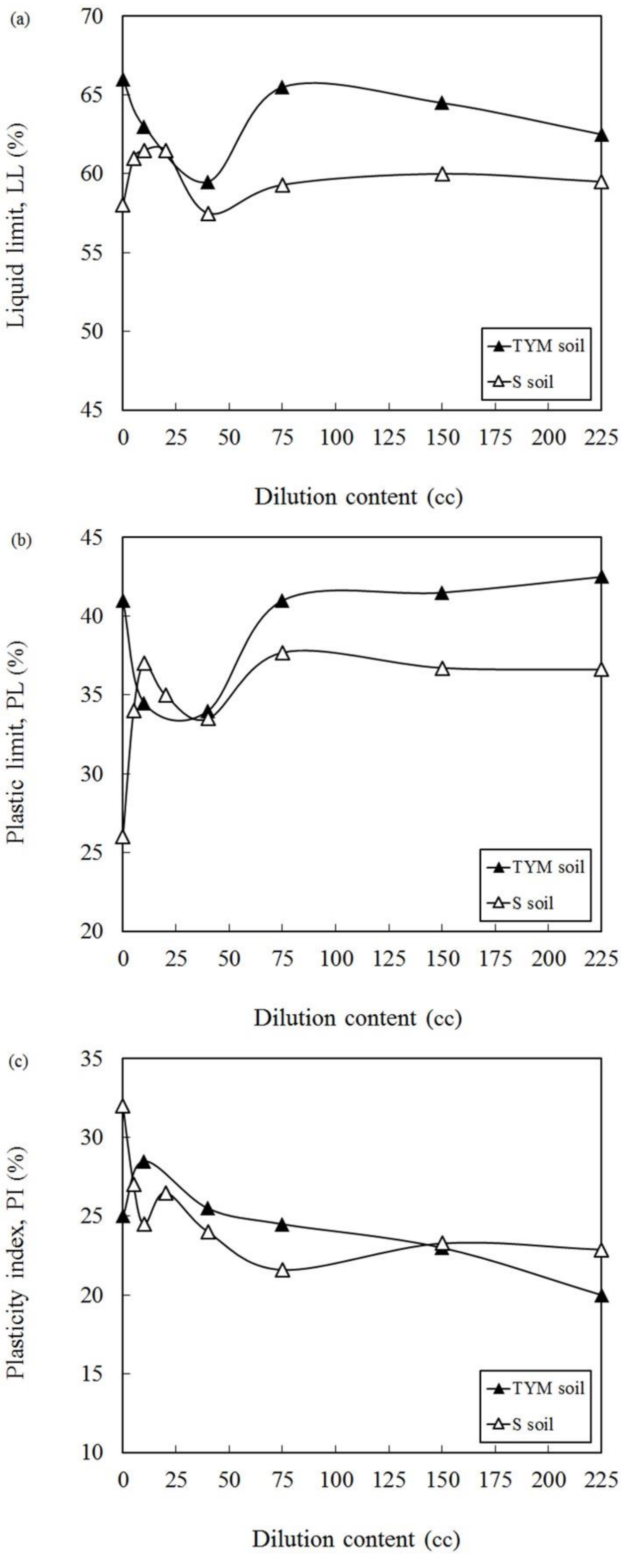

Figure 2 Effect of CBR-Plus contents on atterberg limits of Tabriz Yellow Marl and Sayin soils: a) liquid limit, b) plastic limit and c) plasticity index

Reducing LL and PL as well as increasing PL due to CBR-Plus addition may be related to removing the adsorbed water from the soil particles. As reported by Ziaie Moayed & Allahyari (2012) CBR plus reduces ion mobility and ion exchange and simultaneously make the material hydrophobic by eliminating the adsorption of water. The result is a soil material that is much less sensitive to moisture and more workable.

4.2 Compaction Characteristics

Effect of CBR-Plus dilution on compaction curves of soils are indicated in Figure 3. As observed in Figure 3(a), addition of 75 cc CBR-Plus increases the maximum dry unit weight of the TYM about 4.41%, whereas other amounts of the dilution has no sensible effect on compaction characteristics of the natural soil. Addition of dilution to the S soil not only has no significant effect on the compaction characteristics, but also decreases the maximum dry unit weight of the natural soil (Figure 3(b)).

