Determination of hydraulic conductivity of colloidal silica stabilized sand to be used as an impervious liner

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Abstract. An experimental program was performed to study the effects of colloidal silica stabilization on the hydraulic conductivity of sand. An indirect method i.e. oedometer test results were used to estimate the hydraulic conductivity of colloidal silica stabilized sand. The stabilizing agent was Dupont Ludox SM colloidal silica. 12.5 wt. %, 11 wt. % and 10 wt. % was added in relative densities 30 RD, 40 RD, and 60 RD of sand respectively. These are the optimum colloidal silica percentages which are obtained from triaxial test results. The percentages of variations are obtained from the optimum value of colloidal silica from triaxial test results. The tests were conducted after curing for 3, 7 and 28 days in order to find the variations of hydraulic conductivity with the curing period. Based on the experimental investigations the addition of colloidal silica reduces the permeability in colloidal silica stabilized samples. The reduction in permeability can make use as an insulation barrier for waste disposal management. According to the results obtained from this oedometer experimental study, the hydraulic conductivity varies inversely with the loading pressures for all soils. The effect of applied loading pressures on hydraulic conductivity is less significant, once become more than 500 kPa in all the colloidal silica treated sand. According to the SEM analysis test results, the colloidal silica and sand particles create a continuum of soil and silica particles. Colloidal silica acts as a binder and holds the sand particles together along with creating a cover around the sand particles in order to create a siloxane bond.

Keywords: Colloidal silica, Hydraulic conductivity, Insulation barriers, Sand.

1 Introduction

Soil stabilization is a method used in ground engineering to enhance the strength of the soil according to constructional requirements. The process of soil stabilization improves the shrinking and swelling properties of soil. This leads to the enhancement in the bearing capacity of the soil, thereafter foundations and pavements are supported over these strata. Soil stabilization techniques lead to the preservation of soil, improvement in roadways, and waterways. Soil reinforcement using different natural fibers has been carried since old times. There are various soil stabilization techniques which are used according to the requirement. Traditional methods like soil reinforcement, lowering of the water table, vibration compaction, soil replacement etc. are not always feasible and suffer from some major drawbacks [1]. Due to the lack of application of the aforementioned methods in large areas and low economic and environmental viability chemical grouting is becoming popular.

Chemical grouting uses a chemical which percolates into soil strata and provides required strength by bond formations [2]. Cement, sodium silicate, microfine cement, colloidal silica and mineral grout are some of the popular chemical grouts. Cement grouting has been found to be extremely detrimental to the environment and pollutes soil strata. Colloidal silica is one such material which is environmentally friendly, economically viable and has an appreciable life span [3, 4].

Yonekura and Kaga [5] proposed the new concept of stabilizing sands grouted with colloidal silica as a substitute for sodium silicate. The success of grouting mainly depends on grout fluid properties used for injection. Strength of the grout mainly depends on workability and viscosity. Colloidal silica is an aqueous suspension of fine amorphous, nonporous, and typically spherical silica nanoparticles (7-22 nm) manufactured from saturated solutions of silicic acid which has low viscosity and controllable gel times in order to flow easily through the porous layer. The Colloidal Silica chemical grout has excellent durability characteristics, biologically inert and not harmful. The pioneers who recommend the use of colloidal silica as grout in the sand are Persoff et al. [6], Gallagher and Mitchell [7] and Liao et al [8]. Currently, colloidal silica has become widely popular among researchers due to its enhancement in mechanical properties of colloidal silica grout. The two main phases which can be considered during grouting with colloidal silica are its gelling phase and curing phase. Feasibility of using colloidal silica as grout in sand stabilization is the main concern and many researchers have made an attempt to summarize the use of colloidal silica grout. It has been reported that the treated sand with colloidal silica exhibit liquefaction resistance as well as unconfined compression strength.

Grouting can be considered as an effective way to increase the strength of granular soil and decrease its permeability. Permeability is the main parameter which measures the quality of a landfill's performance. Permeability is a property of material which allows the movement of any liquid through its interlinked pore spaces. Permeability reduction in colloidal silica treated sand can be made using an insulation barrier. Reduction in hydraulic conductivity is the main benefit of colloidal silica grout which forms chemical bonds among sand grains. This property can be utilized in preventing leakage of water through dam foundations, underground facilities and retaining walls. The concept of obstructing water flow through porous media was originally evolved from the petroleum industry [9, 10]. The colloidal silica treated matrix could be used as a low permeable cover and bottom liner material for a sanitary landfill in preventing contaminants from transporting to the nearby unpolluted areas. Colloidal silica grouted sand thus act as an in-situ impermeable barrier to control the flow of contaminants into underground water and soil beyond the affected area. In order to use colloidal silica as a landfill material, better estimation and clear understanding of the permeability of the colloidal silica grout treated sand, as well as the factors influencing the permeability, is necessary. An insulation barrier should possess low permeability and high physical stability to be effective [11, 12]

In the present study, a comprehensive test program was undertaken with the aim of developing colloidal silica sand as an impermeable landfill layer. In this research, a one-dimensional consolidation test was conducted to indirectly investigate the permeability characteristics of the colloidal silica solution injected sand sample. The study proposed the use of colloidal silica stabilized sand as an insulation barrier which is beneficial to avoid groundwater pollution and environmental degradation. Post-treatment settlement studies over colloidal silica treated soil samples for three different relative densities have been closely studied in this research. 1D consolidation tests were conducted for different curing periods and the hydraulic conductivities were calculated.

