Investigation of the short-term behaviour of silty sand stabilized by colloidal silica

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Abstract

Injection in soils using traditional materials, such as cement grout, has its inherent problems and has not shown the potential for further development in industrial applications. Accordingly, application of novel materials for injection in soils with considerable content of fines for stabilizing and even making them impermeable is suggested. Among different stabilizers that are injectable in soils with fine, colloidal silica seems very suitable due to its very low viscosity, nontoxicity in the nature, and adjustability of the setting time for slow injection in soils with fine. Based on laboratory tests performed in this research, the effect of colloidal silica on the strength parameters and the short-term behaviour of silty sand was examined. For characterizing the soil stabilized by colloidal silica, the silty sand samples with different silt values, in both unstabilized and stabilized conditions, were prepared with different concentrations of the stabilizer. 45 Uniaxial tests and 75 unconsolidated- undrained compressional triaxial tests were conducted. An increase in the undrained cohesion of all samples was observed. On the other hand, two different trends were observed in the alteration of the undrained internal friction angle of soils with low and high fines content.

Keywords: Soil stabilization; Colloidal silica; Silty sand; Short-term behaviour; Strength parameters.

1. Introduction

Stabilization by injection is a technique for filling the pores of soils or cracks and the joints of rocks to improve their permeability and mechanical properties. The three general types of injectable materials are: suspension state grout, emulsion state grout, and soluble state grout. The suspension state grout includes clay, cement, and lime mixed with water, whereas the emulsion state grout includes water and bitumen. The soluble state grout encompasses a wide range of chemicals [1].
Only emulsion and soluble grouts are applicable in fine grained soils and suspension grouts are usually of no use. The first advantage of chemical grouts lies in their low viscosity and suitable control of their setting time. However, their disadvantages are likely emanation of toxicity of some types in the nature and the relative cost of these materials in comparison with other grouts. Some types of chemical grouts include sodium silicate, lignosulfite, acrylamide, calcium acrylate, and resins such as resin epoxy and resorcinol formaldehyde [2].

Considering the efficiency of silicates in soil stabilization and their chemical and biological neutrality, there is a great tendency towards these materials. Recently, application of nanotechnology in silicate based chemical grouts has resulted in fabrication of colloidal silica which has remarkable properties in terms of chemical injection. According to Towhata I. (2008) colloidal silica due to no deterioration in mechanical strength (no weathering), uniform seeping of liquid and not being harmful to human health [3] is a suitable stabilizer to use in soil medium.

As seen earlier on published researches, stabilization of soil by colloidal silica can improve soils by increasing cyclic and post-cyclic strength, increasing uniaxial strength, decreasing soil settlement and cyclic deformation and making the stabilized soil, impermeable. So stabilizing the soils by injecting colloidal silica can be used in practice in order to triggering liquefaction, increasing bearing capacity, stabilizing slopes and forming subsurface barrier.

So far, the effects of stabilizing the soil by colloidal silica on the mechanical properties of it, have been not investigated comprehensively so in this research, the effects of colloidal silica on the mechanical parameters of silty sand with different amounts of silt have been investigated.
1.1. Background

Persoff et al. (1999) performed permeability and uniaxial tests on sandy soil samples stabilized by colloidal silica. Following one month, three months, and one year, they found that the uniaxial strength of the sandy soil stabilized by colloidal silica is dependent on the concentration of silica particles in the solution. According to their tests, the uniaxial strength reached over 400 kPa in some samples. Furthermore, the hydraulic permeability of the sand stabilized by colloidal silica grout decreased to less than $10^{-7} \text{cm/s}$ with the increase in concentration [4].

Gallagher and Mitchell (2002), in a study to stabilize liquefiable sands, indicated that usage of colloidal silica 5% results in development of a proper strength against cyclic deformation [5].

Diaz Rodriguez et al. (2008) in a study of natural liquefiable sand stabilized with colloidal silica grout found that cyclic resistance of soil grouted with colloidal silica is influenced by the initial relative density of the sand, the initial effective vertical stress, and the colloidal silica concentration. As the amount of initial effective vertical stress on stabilized sample increases, dilation progressively contributes more than cementation to the cyclic resistance of treated sands; consequently, dense sands (which dilate more than loose sands) exhibit greater liquefaction resistance at higher initial effective vertical stress [6].