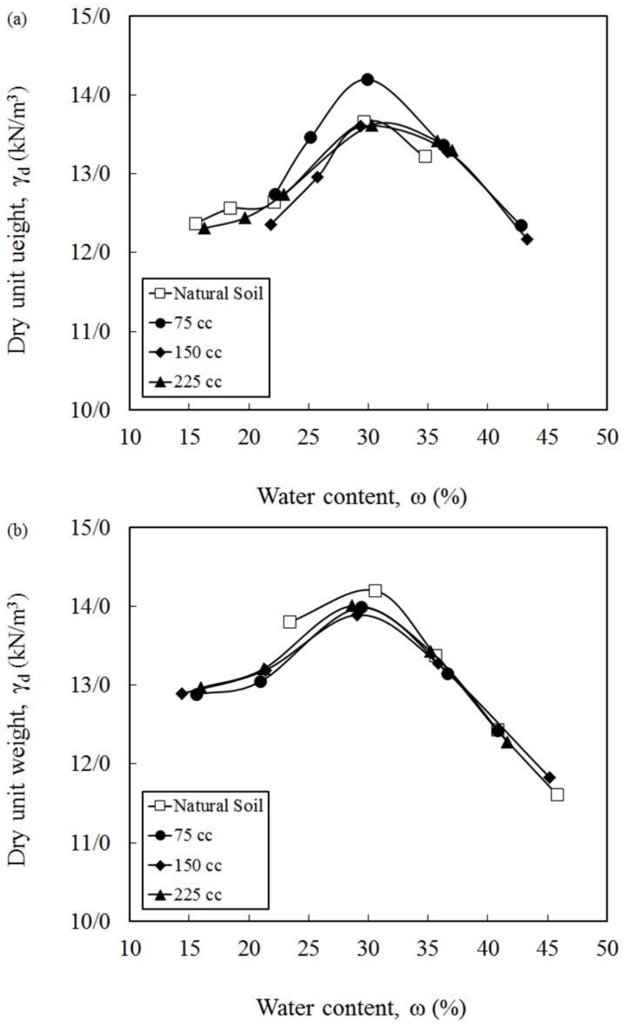

Figure 3 Test results of standard proctor compaction on natural and stabilized specimens: a) TYM soil, b) S soil

Moreover, the effect of this material on optimum water contents of TYM is negligible, but it reduces optimum moisture of the S soil from 30.0% to 28.0%. It can be concluded that the effect of CBR-Plus on compaction characteristics of the tested soils is insignificant.

4.3 Undrained Behaviour

In this part, the effect of CBR-Plus polymer on the mechanical properties of specimens is discussed. The results of triaxial tests on natural and stabilized TYM and S soils are presented in Figures 4 and 5, respectively, in the form of stress-strain curves, excess pore water pressure, and stress paths under $\sigma'_c = 200\ kPa$. The similar results for TYM soil under $\sigma'_c = 300\ kPa$ are presented in Figure 6. It should be noted that in stress-strain and excess pore water pressure diagrams, vertical axis is deviator stress $(q' = \sigma_1\text{-}\sigma_3)$ and excess pore water pressure due to shearing (Δu), respectively. Horizontal axis in both of these diagrams is total axial strain (ε_a). In stress path diagrams, vertical and horizontal axes are deviator stress and mean normal effective stress $(p' = (2\sigma'_3+\sigma'_1)/3)$, respectively.

4.3.1 Stress-Strain Behaviour

Figure 4(a) shows that stress-strain curves of the stabilized specimens are located above or coincided to that of untreated TYM soil. Specimens containing 40 cc and 75 cc dilution show more shear strength in comparison with other specimens. For S specimens, stress-strain curves of specimens containing 40 cc and 75 cc dilution are located upper from the others. It means that 40 cc and 75 cc CBR-Plus dilution have positive effect on shear strength of TYM and S soils (Figures 4(a) and 5(a)).

As mentioned, some of the tests were conducted on TYM specimens under isotropic effective consolidation stress of *300 kPa*. In this case, the same trend was observed and the specimen stabilized with 40 cc and 75 cc dilution showed greater shear strength (Figure 6(a)).

4.3.2 Excess Pore Water Pressure

The changes of excess pore water pressure in TYM and S specimens with different CBR-Plus contents under $\sigma'_c = 200\ kPa$ are depicted in Figures 4(b) and 5(b). Similar graph is displayed in Figure 6(b) for TYM and its stabilized samples under $\sigma'_c = 300\ kPa$. For TYM specimens, the more CBR-Plus, the more shear-induced pore water pressure, whereas in S soil the pore water pressure decreases with an increase in CBR-Plus dilution. The maximum amount of the excess pore water pressure in TYM and S specimens is related to the specimens stabilized with 150 cc dilution.

