Mechanical Behaviour of Sand Treated with Colloidal Silica

Jiji Krishnan and Shruti Shukla

Abstract The present research focuses on the compressive strength characteristics of colloidal silica-stabilized sand in comparison to that of untreated sand of similar relative density (55%). Specimens were prepared in the laboratory by treating sand with different weight percentages of colloidal silica solution. The research on the soil improvement with the addition of colloidal silica is slowly yet increasing day by day due to its mechanical stability with respect to most other chemical grouts. Colloidal silica is also nontoxic, biologically and chemically inert, and has excellent durability characteristics. The sand specimens stabilized with colloidal silica were cured for seven days. It was observed that stabilized sands showed a significant improvement in strength and static loading. This paper is also an attempt to review the technical benefits and feasibility of applying colloidal silica gel as grout in soil stabilization. A number of laboratory unconfined compressive tests and unconsolidated undrained triaxial tests were performed in order to evaluate the shear strength and compressive strength of sand-grouted colloidal silica gel.

Keywords Colloidal silica · Unconfined compression strength · Shear strength

1 Introduction

Soil stabilization using chemicals is a well-established method used for underground as well as foundation constructions. In chemical stabilization, lime, cement, fly ash, silica can be used. Soil stabilization is nothing but the modification of soils to upgrade their properties. Yonekura and Kaga (1992) proposed the new concept of stabilizing sands grouted with colloidal silica as a substitute for sodium silicate. The pioneers in this field are Persoff et al. (1999), Gallagher and Mitchell (2002) and Liao et al. (2004). It has been reported that the treated sand with colloidal silica exhibits liquefaction resistance as well. Many researchers observed liquefiable soils treated with colloidal silica grout have appreciably improved the liquefaction resistance as well

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as unconfined compression strength. As expected, they also noticed a reduction in the settlement as well as hydraulic conductivity. Passive site remediation is an advanced concept which involves liquefaction mitigation without disturbing the existing structure. It involves the delivery of a suitable stabilizer with the natural groundwater flow to the target location. The stabilizing material is slowly injected at the upgradient edge of a site, and the groundwater flow is used to deliver stabilizer to the liquefiable sand layers. In order to speed up the entire process, extraction wells can also be dug above the liquefiable layer. A suitable stabilizer must have low viscosity and controllable gel times in order to flow with the groundwater, and it does not gel until the target location is reached. Colloidal silica is a prospective stabilizer because at low concentrations, it has a low viscosity and a wide range of controllable gel times up to 3 months (Gallagher and Mitchell 2002).

Colloidal silica is an aqueous solution of silica particles and has viscosity same that of water in dilute conditions. Various researchers considered colloidal silica to be stable under typical subsurface conditions (Gallagher et al. 2007).

During manufacturing, gelation is stopped by increasing the pH of the colloidal silica. Continuous stirring of colloidal particles decreases the strength of the bond. The mechanical behaviour of grouted sand is affected by grout content, type, density, size and confining stress.

The aim of the present research is to investigate the effects of concentration of grouts with the help of unconfined compression tests and unconsolidated undrained triaxial tests.

2 Mechanism of Colloidal Silica Stabilization

Colloidal silica particles develop when H_4SiO_2 molecules form siloxane bonds (Si–O–Si) because the surface of the particle has an uncombined silanol (SiOH) group. Silica particles contain a negative charge on the surface (Scott1993). The silica sol will be stabilized by changing the pH when it reaches its desired size. Response and structure of the particles are primarily due to its electrical interparticle forces, a negative surface charge of silica particles as well as its tiny size (Scott 1993; Santamarina et al. 2001; Spencer et al. 2008).

Colloidal silica particles show different behaviour with the change in pH. Changing the repulsive forces of silica particles in a controlled manner will lead to gelation in a solution. Colloidal silica gel has a broad range of gel times which in turn related to different properties. The reduction in double-layer thickness, as well as ionization, initiates with the help of adding silica sol to the solution which contains alkaline solutions. Alkalis create a negative charge on the surface due to which the particles repel each other. This leads to a decrease in bond formation and an increase in the gel time (Gallagher et al. 2007). The longest gel time occurs for a given silica concentration without any salt content, whereas the lowest gel times occur at a pH between 5 and 7 (Gallagher and Lin 2009). The greater the ionic charge, the lesser the gel time, which creates a chance of interparticle conflicts.

