Improving Physical Characteristics of Collapsible Soil (Case Study: Tehran-Semnan Railroad)

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Abstract

Collapsible soils could widely be found in central part of Iran and has caused lots of problems for roads and railroads in that region. Appearance of wide cracks in the collapsible soil near the Tehran-Semnan railroad tracks has caused some worries regarding the safety and performance of the railroad. However, due to the high traffic of the railroad, it is impossible to block the road for remedy. Therefore using injection method was found the most suitable alternative to improve the soil along railroad. The results of field and laboratory tests revealed that the injection of lime has better effects on improving soil characteristics than the other materials. It will significantly decrease the collapsibility potential of soil in saturated condition and will cause an increase in loading capacity of soil. Lime injection was suggested as the most appropriate solution for projects with similar geological condition.

Keywords: Collapsible Soil, Triaxial Test, Injecting Grout, Lime, Cement, Micro silica.

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Introduction

Basically, all kinds of soils that are not suitable for construction and their bearing capacity under different weather conditions are variable, are called problematic soils. These kinds of soils are generally found in different forms such as swelling soil, water attracting soil, collapsible soil and weak soil. The phenomenon of collapsibility in soil is described as sudden collapse due to loosing of shear resistance of soil's particle which would be because of changes in humidity. The amount of collapsibility generally is depended on initial ratio of soil porosity. High porosity (more than 40%), low saturation degree (lower than 60%), high layering degree (more than 30%, sometimes 90%) and prompt softening in water are the main characteristics which cause a soil to be collapsible.

In order to discriminate the collapsibility potential of soil, several investigations are performed (Abelev (1984), Clevenger (1958), Gibbs & Bara (1962), Denisov (1963), Feda (1966), Fookes & Best (1969), Handy (1973), Jennings & Knight (1975), Lin & Wang (1988), Rollins & Rogers (1994) and Beckwith (1995)) and different criteria were suggested.

The main offered criteria are based on laboratory tests that conducted on undisturbed and remolded samples of collapsible soil. These tests usually are grain size distribution test, hydrometric test, Proctor test and consolidation test.

Methods for remedying collapsible soil are generally replacing the collapsible soils by suitable building materials, compaction of the soil, appropriate drainage system in order to prevent the soil of getting wet, chemical stabilization or injection, pre-wetting or wetting the soil in a controlled manner, dynamic compaction, using pile foundations, using water explosion and compaction of collapsible soils by explosion energy.

This paper is trying to find the best method of remedying collapsible soil for a site near Tehran-Semnan railroad in the north of Iran. Therefore among the above mentioned methods, injection is of interest of this research; because it can be done while this high traffic railroad is being used.

Pengelly et al. (1997) studied injecting of mud in collapsible soil. Covil and Skinner (1994), Stroud (1994), Lee et al. (1997), investigated the effects of different parameters of penetrating injection on collapsible soil. Wang et al. (1998) studied the jet grouting effects on diaphragm wall and the surrounding soil for a project in Singapore with two basements in marine clay. Effects of the jet grouting, direct loading on the Diaphragm Wall (D/W) due to the jet pressure and surcharge due to upheaval were studied by finite element method. The numerical results were compared with the readings from the inclinometer installed in the diaphragm wall and surrounding soils. It was found that jet grouting pressure will cause the deflection to limited extent. The magnitude of the displacement depends upon the soil surrounding the wall, jet grouting type and overburden pressure. A displacement-control method was proposed to reduce the deflection of D/W and the surrounding soils outside the D/W during jet grouting work. Brown and Warner (1973), Graf (1969 and 1992) studied the effects of compacting injection on mechanical parameters of soils. Borden et al. (1992) and the ASCE Committee (1978) performed some investigations on stabilizing the soils by cement injection. Bicalho et al. (2002, 2004a, 2004b) studied the stabilization of lax soils in order to increase loading capacity and decrease collapsibility of soil. They analyzes the application of deep compaction through sand columns driven with Franki-type equipment, and shallow compaction by vibratory plate, for improvement of loose sandy soils supporting heavily loaded structures using shallow foundation. They presented and discussed the results of the compaction processes to provide guidance for future projects. The discussion included distance from the sand column, initial relative density, time delay for results verification after compaction, and depth. The analyses demonstrated the method efficiency. Reznik (2007) introduced structural pressure values as separation “points” between elastic and plastic states of collapsible soils subjected to loading. He identified collapsibility of soils as a non-elastic deformation. He also mentioned that the collapse of soils starts when the applied stress exceeds soil structural pressure values (initial collapse pressures) which depend on change of some soil physical properties. He eventually proposed some new analytical expressions describing dependence of mechanical characteristics of collapsible soils on soil void ratios and moisture contents. The obtained equations were verified by previous published papers. Mendes and Lorandi (2008) analyzed spatial variability of SPT penetration resistance in collapsible soils considering water table depth. In other words, they analyzed the potential of water table depth variations on the spatial variability of penetration resistance (N_{SPT}) in collapsible soils. Geo-statistical kriging approach was used for mapping of water table depth and for checking its influence on penetration resistance observed in standard penetration test (SPT).