4.3.3 Stress Path

Comparison of the stress paths, as shown in Figures 4(c), 5(c), and 6(c), illustrates that the TYM specimens with 40 cc and 75 cc dilution under $\sigma'_c = 200\ kPa$ at first exhibits contractive behaviour but then it becomes dilative. This implies that the specimen acts like lightly over consolidated soils, whereas the behaviour of the other specimens is always contractive and they act like normally consolidated soils. In the basis of soil mechanics principles, lightly overconsolidated soils may behave like normally consolidated soils under high consolidation stresses. Therefore, it is obvious why the specimen with 75 cc dilution acts like normally consolidated clays under $\sigma'_c = 300\ kPa$.

4.3.4 Undrained Shear Strength

For better evaluation of CBR-Plus impact on the shear strength of the soils, undrained shear strength of all specimens under confining pressures of *200 kPa* and *300 kPa* versus polymer content has been presented in Figure 7. It is obvious that for TYM soil under both confining pressures, there is an optimum dilution content, which improves the shear strength (i.e., 75 cc). The shear strength of other

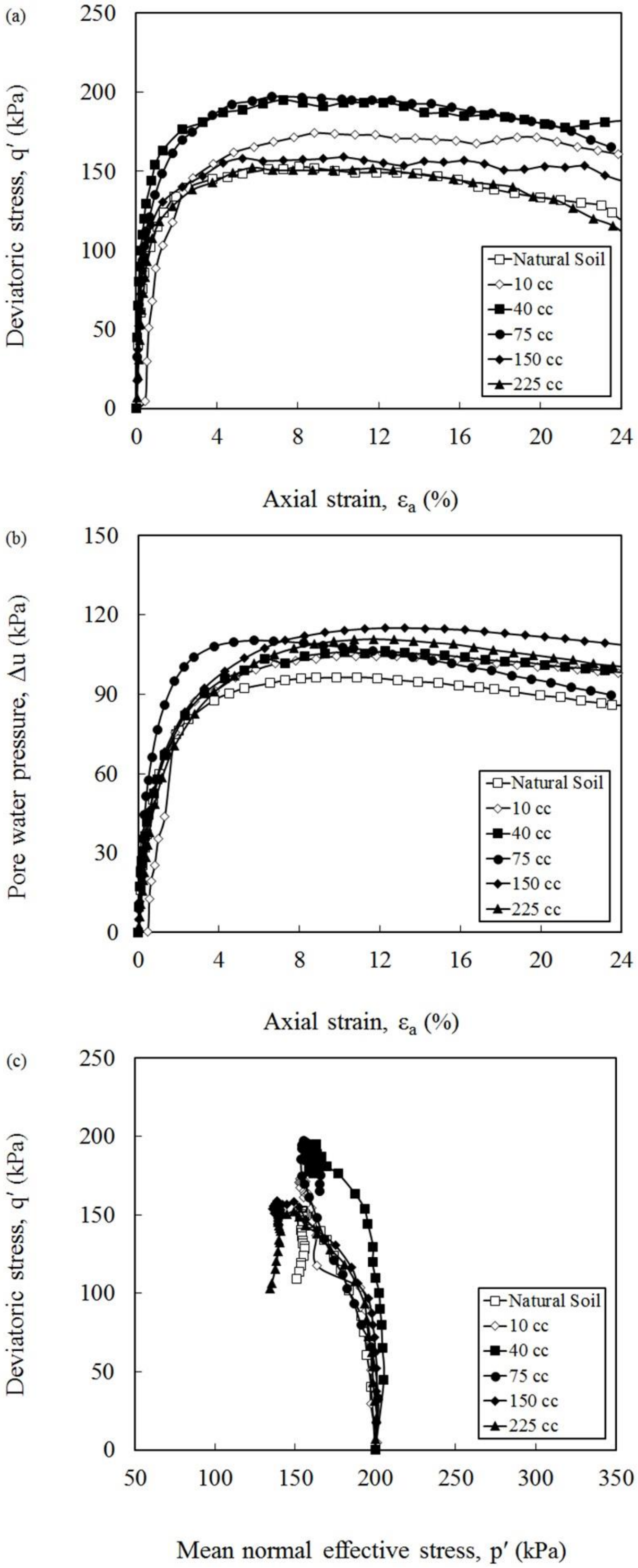

Figure 4 Results of triaxial tests on TYM specimens under σ'_c = 200 kPa: a) stress-strain curve, b) excess pore water pressure and c) stress path