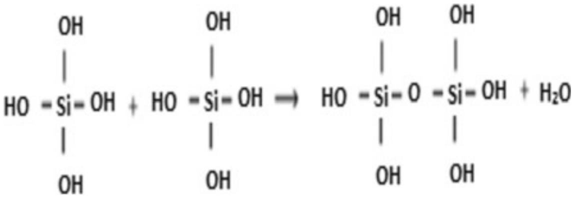

Fig. 1 Formation of siloxane bonding (Spencer et al. 2008)

Formation of siloxane bonds (Fig. 1) and dissociation of water molecules will occur as a result of the reduction in double-layer thickness (reduction in repulsive forces). Gelation binds the soil particles together, thereby restricting the movement of pore fluid in the soil–silica matrix. The water molecules which were dissociated during a chemical reaction stay within the void space of the gelled silica particle network. Soil stabilization using chemicals is a well-established method used for underground as well as foundation.

3 Literature Review

Noll et al. (1992) noticed a decrement in permeability and metal absorption capacity with the addition of colloidal silica in the sand. They noticed a permeability and metal absorption capacity with the addition of colloidal silica in the sand. They noticed a permeability range from 10^{-8} to 10^{-7} cm/s after stabilizing the sand with 5 wt.% of colloidal silica solution.

Yonekura and Miwa (1993) studied the unconfined compressive strength of 335 kPa in 32 wt.% colloidal silica-stabilized sand. They noticed an increment in compressive strength to 1200 kPa in the treated sand, i.e. almost 3.5-fold increment after curing the samples for 347 days. They also reported that unconfined compressive strengths increased with increase in curing days up to 1000 days.

Persoff et al. (1999) determined the one month, three months and one-year compressive strength of colloidal silica-stabilized sand. They reported a percentage increase in compressive strength by adding colloidal silica as a stabilizer (Fig. 2). They engrossed the treated samples in water; water saturated with aniline, CCl_4, PCE, water saturated with different nonaqueous phase liquids (NAPLs), HCl diluted to pH-3. They noticed a gain in strength in samples dipped in water, whereas samples immersed in aniline enfeebled the bond. They hardly observed any difference in strength with the addition of NAPLs and diluted hydrochloric acid to pH 3. They estimated a maximum of 400 kPa compressive strength and concluded that the strength of sand grouted with colloidal silica is proportional to the amount of colloidal silica particles. They also noticed that increment in strength continues for one year after treating with colloidal silica. Also, they generalized that the maximum strength occurred in the samples was cured for four times the gel time. They also

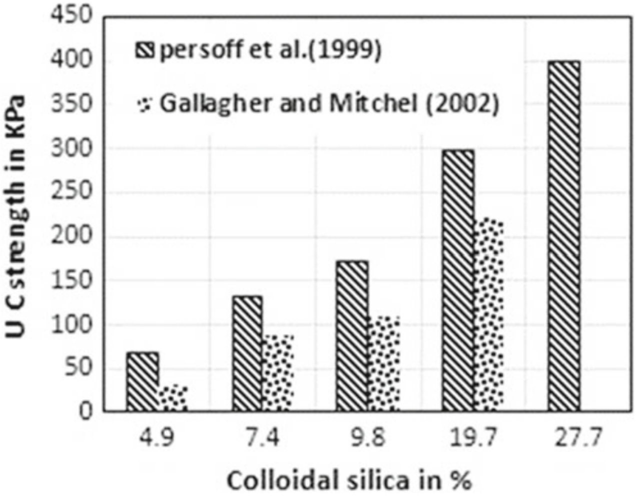

Fig. 2 Unconfined compressive strength of treated samples (Persoff et al. 1999; Gallagher and Mitchell 2002)

studied the hydraulic conductivity of silica-treated sand. They calculated a hydraulic conductivity of less than 1 × 10^{-1} cm/s for colloidal silica percentage greater than 7.4.