Gaaver (2012) presented the effect of compaction on the geotechnical properties of the collapsible soils. Undisturbed block samples were recovered from test pits at four sites in Borg El-Arab district, located at about 20 km west of the city of Alexandria, Egypt. The samples were tested in both unsoaked and soaked conditions. Influence of water inundation on the geotechnical properties of collapsible soils was demonstrated. A comparative study between natural undisturbed and compacted samples of collapsible soils was performed. An attempt was made to relate the collapse potential to the initial moisture content. An empirical correlation between California Bearing Ratio of the compacted collapsible soils and liquid limit was adopted. The presented simple relationships should enable the geotechnical engineers to estimate the complex parameters of collapsible soils using simple laboratory tests with a reasonable accuracy. Benatti and Miguel (2013) proposed structural models for understanding the collapsibility of a colluvial and lateritic soil by conducting oedometric tests with controlled suction executed in laboratory. There were behavioral differences in each soil sample collected at different depths. The behavior of the sample collected at a 1.5 m depth was basically influenced by matric suction. As for the samples collected at 4.5 m and 6.5 m, besides being both influenced by matric suction they were also influenced by the presence of cementing agents (samples collected at 4.5 m) and by the presence of more angular grains of quartz (samples collected at 6.5 m).

Observing considerable surface cracks in soil and some cracks that are vertical to railroad especially adjacent to Semnan station is one of the problems that Tehran-Semnan railroad system is facing to, during recent years. Offering a suitable method for stabilization of bed soil during performance of the railroad is an important issue for maintenance of railroad which has been particularly investigated in this paper. After doing graining test for the soil of the mentioned region and verifying the existence of collapsible soil, the effects of injecting chemical stabilizers such as lime, cement and micro silica were studied. A large number of field and laboratory test were performed and improvement of characteristics of collapsible soil was investigated.

Problem definition

1. General characteristics of collapsible soils

Some soils show a promptly decrease in their volume by increasing the water content and reaching saturate state. These kinds of soils are usually found in environment at semi-saturated or dried state and are just like expanded soils. They do not show any change in their volume and would not cause any problem for structures till the humidity of soil have not been changed. The collapsing soils usually include sand, mud and clay which are found in dry area in vicinity of mountainside. These kinds of soils that are sediment in a form of semi-stable would become instable because of saturation and dehydration. It seems that the structure of soil in semi-saturated condition is stable due to surface tension of water in contact area of soil particles. Saturation will lead the porous area of soil to be filled with water and consequently surface tension of water will become zero and the soil will collapse. In dry soil the stability of soil particles is secured by layers of clay minerals that were absorbed and placed in small holes during dehydration time. In fact, collapsing of this kind of soil is because of suspending the clay particles in water in saturate condition.

In large scale, decreasing of volume due to saturation is a problem that will rise during agriculture and watering some valleys of dry regions. Due to existence of those sediments the watered area will collapse and consequently it will damage existent structures such as pipe line and roads.

2. Different methods for stabilizing collapsible soils

Table 1 shows some of the methods that were suggested by U.S Army (1990) to remedy collapsible soils.

Table1. Different methods for improving performance of collapsible soil (U.S Army (1990))

Depth of Soil (m)	Description
0 to 5	Wetting, mixing, and compaction
> 5	Over excavation and recompaction with or without chemical additives such as Lime or cement Hydro compaction Vibroflotation Lime pressure injection Sodium silicate injection Pre-wetting by pounding; vertical sand drains Promote wetting of subsurface soil

For the railroad that is being studied in this research, because of the high traffic and being impossible to block the railroad, one of the most suitable alternatives is injecting of chemical materials to soil. Its effectiveness and feasibility however was studied by in-situ and laboratory tests in this paper. Injection means filling cracks and holes of ground by fluid material which will result decreasing of the permeability and increasing of soil resistance.