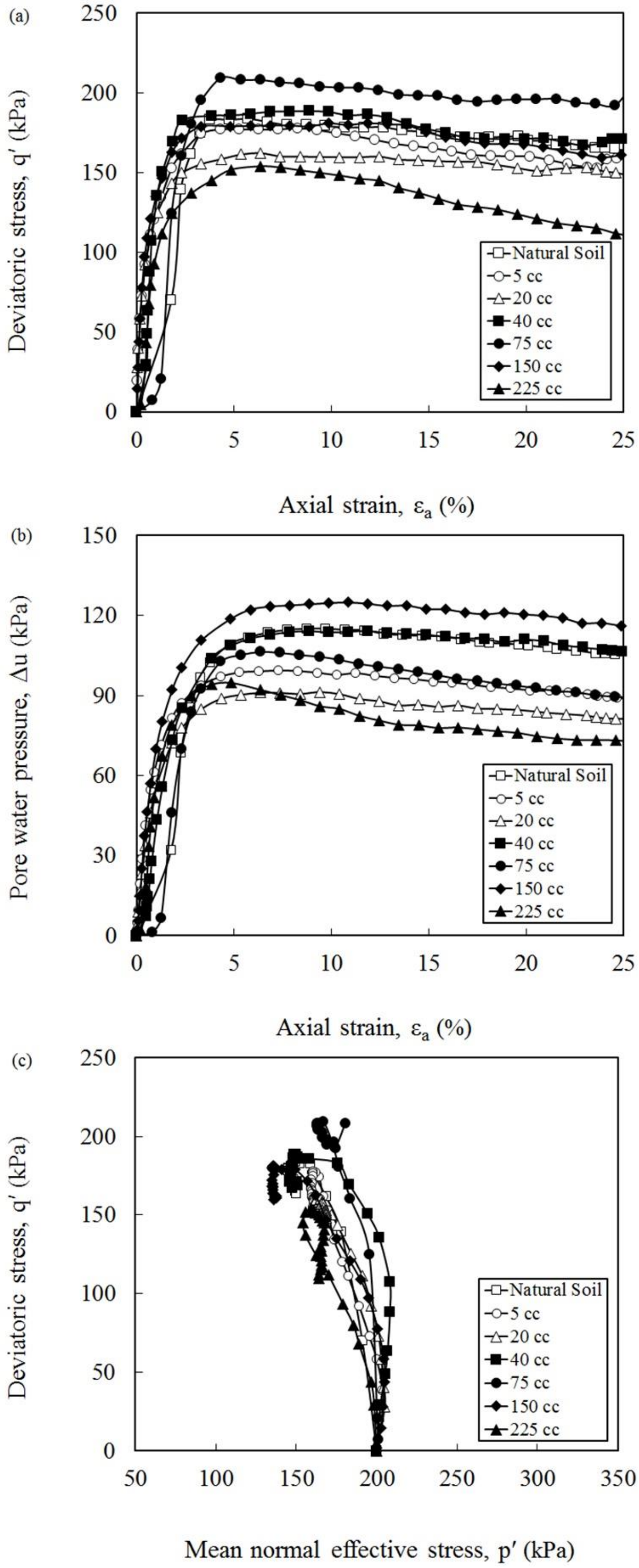

Figure 5 Results of triaxial tests on S specimens under σ'_c = 200 kPa: a) stress-strain curve, b) excess pore water pressure and c) stress path