Towhata and Kabashima (2001) investigated the deformation behaviour and liquefaction resistance on Toyoura sand using a cyclic triaxial test. They noticed a similarity in both the properties in treated specimens (4.5% colloidal silica by weight) with 40% relative density as well as untreated specimens with 75% relative density and more. This indicates that the addition of colloidal silica greatly influences the liquefaction properties.

Gallagher and Mitchell (2002) prepared colloidal silica grout on the deformation properties of saturated loose sand. They have done the cyclic triaxial test on a total of 31 samples grouted with colloidal silica with various concentrations (5, 10, 15 and 20%). Also, unconsolidated compression tests were executed with varying concentrations of colloidal silica. They also noticed that strength gain occurs with the addition of colloidal silica (Fig. 2). In addition to this, 25 samples were tested for unconfined compression strength test after cyclic testing to define the strength reduction due to cyclic loading. They revealed that the untreated samples collapsed in 10–12 cycles, whereas the treated samples remained intact for at least 100 cycles. Figure 3 shows the strain during cyclic loading depleted with the addition of colloidal silica percentage. Thus, it is very clear that the colloidal silica-stabilized sand consequently increased the deformation resistance of loose sand to cyclic loading. Thus, the presence of colloidal silica greatly influences the properties of treated sands.

Gallagher and Lin (2005, 2009) conducted an unconfined compressive strength test on Nevada Sand no: 120 grouted with 5 wt.% colloidal silica solution. Test results varied from an average strength from 47 to 67 kPa. From the test results,

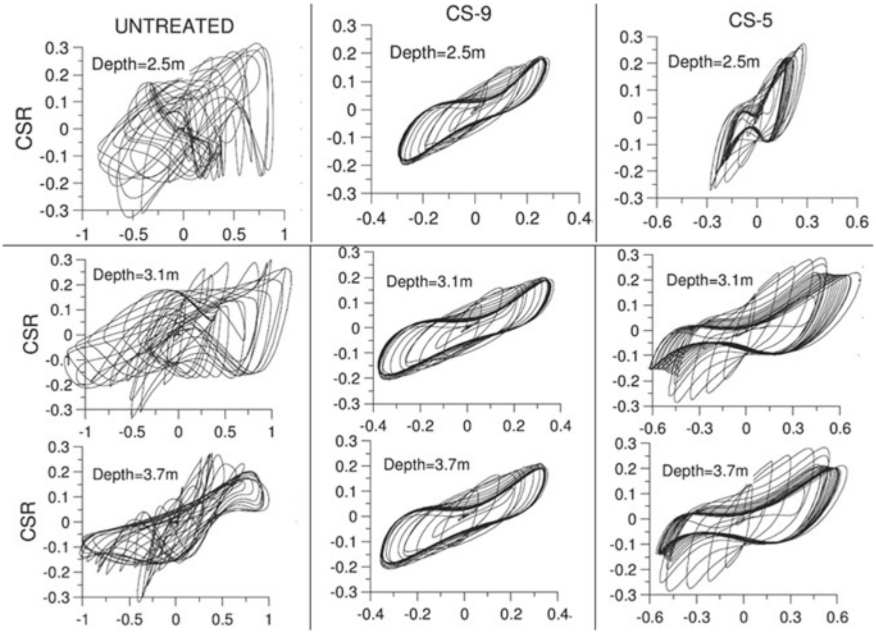

Fig. 3 Stress versus strain plots at particular cycles for different depths (Conlee et al. 2012a)

it was expected to mitigate the liquefaction risk. Though they have not performed any dynamic tests to validate their conclusion, they have compared the results with test results in which experiment is conducted on the same sand and on the same weight percentage of colloidal silica with the exact same laboratory conditions. They proposed that 5 wt.% of colloidal silica-treated sand was suitable for mitigating the risk of liquefaction. They justified that liquefaction resistance as well as the cohesion of sand increases with the addition of colloidal silica.

Conlee et al. (2012b) conducted a study to evaluate the liquefaction mitigation of colloidal silica-treated sand. They conducted a centrifuge test on 4, 5 and 9% of colloidal silica-stabilized sand. After comparing the results, they noticed a decrement in ground deformations in the treated sand. They also evaluated higher cone tip resistance and shear wave velocity as well as a reduction in lateral spreading on treated liquefiable soil layers. Overall they noticed a reduction in CSR and shear strains in colloidal silica-grouted sands. They reported an increase in cyclic resistance ratios with the increase of colloidal silica concentrations. Figure 3 shows CSR versus shear strain for a shake in treated as well as untreated sands at three different depths.