3. Geological Characteristics of Semnan Plain, central north of Iran

The oldest outcrops of Semnan plain is relates to Protozoa period that are scattered in north-west and south-west of the plain. These kinds of deposits are mainly in a form of erosive foothill and are almost amorphous. However, the vast area of studied site is covered by Quaternary deposits that are scattered in all the area. Therefore it can be said that the studied region is completely young and is very sensitive to water erosion. The foothill parts include loose conglomerate texture and red plaster marl which are related to high

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Protozoa (Figure 1). Studying the topography of Semnan plain reveals that the slope of this area is very smooth and because of its other mentioned characteristics, it can be categorized as loess plain.

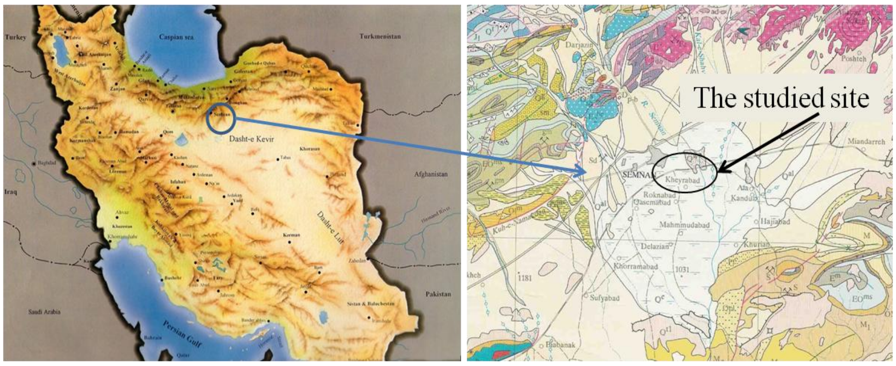

Figure 1. The geological topography of Semnan Plain

In-situ and laboratory studies

During the past several years, due to the heavy traffic of railroad, some big cracks are created near the rail track which seems to be so dangerous for the trains (Figure 2). Several in-situ and laboratory investigations were conducted in order to evaluate the collapse potential of the soil and suggesting the most proper method for remedying the site.

Figure 2. Vertical crack near the railroad in Semnan plain

Both remolded and intact samples were obtained for laboratory tests. The remolded samples were used to conduct initial laboratory test such as liquid limit, plastic limit maximum dry density and finding chemical properties. Meanwhile the monolithic undisturbed samples were obtained by using a 40×40 wooden frame (Figure 3). For humid insulation, paraffin was put between two polystyrene plates at top and bottom of box. These samples were used for consolidation and shear strength tests. Each sample would take 4 to 6 hours to be obtained. Since the soil is so sensitive to shaking, pushing the box in the soil was not possible. Therefore, to minimize the effect of carving on the sample, a thin brush was used to sweep the soil around the box which has already placed on the ground. Continuing of sweeping will cause the box to be pushed in the soil by its own weight. Therefore a sample with minimum disturbance can be obtained for laboratory tests. It should be mentioned that this method is also used by archeologist in new found historical places to excavate historical objects.

Figure3. Monolithic sampling method

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After primary laboratory investigation on samples, three materials found to be suitable for injection: lime, because of existence of clay in soil, cement, in order to create proper cohesion between soil particles, and micro silica, due to its filling property. Injections were performed by using injection instrument at depth of one meter. In order to prevent uprising and to increase bearing capacity of soil to stand compression of device during injection, cement-sand mortar with adding micro silica (to reduce permeability of the mortar) was placed over ground with height of 20 cm and at a radius of 35 cm from center of injection. Chemical material which was mixed with the same amount of water was made the slush ready to inject. The injections were done in three boreholes with depth of 1m and diameter of 10 cm in a triangular arrangement with distance of 30 cm in each side (Figure 4). Operating pressure was between 200 and 250 kPa.

Figure4. Injection plan

Sampling was done 28 days after injection. The temperature was 32°c and intact samples were obtained by monolithic method that describe above. Soil samples with different injected materials have been shown in Figure 5.