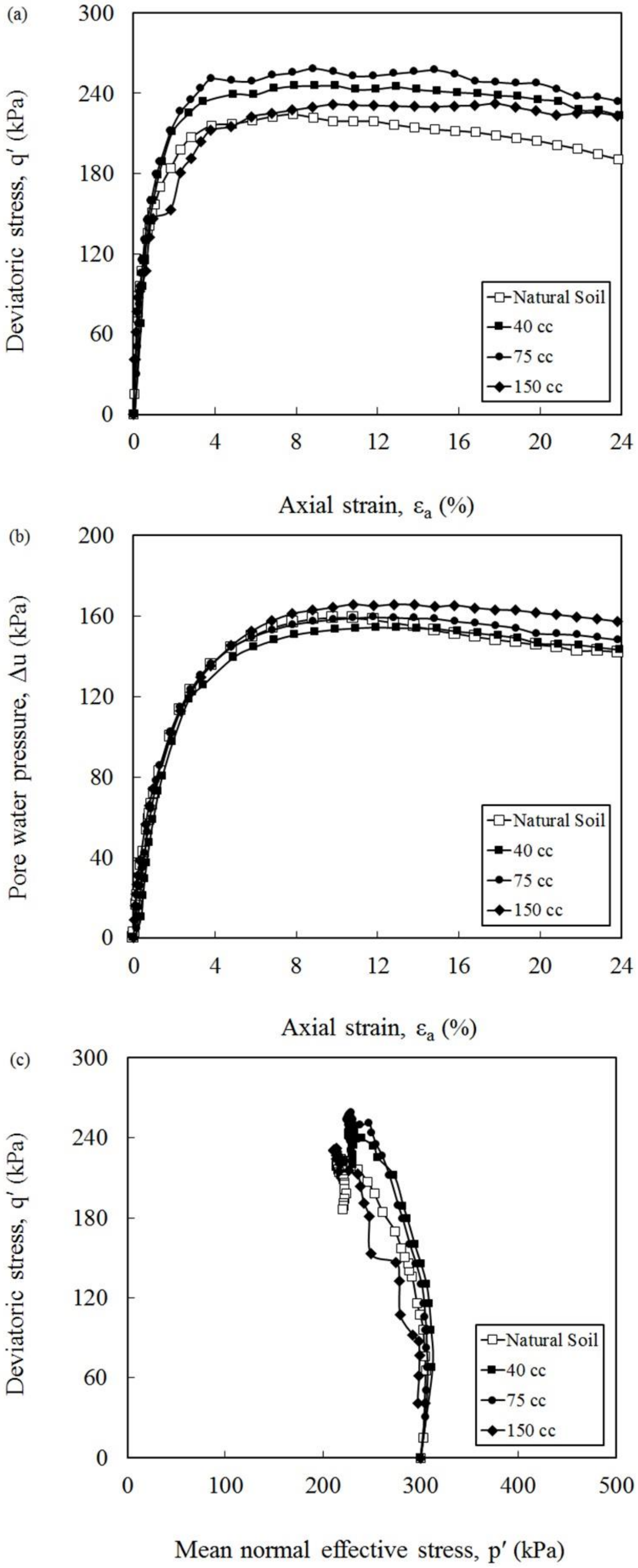

Figure 6 Results of triaxial tests on TYM specimens under σ'_c = 300 kPa: a) stress-strain curve, b) excess pore water pressure and c) stress path

stabilized specimens with polymer content more than 75 cc not only is not greater than the shear strength of the natural specimen, but also the CBR-Plus dilution has been reduced their shear strength. The maximum improvement in the shear s trength of the TYM under σ'_c = *200 kPa* and *300 kPa* is 29.0% and 15.0%, respectively (Figure 7(a)). The same strength development pattern was found for the S soil specimens in Figure 7(b). So that adding only 75 cc CBR-Plus dilution has increased shear strength about 14.0%.

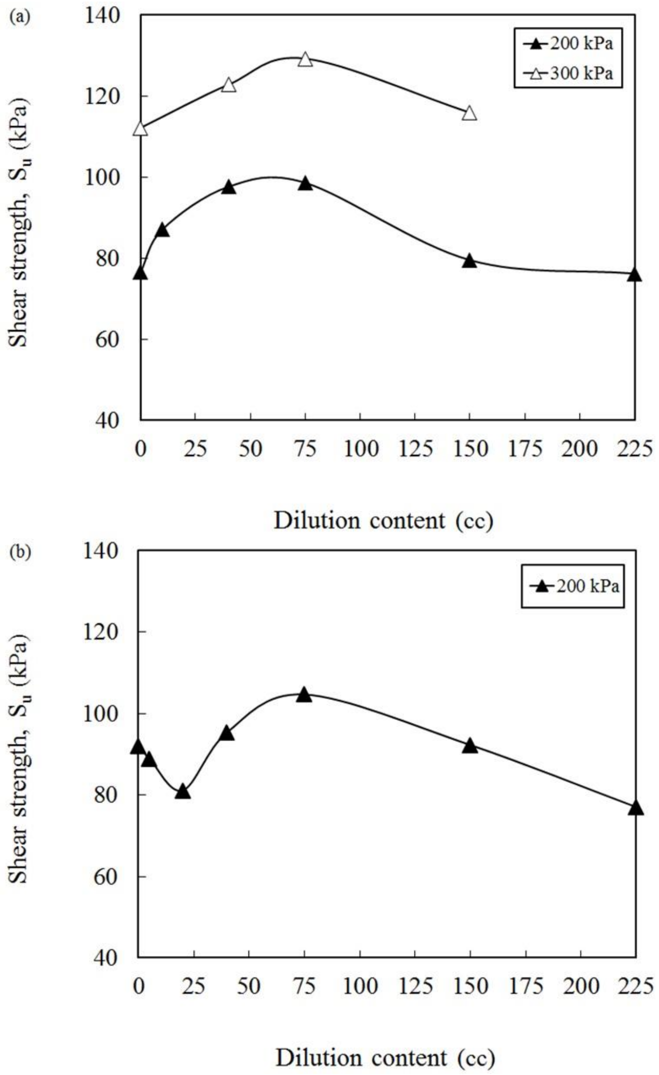

Figure 7 Variations of shear strength of specimens versus CBR-Plus contents under σ'_c = 200 and 300 kPa: a) TYM soil, b) S soil