Moradi and Seyedi (2015) studied the effect of sampling method on the strength of stabilized silty sands with colloidal nano-silica. They prepared various samples with silt content from 0 to 30% prepared by sedimentation method in 4.5 wt.% colloidal nano-silica suspensions. They conducted unconfined compressive strength

Table 1 Summary of research considered

Researchers	Remarks
Noll et al. (1992)	The decrement in permeability and metal absorption capacity
Yonekora and Miwa (1993)	The gain in compressive strength
Persoff et al. (1999)	Increase in unconfined compressive strength and a decrease in hydraulic conductivity
Towhata and Kabashima (2001)	The increment in liquefaction resistance
Gallagher and Mitchell (2002)	Unconfined compressive strength tests, as well as cyclic triaxial tests, showed an increment in strength
Gallagher and Lin (2009)	Gallagher and Lin (2005) Mitigate the liquefaction risk
Conlee et al. (2012a)	Reduction in CSR and shear strains. Increase in cyclic resistance
Moradi and Seyedi (2015)	Increment in unconfined compressive strength

tests after a curing period of 6 weeks. It has been reported an increment in unconfined compressive strength when the silt content was up to 10%, whereas strength is decreased with the increment of silt content more than this. They also examined the scanning electron microscope (SEM) analysis to observe the variations in colloidal silica-treated soil.

This review is an attempt to give a wide knowledge about the mechanism of colloidal silica stabilization as well as the use of colloidal silica as an additive in soil stabilization. Table 1 shows a summary of the research considered. Also, the following points can be inferred from this review:

- Adding colloidal silica suspensions to soil greatly increases the unconfined compressive strengths.
- A drastic increment in deformation resistance on loose sands stabilized with colloidal silica was observed during cyclic triaxial tests. The increase in treatment level also showed an increment in cyclic ratios.
- More work needs to be done on soil stabilization using different colloidal silica concentrations and soil densities.
- Cost-effectiveness of colloidal silica suspensions in the soil is inevitable. So more research on this study should be encouraged.
- Permeability reduced with the addition of colloidal silica in the sand.
- The experimental studies that are specifically based on the effect of viscosity in gelling time as well as curing time of colloidal silica in the soil are limited.

4 Sample Preparation and Materials Used

4.1 Sand

The materials used in the research are river sand as well as colloidal silica. The gradation curve of the sand studied is shown in Fig. 4 and index properties are shown in Table 2. Sands used for the experiment are passed through 2 mm and retained on 75-micron sieve. According to Indian Standard Soil Classification, sand is classified as SP.

Fig. 4 Particle distribution curve

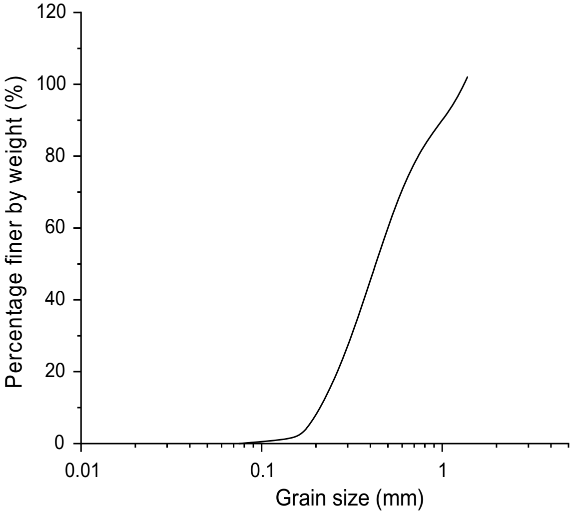

Table 2 Index properties of sand used for the study

Material property	Value
Specific gravity	2.692
Minimum unit weight	15.74 kN/m^3
Maximum unit weight	18.56 kN/m^3
Effective grain size (D_{10})	0.20 mm
Coefficient of uniformity (C_u)	2.50
Coefficient of curvature (C_c)	0.90
Indian Standard Soil Classification	SP
$e_{\max}$	0.71
$e_{\min}$	0.45