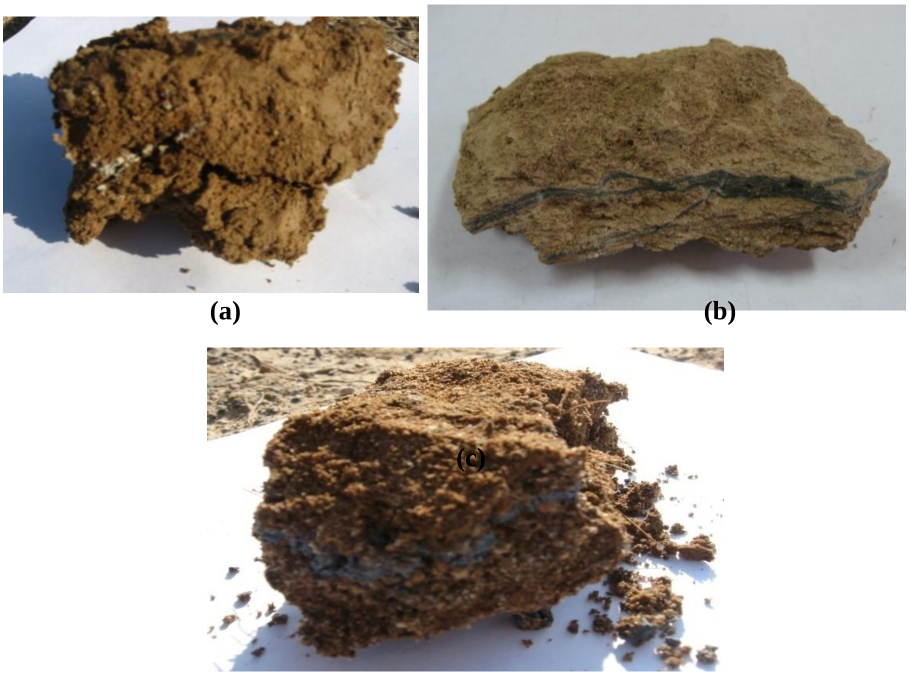

Figure 5. Veins of injected materials in in-situ soil sample (a). Lime (b). Cement (c). Micro silica

Results and discussions

Basic laboratory tests were performed on the soil samples to find different characteristics of soil. Table 2 lists the physical and chemical characteristics of the soil, while Figure 6 shows its grain size distribution curve. The soil is classified as ML according to the Unified Soil Classification System (USCS) and natural water content of soil was equal to 5 percent. The result of SPT test shows that the soil is classified as medium dense.

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Consolidation tests (ASTM D5333-03) were also performed to measure potential of soil for settlement. Different stresses equal to 0.25, 0.5 and 1 kg/cm^2 were applied to soil at natural water content and then samples were consolidated under various stresses (1, 2, 4 and 8 kg/cm^2) in saturated condition. Figure 7 shows soil consolidation curve with natural water content.

Table2. Soil characteristics

LL	PL	N_{SPT}	γ_d (kN/m^3)	G_s	PH	Calcium content Ca (mg/L)	Sodium content Na (mg/L)	Electrical Conductivity EC (dS/m)
32	17	14	13.8	2.56	8	48	40	25.4

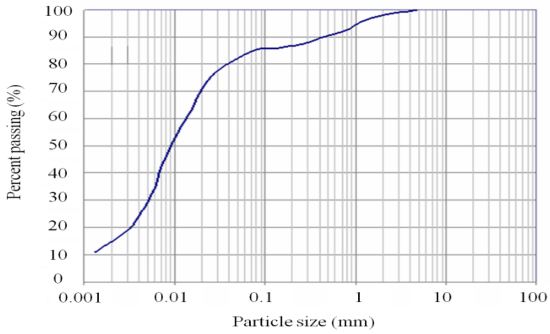

Figure 6. Grain size distribution curve of soil

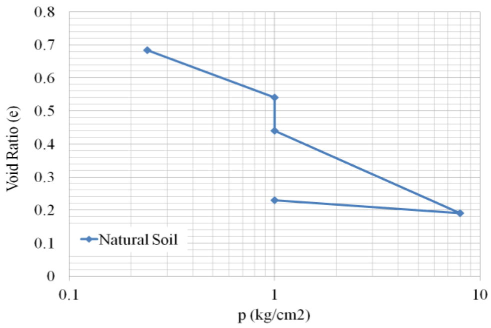

Figure 7. Soil consolidation curve with natural water content (ω=5%)

There are different criteria for determining the collapse potential of soil. Some of these criteria were presented in Table 3 and the coefficients of collapsibility of Semnan plain are calculated according to these criteria. The results show that the intensity of collapsibility of the soil is medium and high.