4.3.5 Secant Deformation Modulus

For considering the influence of the polymer CBR-Plus on deformability of the stabilized specimens, the secant deformation modulus (E_{50}) of each specimen was obtained using the results of the CU triaxial compression tests. The changes of secant deformation modulus of TYM *(under σ'_c = 200 kPa* and *300 kPa)* and S soils *(σ'_c = 200 kPa)* versus CBR-Plus contents are presented in Figure 8.

It is obvious from Figure 8(a), the specimens containing 75 cc dilution exhibit the maximum secant deformation modulus under both consolidation stresses and thereby their deformability reduces. The deformation modulus of the specimen with 150 cc dilution has decreased extremely as its shear strength.

For S specimens, the similar pattern was observed, so that the deformation modulus of the specimen with 75 cc dilution increased extremely. Afterwards, the changes of deformation modulus with increasing CBR-Plus had a descending manner, as it was seen for TYM specimens.

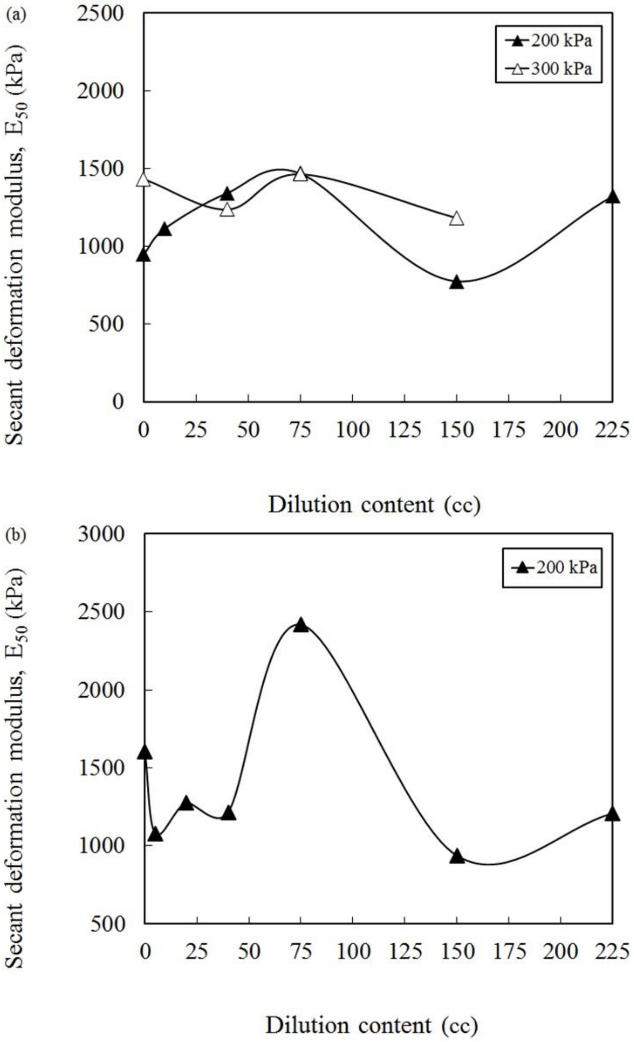

Figure 8 Variations of secant deformation modulus of specimens versus CBR-Plus contents under σ'_c = 200 kPa and 300 kPa: a) TYM soil, b) S soil

5. DISCUSSION

Ziaei Moayed and Allahyari (2012) reported that CBR plus induces a thin oily layer on the surface of clay particles, which facilitates the compaction of soil and allows water to be driven out of the soil matrix. In this process the soil can be compacted to a higher density. Moreover, CBR plus neutralizes the natural electrical charges on the surface of soil particles and then, the particles can be compacted in better manner. Therefore, it increases internal friction between the soil particles, which is resulted in a higher soil bearing capacity. These conclusions confirmed by Romel et al. (2015) for soil treated with PAM. Moreover, several researchers obtained a gain in unconfined strength of soil due to polymeric additive treatment (Liu et al, 2011; Chang and Cho, 2012; Rezaeimalek et al., 2017).

However, the test results in this study show that the effect of the CBR-Plus polymer on compaction characteristics of the studied soils is not significant. Also, there is an optimum content for this polymer that the shear strength increases. In less or more than this optimum additive amount, the shear strength decreases as well.