Gallagher and Lin (2009) stabilized the sand samples in several cross-sections in their constructed injection columns and conducted uniaxial test. Their study illustrated the usefulness of uniaxial tests in indicating the degree of stabilization in their samples. Based on their tests, the average uniaxial strength for the sand stabilized by colloidal silica 5% was between 40 and 60 kPa [7].
Gallagher et al. (2007) conducted physical modelling of Nevada 120 loose sand soil stabilized by colloidal silica 6%. The relative density of the soil in centrifuge tests was 40% and was prepared by dry pluviation. To ensure that soil pores are totally filled by the stabilizer, the injected grout volume was 1.5 times bigger than the pores volume. Based on the performed measurements, the tested grout was changed into shaking solid gel following 56 hours. Therefore, following 240 hours of treatment (four times longer than the gelation time), the model underwent the tests. After the injection and treatment of the soil, 21 samples were extracted from the centrifuge tests container (by trimming method) and uniaxial tests were performed. Test results revealed that the uniaxial strength of the treated soil varies between 16 kPa and 61 kPa [8].

Conlee et al. (2012) performed centrifuge model tests on sand slopes stabilized by colloidal silica. They compared the liquefaction and deformation responses of the unstabilized loose sand slope with those stabilized by colloidal silica with 4, 5, and 9 weight percent. The following results were obtained from their studies [9]:

- With the increase in the concentration of colloidal silica, the soil settlement gradually diminished.
- Stabilization by colloidal silica in soil slopes located on liquefiable soil layers significantly prevented lateral spreading of the slope.
- The sand stabilized by colloidal silica caused a higher tip resistance in the cone penetration test. Furthermore, the shear wave velocity increased in these stabilized soils. Because the gelled sand matrix continued to provide significant shear resistance which also translates well with the expanded dilation region observed for colloidal silica stabilized sand during phase transformation under monotonic loading.
2. Materials and methods

To fabricate the silty sand samples, Babolsar sand and Babol silt with different mixing percentages were used. The physical specifications of these materials are as table 1.

Dr. Khan Industrial Consultants – CS30 colloidal silica was used for this testing program. According to Dr. Khan Industrial Consultant's product information, CS30 has 30 wt% silica, a specific gravity of 1.210 and a specific surface area of 210 m$^2$/g with appearance of milky white color (Fig.1). Before dilution, the pH of the solution is 10.0 and the viscosity is 5 cP.

2.1. Sample preparation

According persoff et al (1999) to prepare samples most accurately represent field conditions, one can inject the grout into the ground, forming a bulb, excavate the bulb, and core or carve out a cylindrical sample for testing. Such a sample is subject to many variables that are difficult to control, including the techniques of injection and sample recovery, the permeability and heterogeneity of the soil, and how completely the grout fills the pore space. Injecting grout into laboratory sand packs eliminates soil heterogeneity and encourages uniform penetration of grout by confining its flow to one direction, but does not guarantee that the filling of pore space by the grout will be the same in all samples. This second method sacrifices representation of field conditions without maximizing sample reproducibility. Systematic determination of the effects of controlled variables upon properties of the grouted samples requires that samples be prepared as reproducibly as possible [4]. Therefore, the method of sample preparation was chosen to maximize reproducibility.

Different samples containing clean sand and silty sand with different fines content (silt percentage of 0, 10, 20, 30, and 40% of the sample weight) were used in this study. According to ASTM, to control the density of soil samples with fines content (particles
finer than 0.074 mm or passing sieve #200) lower than 15%, a variety of laboratory tests can be used, including relative density (Dr) definition and minimum void ratio and maximum void ratio [10,11] determination tests or compaction percentage (Rc) definition and Proctor test [12]. However, it is not possible to perform the minimum and maximum void ratio tests in soil samples with fines content percentages of over 15% [10,11]. Accordingly, in this research, in order to have a consistent control on the density of the samples, compaction percentage (Rc) parameter and standard compaction test were employed. The compaction percentage of the samples was chosen to be 93% in all tests. This compaction percentage is expected to be equivalent to a relative density lower than 65% (i.e. the sample is in medium-compact conditions).