2 Materials used for the study

The materials used in the present experiment were river sand and colloidal silica. Each of the tests explained in the following sections was carried out for 3 different relative densities, viz., 30 %, 40 % & 60 % in colloidal silica treated sand for three different percentages, viz., 12.5 %, 11 %, 10 %. Undrained triaxial tests were conducted in order to evaluate the optimum amount of colloidal silica in the sand. The optimum percentage of colloidal silica at 30 % RD, 40 % RD, and 60 % RD was found to be 12.5 %, 11 % and 10 % respectively. The optimum percentage of colloidal silica decreases with an increase in relative density. Each sample was tested after 3, and 7 days in order to identify the effect of curing time in permeability behaviour of soil samples grouted with colloidal silica. Colloidal silica treated sand was cured for at least five times the gel time in order to ensure proper bonding so as to gain the needed strength. All the tests were repeated several times in order to ensure the accuracy of test results.

2.1 Soil Properties

The sand used in the present study was poorly graded cohesionless sand. All the properties were calculated using the procedures mentioned in IS codes [13–15]. The properties of sand used are listed in Table 1 and grain size analysis curve is shown in Figure 1. The sand was passed through 2 mm and retained on the 75-micron sieve.

Table 1. Properties of soil considered for the experimental 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

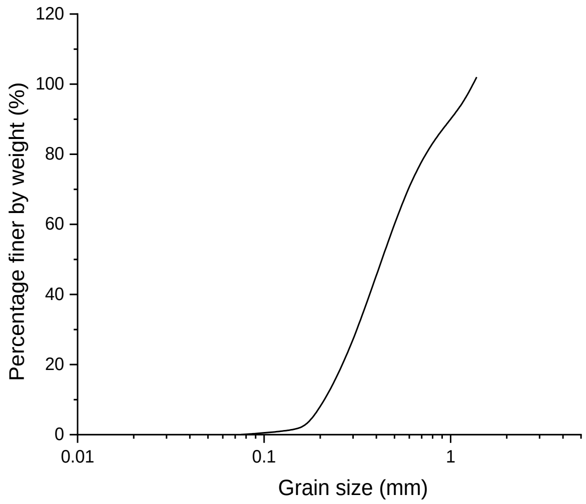

Fig. 1. Grain size distribution curve of untreated sand

2.2 Colloidal Silica Properties

Colloidal silica used in the present experiment was Dupont Ludox SM. The solution consists of 30 % by the weight of silica with an average particle size of 7 nm. The details of the colloidal silica used in the test are described in Table 2. HCl (0.6 N) was used in the test to change the pH and reagent grade NaCl was used to adjust the salt concentration.

Table 2. Properties of colloidal silica considered for the experimental study

Colloidal silica properties	Value
Stabilizer counter ion	silica
Particle charge	negative
pH (at 25^0c)	9.7-10.3
Density	1.22 g/mL at 25^oc
Molecular weight	60.08 g/mol
Initial viscosity (at 25^0c)	5.5 cP
Particle size	7 nm
Silica weight concentration	30 %

3 Gelling Mechanism of Colloidal Silica

Gel time is defined as the amount of time between mixing and the formation of a firm gel. It depends on various factors such as ionic strength, pH, the temperature of the solution, silica percentage in the solution and particle size of silica. It has also been reported that the strength of the treated soil increases with the curing time[8].

Colloidal silica gels under certain pH range or on the addition of NaCl salt in it. Generally, the pH provided by the manufacturer is greater than 10 in order to cease the gelling process. A gelling process on the molecular level happens on the formation of a siloxane bond which is ideally formed in the pH range of 5-7. Repulsive forces between the silica particles decreases and the gel which is formed bind the soil particles together.

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 negative charge on the surface [16]. The silica sol will stabilize 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 [16–18]. During manufacturing colloidal silica is stabilized against gelation i.e. by increasing the double layer thickness. 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.

Colloidal silica particles show different behaviour with the change in pH. Sodium hydroxide alkaline solutions are generally used by the manufacturers in order to prevent colloidal silica from gelling. Alkalis create a negative charge on the surface due to which the particles repel each other. When the pH of the colloidal silica reduces the particle charge in colloidal silica also decreases in proportion to the concentration of hydroxyl ions in the solution. This leads to the formation of siloxane bonds. At further lower pH, hydroxyl ions disappear and the particles become uncharged. This leads to a decrease in bond formation and an increase in the gel time [19].