When polymer additives are added to the soil may fill up the voids between soil particles, stay on the soil aggregates surface. Its hydrophilic groups in molecular structure chemically react with positive ions of clay particles and creates physicochemical bonds between molecules and soil aggregates (Liu et al., 2011). As a result, the strength and cohesion of the soil is improved after polymer treatment. Adding more concentration of polymer additive can fill up more voids and produce more bonds and hence result in the greater strength of the soil.

SEM micrographs, presented in Figures 9 and 10, compare total texture, spatial distribution, connection between soil particles for natural and treated specimens of both TYM and S soils. Figure 9(a) shows clay matrix and inter-assembling voids of the natural TYM specimen. Addition of 10 cc polymeric dilution to the soil lead to decrease the inter-assembling voids fairly (Figure 9(b)). As indicated in Figure 9(c), with increasing CBR-Plus dilution content, the changes in morphology of clay particles and their arrangement have occurred, so that the external surface area reduced by filling the soil pores with new gel-like cementitious materials (Latifi et al., 2015a; Latifi et al., 2015b).

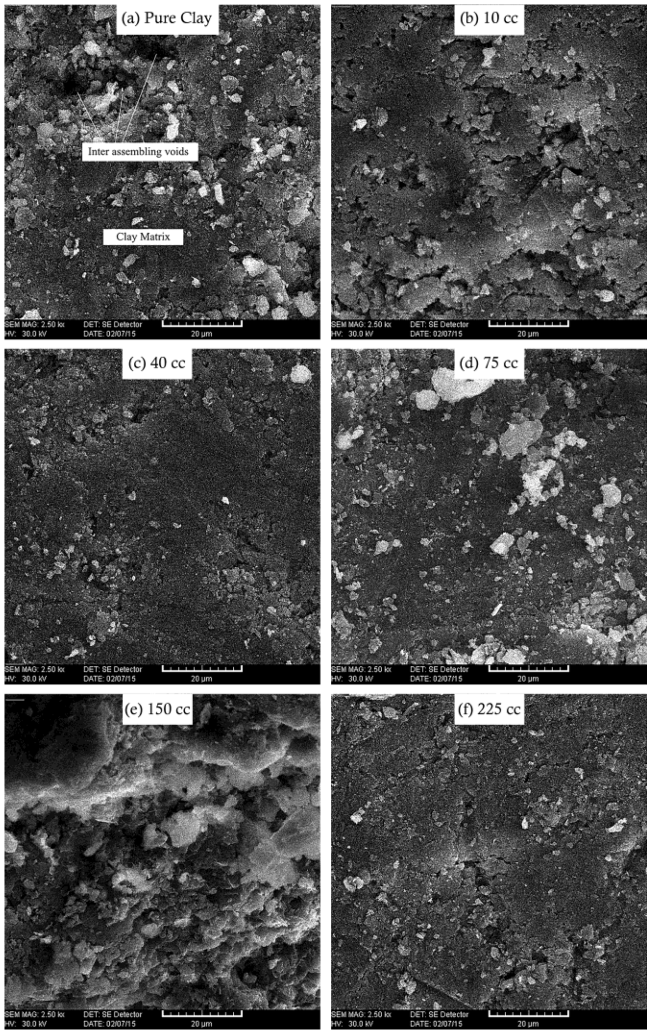

Figure 9 SEM micrographs of TYM specimens with: a) 0 cc, b) 10 cc, c) 40 cc, d) 75 cc, e) 150 cc and f) 225 cc CBR-Plus dilution

The SEM micrograph of the TYM soil with optimum CBR-Plus content (i.e., 75 cc dilution) shows that the micro-structure of the soil has changed significantly, so that it has a dense and continuous matrix and less inter-assembling voids than the natural one (Figure 9(d)). Mentioned mechanisms has been led to transform soil structure from a porous structure into a more flocculated dense structure in CBR-Plus treated soil with optimum additive (Latifi et al., 2016b). That is why this specimen has shown more shear strength. Also, reducing pores and continuity of the matrix has led to deformability reduction and increasing of stiffness of the specimen. Other treated specimens showed little structural modification as they had less increase in their shear strength.

A similar scenario was seen for S specimens. At low CBR-Plus contents it appears that the soil-CBR-Plus mixture is rather homogeneous as shown in Figures 10(a) to 10(d), but in the specimen containing 75 cc dilution the soil particles are well bonded together (Figure 10(e)). This specimen has a dense and continuous matrix and extremely reduced inter-assembling voids, which is the main reason for high shear strength of this specimen. It means that these images prove results authenticity with respect to shear strength.