Table 3 Properties of LUDOX colloidal silica sols

	LUDOX SM
Stabilizer counter ion	silica
Particle charge	negative
pH	9.7–10.3
Relative density	1.22 g/mL at 25 °C
Molecular weight	60.08 g/mol

Table 4 Gel state criteria (Sydansk 1990)

Samples	Gel state descriptions
1	No noticeable gel shape
2	Flowing gel with more viscosity than the initial polymer solution
3	During inversion of the bottle with colloidal silica, the gel seems like flowing
4	Reasonably flowing gel. Less than 15% of the gel does not flow easily during inversion of the bottle containing colloidal silica
5	Hardly flowing gel. More than 15% of gel does not flow upon inversion during inversion of the bottle containing colloidal silica
6	Highly deformable nonflowing gel. Hardly any gel flow upon inversion during inversion of the bottle containing colloidal silica
7	Moderately deformable nonflowing gel. Gel flows about halfway down bottle upon inversion
8	Slightly deformable nonflowing gel. Only gel surface deforms slightly upon inversion
9	Firm gel. During inversion of a bottle containing colloidal silica, difficult to notice any gel formation at all
10	Ringing firm gel. During tapping in bottle vibration as well some sound occurs
11	Firm gel without any sounds and vibrations

4.2 Colloidal Silica

Properties of colloidal silica used for the study are mentioned in Table 3. Sydansk (1990) has described the gelling criteria visually, and it is mentioned in Table 4.

4.3 Sample Preparation

Three different percentages of colloidal silica (i.e. 4, 5 and 7% by weight of sand) were chosen in this investigation. Adjustments in pH were made using 6 N hydrochloric acid for colloidal silica sols to be gelled. Colloidal silica-stabilized samples have

Fig. 5 Sample in a triaxial setup

been kept intact for 7 days. Split moulds were used in this experiment for preparing the grouted sample in order to avoid their disturbance during sampling.

The undrained triaxial test and unconfined compression tests have been conducted on both treated and untreated specimens of sand with a relative density of 55%. Triaxial tests on untreated and treated samples were performed under effective confining pressures 50, 100 and 150. The purpose of this test is to measure the static properties of the treated sand. Unconsolidated undrained tests were chosen because they are more representative of the stress state of the soil formation in the field so that they might give a better idea of the strength of the grouted mass prior to earthquake loading. The sample is shown in Fig. 5.

5 Test Results

p-q plot for all the samples was prepared, φ values were found, and the angle of internal friction was calculated and shown in Table 5.

Specimens of stabilized as well as nonstabilized sand were isotropically consolidated to pressures varying between 50 and 150 kPa before shearing undrained while keeping the cell pressure constant. The stress–strain response during shearing at 100 kPa is shown in Fig. 6.

Table 5 Variation of φ values

No.	Mix	φ (°)
1	Sand	40
2	Sand + 4%CS	46
3	Sand + 5%CS	49
4	Sand + 7%CS	50

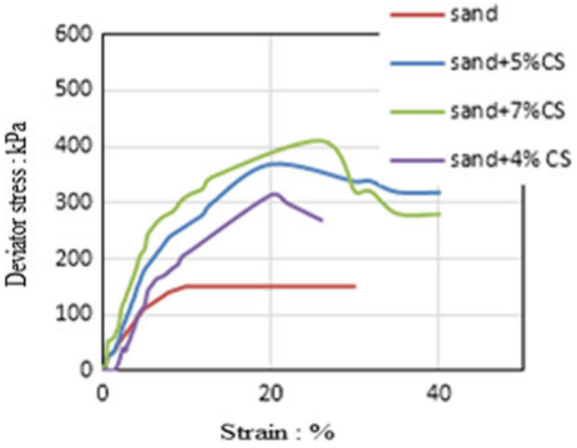

Fig. 6 Stress–strain response of sand and colloidal silica-stabilized sand for confining pressures 100 kPa

The shear strength of the colloidal silica-stabilized sand is calculated to be about three to four times that of the pure sand (Fig. 6). Also, shear stress versus displacement relationship for stabilized sand at different stresses is shown in Fig. 7.