Before beginning the fabrication of the samples, the weight of each constituents was determined. For this purpose, considering the compaction percentage of the samples (medium dense samples with compaction percentage of 93% of the standard compaction), the specific dry weight of the sample is determined. Thereafter, having the volume of the mold, the dry weight of the soil is calculated. Next, based on the relative density of each soil sample, the volume of the voids is specified using weight and volume relations. The volume of the stabilizer is then calculated in a way that it fills all void spaces of the soil. Finally, the materials of interest are mixed with each other and the samples are fabricated by wet soil tamping method.

\[ \text{2.2. \textit{Age of the samples in the experiments}} \]

Colloidal silica-stabilized samples with different ages are used in laboratory tests performed by different researchers. For example, Persoff et al. (1999) [4] and Diaz Rodriguez et al. (2008) [6] used samples with an age of 7 days for the tests. Gallagher et al. (2007) conducted their tests on samples with an age 4 times as long as the gelation
time [8]. Gallagher and Mitchell (2002) proposed the suitable time for the tests is at least 10 times longer than the gelation time [5]. Liao et al. (2003) carried out their tests 7, 14, and 28 days following fabrication of their samples [13].

To determine the suitable age for performing the experiment, uniaxial tests were used. Uniaxial tests were done by ELE apparatus according to ASTM D-2166 standard [14] using axial strain rate of 1.2 percent per minute. These tests were carried out on the stabilized soil samples with different ages. Uniaxial tests were done on clean sand soil samples stabilized by colloidal silica 5% (the most diluted state in this research). In ages with 1-21 days off the fabrication time, two to three samples were tested. Based on 45 uniaxial tests performed in this section, the average uniaxial strength versus sample age relationship was obtained and is presented in Fig. 2.

According the results of uniaxial tests that are shown in Fig. 2, the average strength of clean sand stabilized by colloidal silica 5% in this study was approximately 18 kPa. Considering the fact that uniaxial strength of stabilized sample is affected by sample relative density and colloidal silica concentration, the results of this study comparable with the results of other published researches like the study done by Gallagher and Mitchell (2002) that was about 32 kPa and Gallagher et al (2007) that was further 16 kPa.

As can be seen in Fig. 2, up to three days, the uniaxial strength of the sample has a sharp ascending trend. Following three days, the rate of growth of uniaxial strength diminishes significantly. Therefore, the age of performing tests in this research was chosen to be three days.

2.3. Unconsolidated- undrained triaxial tests

In order to evaluate the undrained behaviour of clean and silty sand soils stabilized by
colloidal silica, 75 unconsolidated- undrained triaxial tests were conducted by ELE triaxial device and according to ASTM D-2850 standard [15]. The triaxial device was a manual one and the strain, force and pressure read by operator. The tests were carried out in strain controlled method with axial strain rate of 1 percent per minute on the samples with the diameter of 52 mm and the height of 104 mm, and compaction percentage of 93%. The tests were performed on clean and silty sands (10, 20, 30, and 40% silt) under stabilized and unstabilized conditions (with colloidal silica 5, 10, 20, and 30%). Based on the results obtained from the uniaxial tests, all of the stabilized samples were tested at the age of 3 days off the fabrication time and under the confining pressure of 400, 600, and 800 kPa.

3. Results

After conducting the unconsolidated- undrained triaxial tests on the samples, different corrections including sample area and membrane force effect were performed according to the standard. Consequently, the diagram of stress-strain changes and Mohr circles of the soil samples were plotted under undrained loading conditions in order to determine internal friction angle and soil cohesion. Some stress-strain curves obtained from the tests are presented in Fig. 3.

Note that over the course of the majority of the tests, the soil samples were changed into barrelling form under loading and no shearing surface was observed in the samples. According to the standard, the maximum axial stress was equal to the stress in 15% axial strain.

The results of unconsolidated- undrained triaxial tests performed in this section of the experiments, are presented in Table 2.
4. Discussion

Deviator stress versus stabilizer concentration obtained through unconsolidated-undrained triaxial tests is presented in Fig. 4. As can be seen in the curves of Fig. 4, the trend of changes in the undrained resistance of soil in the unconsolidated-undrained tests with different confined pressures follows two different patterns. The first pattern is related to the samples with fines contents lower and equal to 20%, where with the increase in the concentration of the colloidal silica, the undrained resistance of soil is first descending and then ascending. The second pattern is associated with the samples with fines contents of over 20%, where with the increase in the concentration of the colloidal silica, the undrained strength of the soil has an ascending trend.