As obvious in Figures 9(e) and 9(f), the addition of CBR-Plus more than optimum content to the soil may lead to strength reduction, because in this condition most of the voids fill up by enough polymer content and clay particles fully react with the hydrophilic groups, but an excessive amount of polymer reduces the connections between soil particles.

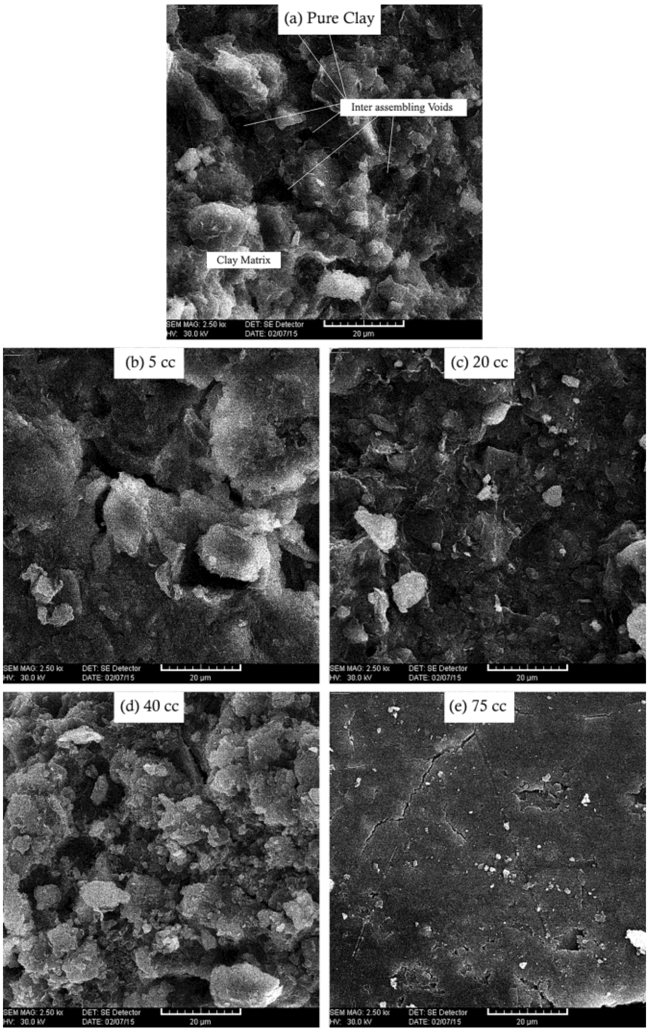

Figure 10 SEM micrographs of S specimens with: a) 0 cc, b) 5 cc, c) 20 cc, d) 40 cc and e) 75 cc CBR-Plus dilution

6. CONCLUSION

In this study, the effect of the CBR-Plus polymer on physical and mechanical properties of two fine-grained soils and their microstructural changes was investigated. In this regard, the following conclusions can be drawn:

- The maximum decrease in plasticity index of TYM and S soils are 20.0% and 32.5%, respectively. In general, addition of CBR-Plus polymer more than 150 cc on Atterberg limits of the studied soils is inefficacious. It could be said that, depending on the type of clay and its PI, CBR-Plus polymer changes the plasticity properties of fine-grained soils.
- The maximum dry unit weight of the TYM soil increases about 4.41%, only in the specimen stabilized with 75 cc dilution. Other CBR-Plus concentrations has no significant effect on compaction characteristics including optimum moisture content of the TYM and S specimens.
- The CBR-Plus polymer does not always increase the shear strength of the clayey materials. Maximum increase in the shear strength of TYM and S soils is 29.0% and 14.0%, respectively, which is observed at the CBR-Plus content of 75 cc. In fact, depending on the type of the soil, there is an optimum amount for this polymer, in which the shear strength increases. However, the strength decreases when the dilution exceeds this optimum amount. Since the used amount of this polymer in practice is so sparing therefore, this reduced strength would be because of excess use of the material and lubrication between soil particles.
- CBR-Plus increases secant deformation modulus of TYM and S soils up to 55.0% and 51.0%, respectively on the specimens stabilized with 75 cc dilution. As a result, the maximum reduced deformability and more stiffness has been seen in these two specimens.
- Evaluation of the SEM images shows that both TYM and S samples stabilized with 75 cc CBR-Plus dilution has a dense and continuous morphology, so that inter-assembling voids decrease extremely. Therefore, these specimens exhibit more shear strength compared to other specimens.

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8. ACKNOWLEDGEMENT

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