Table3. Assessing the collapsibility of soil according to different criteria (before injection)

Proposed criterion	Collapsibility coefficient	Collapsibility coefficient rang	Collapse intensity
Abelev (1948)	$\delta_S = \frac{\Delta e}{1+e_1} = \frac{0.54-0.45}{0.45+1} \times 100 = 6.2\%$	6.2 > 2	High
Denisov (1964)	$\frac{e}{e_{LL}} = \frac{0.54}{0.45} = 1.2$	1.2 > 1	Medium
Clevenger (1985)	$\gamma_d = 1.38\ g/cm^3$	1.28<1.38<1.44	Medium
Jennings & Knight (1975)	$C_{col} = \frac{\Delta h}{h} = \frac{0.1}{1.9} \times 100 = 5.26\%$	$5 < 5.26 < 10$	Medium
ASTM D-5333	$I_C = \frac{\Delta h}{1+h_0} \times 100 = \frac{0.1}{1+1.9} \times 100 = 3.45\%$	$2.1 < 3.45 < 6$	Medium

4.1. Effect of injection on collapsing potential of soil

Several consolidation tests (ASTM D5333-03) were performed on different samples including natural soil and samples with different injected materials. Figure 8 makes a comparison between the results of these consolidation curves. Characteristics of natural and injected soil samples are presented and compared in Table 4. Results reveal a great improvement in most of soil characteristics.

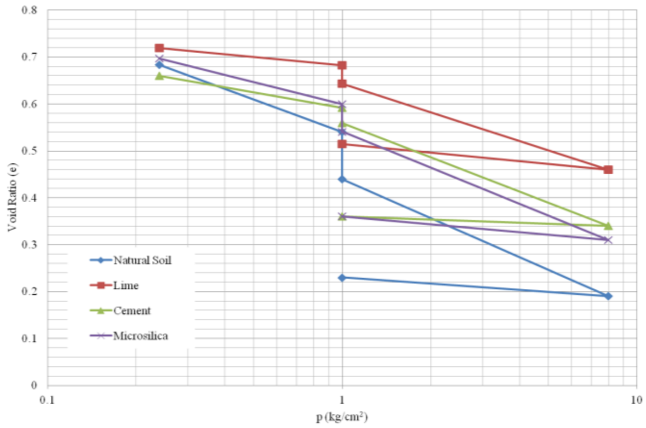

Figure 8. Comparison between natural soil consolidation curve and injected samples

Table4. Characteristics of natural and injected soil samples

Samples	Initial void ratio (e_0)	Final void ratio (e_F)	Liquid limit (LL)	Plastic limit (PL)	Swelling index (C_s)	Compression index (C_c)	Specific gravity (G_s)	N_{SPT}
Natural Soil	0.95	0.23	29	22	0.040	0.20	2.56	14
Lime	0.79	0.46	17	11	0.060	0.21	2.59	21
Cement	0.81	0.34	18	13	0.025	0.26	2.65	26
Microsilica	0.85	0.31	24	17	0.061	0.28	2.65	23

Results of consolidation tests show that the amount of soil settlement after saturation was 0.036, 0.037 and 0.062 cm for lime, cement and micro silica injected samples respectively. Results of standard penetration test (SPT) in different injected soil show 50~85 percent increase which implies a significant improvement in soil resistance. On the other hand, Atterberg limits reveal reduction in soil

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plasticity properties. However in order to find a better understanding on the effect of injection on collapsing potential, collapsibility coefficient for all samples were calculated according to ASTM D-5333 (2003) and are presented in Table 5. As it can be seen, collapsing potential is decrease about 70, 63 and 40 percent for lime, cement and micro silica injected samples respectively.

Table5. Collapsing potential

Soil Sample	Collapsibility coefficient	Collapsibility coefficient
Natural soil	$I_C = \frac{\Delta h}{1+h_0} * 100 = \frac{0.1}{1+1.9} * 100 = 3.45\%$	3.45
Lime	$I_C = \frac{\Delta h}{1+h_0} * 100 = \frac{0.033}{1+1.9} * 100 = 1.14\%$	1.14
Cement	$I_C = \frac{\Delta h}{1+h_0} * 100 = \frac{0.037}{1+1.9} * 100 = 1.28\%$	1.28
Microsilica	$I_C = \frac{\Delta h}{1+h_0} * 100 = \frac{0.062}{1+1.9} * 100 = 2.13\%$	2.13

2. Effect of injection on shear resistance of the soil

To investigate the effect of injection on shearing resistance of soil, some triaxial tests are conducted. These tests are performed on intact samples and in CU (Consolidated-Undrained) condition (ASTM D-2850-03a (2007)) to simulate natural circumstance. Figure 9 shows the stress-strain curves for different samples which are obtain from triaxial tests.