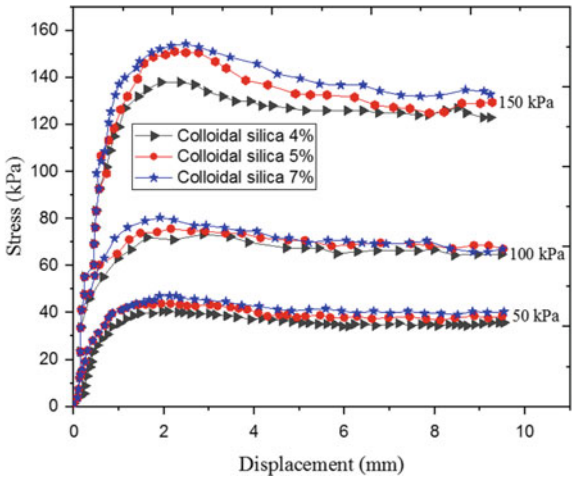

Fig. 7 Shear stress versus displacement relationships for stabilized sands (colloidal silica 4, 5 and 7%)

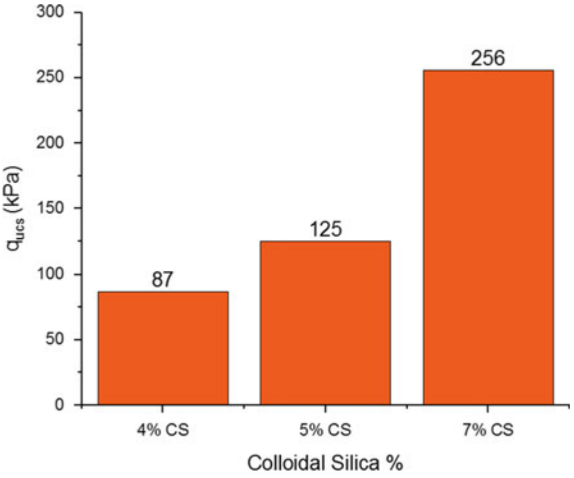

Fig. 8 Variation in unconfined compressive strength with the addition of colloidal silica content

Addition of colloidal silica in sand causes the shear strength to decrease after reaching a peak value, a behaviour that is typical to medium to very dense sands. So it is very much clear from the sand that the 55% relative density sand increased in strength with the addition of colloidal silica in various percentages such as 4, 5 and 7%.

The unconfined compression test results obtained with the addition of colloidal silica are shown in Fig. 8. It should be noted that the presence of colloidal silica gel within the pores of sand grain skeleton dramatically increased the load-carrying mechanisms. This supports the previously mentioned literature from various researchers.

6 Conclusions

As per the papers reviewed and the experiments conducted, the following conclusions are obtained.

- Ionic strength, pH, silica concentration, particle size and specific surface area are important factors to be considered for the gelling of colloidal silica to initiate strength.
- Adding colloidal silica suspensions to soil greatly increases the unconfined compressive strengths. Unconfined compressive strength test can be considered as an ordinary indicator of the degree of stabilization accomplished. Unconfined compressive strength of sand treated with 4, 5 and, 7 wt.% of colloidal silica ranged from 87 to 256 kPa.
- Addition of colloidal silica (4, 5 and 7% by weight) increases the shear stress as well as φ value from 40° to 50°. With the addition of colloidal silica in sand, shear

strength increases. However, it is noted that the increment rate reduces with the addition of colloidal silica.

- A drastic increment in deformation resistance on loose sands stabilized with colloidal silica was observed during cyclic triaxial tests. The increase in treatment level also showed an increment in cyclic ratios.
- More work needs to be done on soil stabilization using different colloidal silica concentrations and soil densities.
- Cost-effectiveness of colloidal silica suspensions in the soil is inevitable. So more research on this study should be encouraged.
- Permeability reduced with the addition of colloidal silica in the sand.
- The experimental studies that are specifically based on the effect of viscosity in gelling time as well as curing time of colloidal silica in the soil are limited.
- For a better understanding of colloid transport, further systematic studies are necessary which consider the transport behaviour of colloidal silica, particle aggregation, etc. to be considered.
- At a relative density of 55%, the 7 wt.% of colloidal silica-grouted specimens exhibits a usual dense sand behaviour with no observed peak value.

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