In order to investigate the reason of the above observations, with a more precise glance at the parameters affecting the soil undrained shear strength revealed that according to Table 2 and Fig. 5, in all of the different percentages of fines content, the increase in the concentration of the colloidal silica stabilizer results in elevated value of soil cohesion in undrained conditions. This phenomenon is due to the gelation property of colloidal silica and attachment of soil particles to each other, which was observed in all soil samples. The cohesion in the samples with different fines contents ranges from soil's natural cohesion and increases up to an almost constant value, which is equivalent to the cohesion of colloidal silica at a certain concentration.

The effect of stabilization on the soil's internal friction angle, as can be seen in Table 2 and Fig. 6, has two different trends across various samples. The first trend of the alteration of internal friction angle is observed in clean and silty sand with 10 and 20% silt. In these soils, considering the fact that the behaviour of soil under shear is a frictional behaviour, addition of colloidal silica results in filling the roughness across the surface of the soil particles, which results in a reduction in the internal friction angle
of the soil. In other word, because colloidal silica is a smooth gel that encasing the soil
grains, in the case of frictional soil, addition of colloidal silica is resulted the reduction
of the frictional properties of soil. This phenomenon is more dominant if the colloidal
silica around the grains is became thicker. So by increasing the concentration of
colloidal silica on stabilized frictional soils, the undrained friction angle of them are
reduces.

The second trend of altered internal friction angle was seen in sands with silt
percentage of over 20%. In these soils, the fine part fills the interparticle space of coarse
particles and results in separation of coarse grains off each other [16]. Accordingly,
rather than the friction of coarse-grained particles, the mechanism of soil shear loading
is determined based on cohesion of fine-grained particles. For this reason, it is observed
that the initial internal friction angle of these soils is low, but with the increase in the
concentration of the stabilizer, the silt fine-grained particles attached to each other with
a stronger bond and form a soil similar to a coarse-grained soil. Therefore, with the
increase in the concentration of the stabilizer in the fine-grained soils, the internal
friction angle grows. This phenomenon is similar to the observations by Lade and
Overton (1989) on soils stabilized by cement [17].

With a more careful look at Fig. 6, it is observed that in the sand with 10 and
20% silt, with the increase in the concentration of colloidal silica, the trend of changes
in the internal friction angle is first descending and then ascending. The reason of this
phenomenon is the twofold mechanism of silty sand under shear, which is controlled by
both particle friction and cohesion of fine-grained soil. At low concentrations of the
stabilizer, the first trend mentioned above leads to diminished friction angle and with
the increase in the concentration of the stabilizer, the second trend mentioned above
results in increase of the internal friction angle of the soil.
5. Conclusions

(1) Based on uniaxial tests performed on samples stabilized by colloidal silica, considering the setting time of the stabilizer which was 2 hours, with an increase in the sample age up to three days, the uniaxial strength of the sample has an ascending trend. After three days, the rate of the growth of uniaxial strength diminished significantly. Therefore, 3-day samples were found suitable for performing the tests.

(2) Across all of the different percentages of fines content, increasing the concentration of the colloidal silica stabilizer resulted in increased soil cohesion in undrained conditions. This is due to the gelation property of colloidal silica and attaching soil particles to each other, which was seen in all soil samples. The cohesion in samples with different fines content starts from initial cohesion of soil and increases up to a constant value which is the cohesion of colloidal silica at a certain concentration.

(3) In the clean sand and the sand with 10 and 20% fines content, it was observed that the addition of colloidal silica resulted in smoothing the rough surfaces of the sand particles causing a reduction in the internal friction angle of the sand.

(4) In sands with silt percentage of over 20%, it was seen that the initial internal friction angle of these soils was low. However, with the increase in the concentration of the stabilizer, the silt fine-grained particles attached to each other with a stronger bond and formed a soil similar to coarse-grained soil. That is, with the increase in the concentration of the stabilizer in fine-grained soils, the internal friction angle increased.
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7. **Conflict of interest**

The authors confirm that there are no known conflicts of interest associated with this publication.

8. **References**


Table captions:

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Table 2. Unconfined-undrained triaxial test results performed on various sample

Figure captions:

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Fig. 4 Variation of deviatoric stress by increasing colloidal silica concentration in confining pressure of: a) 400 kPa b) 600 kPa c) 800 kPa
Fig.5 Variation of stabilized sample cohesion by increasing colloidal silica concentration
Fig.6 Variation of stabilized sample internal friction angle by increasing colloidal silica concentration
Table 1. Physical specifications of materials

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Table 2. Unconfined-undrained triaxial test results performed on various sample

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