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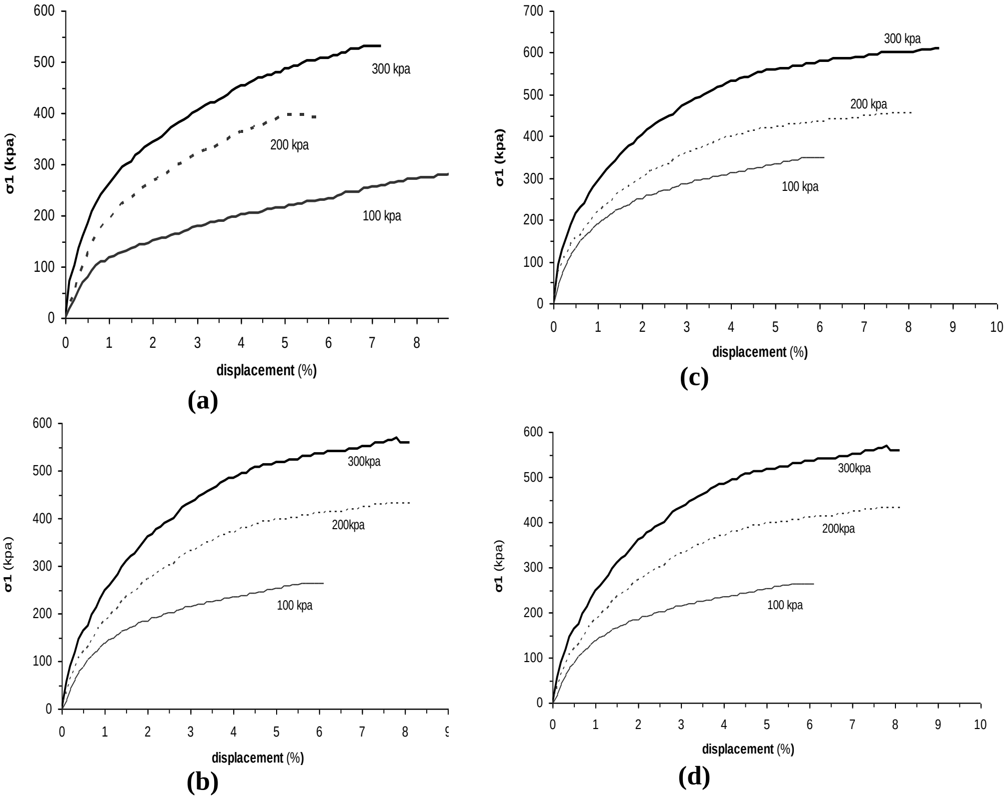

Figure 9. Stress-strain curves for different samples, (a). Natural soil (b). Lime injected soil (c). Cement injected soil (d). Micro silica injected soil

Table 6 shows the undrained and effective shear parameters of soils. As it can be seen, φ_{cu} and φ' have increased up to 2.5 times and 1.5 times of their initial values in natural soil respectively.

Table6. Shear parameters of different samples

Samples	C_{cu} (kPa)	φ_{cu} °	C´ (kPa)	φ' °
Natural Soil	70	5.7	54	13
Lime	46	14.7	35	20
Cement	45	18.6	32	24
Microsilica	42	14.4	25	20.4

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Conclusions

Laboratory and field investigation were done to study the effect of injecting different materials on remedying collapsible soil. The following specific conclusions can be drawn from the study:

1. Based on the results of consolidation tests for natural soil, and consideration of different standards, it can be concluded that the soil of Semnan plain is a kind of collapsible soil which Jennings & knight (1975) and ASTM (2003) criteria. Therefore, these criteria can be used in plain with similar geological condition for evaluation the collapsing potential.
2. Results of consolidation test on intact soil samples before and after injection show that the collapsing potential of the soil would decrease up to 70, 63 and 40 percent for lime, cement and micro silica injection respectively. It can be said that injection of proper materials significantly decreases the collapsing potential of the soil.
3. Lime and cement injection have more efficiency in comparison with micro silica injection which would be because of proper chemical reaction between soil particles and injected materials, and filling of void in soil.
4. Injection of lime, cement and micro silica considerably increase internal friction angle of soil and consequently shear strength properties of soil.

5. Injection would increase the soil bearing capacity and increase N_{SPT} up to 85% while it would decrease soil plasticity properties.

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