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. The other properties that affect gel time are silica concentration, ionic strength, pH, particle size and specific surface area. The longest gel time occurs for a given silica concentration without any salt content. However, the lowest gel times occur at a pH between 5 and 7 [20]. The greater the ionic charge the lesser the gel time which creates a chance of interparticle conflicts. Formation of siloxane bonds (Figure 2 and Figure 3) and dissociation of water molecules will occur as a result of the reduction in double-layer thickness (i.e. reduction in repulsive forces). Gelation binds the soil particles together thereby restrict the movement of pore fluid in the soil-silica matrix.

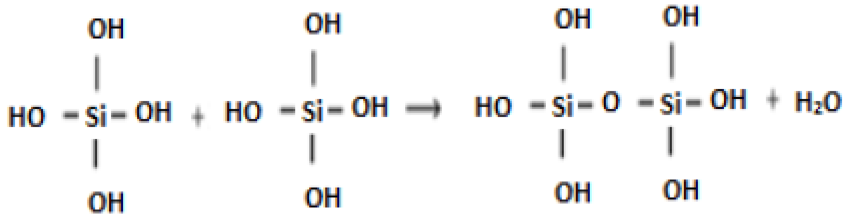

Fig. 2. Illustration of siloxane bonding [18].

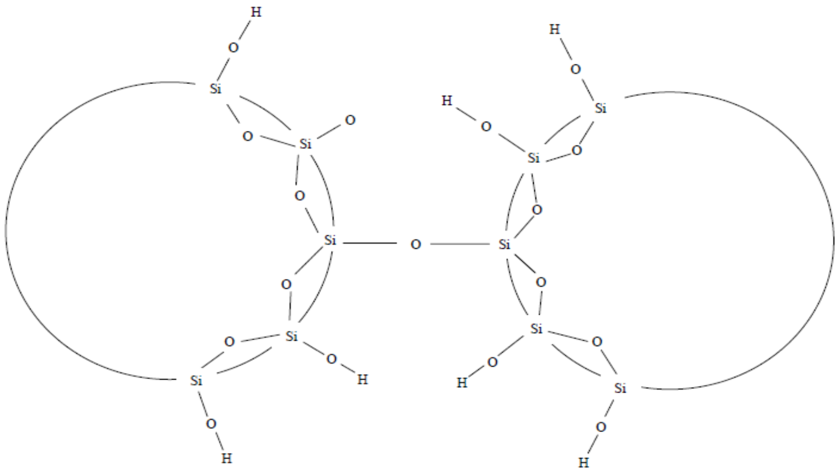

Fig. 3. Siloxane bond formation during gelation of colloidal silica particles [21]

4 Experimental Procedures

Prior to one-dimensional oedometer tests, extensive triaxial tests were performed in order to identify the magnitude of introduced cohesion and improved angle of friction in the grouted sands. Samples were prepared in the standard plastic moulds of 76 mm height and 38 mm diameter by injecting the desired colloidal silica weight percentage in the sand. Four different colloidal silica weight percentages were taken in the range from 5 wt. % to 30 wt. % for each of the three relative densities, 30 %, 40 % and 60 %.

4.1 Methods of Sample Preparation

The permeability behaviour of colloidal silica gel treated sample was investigated using the one-dimensional oedometer Test. 1-D compression tests were conducted in a front-loading oedometer cell (60 mm × 20 mm) as per IS: 2720 (Part 15). Porous stones are placed at the top and bottom of the specimen in order to ensure the free drainage throughout the test. The samples prepared for the experimental study were immersed underwater in the oedometer cell preceding to loading. All the samples tested in the consolidation apparatus were compressed in progressive incremental stages and then unloaded and again reloaded to the fixed vertical stress. This recompression was done to study the effect of colloidal silica on rebound behaviour. The specimen was allowed to consolidate for 24 hrs to reach equilibrium for each loading and unloading steps. This time was found to be adequately long enough for at least 90 % of the consolidation for all samples.

4.2 Indirect Method to Measure Hydraulic Conductivity Using Oedometer

Olson and Daniel [22] developed an indirect method for estimating saturated hydraulic conductivity (k) based on the results of the oedometer test. In this method, the coefficient of volume change m_v (m^2/kN) and coefficient of consolidation C_v (m^2/s) is inferred from compressibility and consolidation curves respectively. This m_v and C_v are used to obtain the hydraulic conductivity coefficient (k). In the present study, the coefficient of consolidation (C_v) is evaluated by Taylor's approach.

$$k = C_v m_v \gamma_w \tag{1}$$

Colloidal silica treated sand forms a continuum and all the void spaces of sand are occupied by colloidal silica. Colloidal silica introduces cohesion in the sand after the grouting process therefore 1D consolidation tests opted. Direct permeability tests were not performed as colloidal silica when comes in contact with water dilutes itself and then blocks the porous stone used in the conduction of tests. As the size of the apparatus in direct permeability tests such as falling head tests is large the effect of clogged pores in pervious stone is enlarged and doesn't lead to authentic results

5 SEM Analysis

SEM (Scanning electron microscope) is an innovative technique to obtain high-resolution images of any sample's surface topography. A focused beam of electrons is used to create these high magnification images. The atoms of the substance being tested interact with the electrons and various signals are produced having information about the composition and topography of the sample's surface. In the present study, a sand sample having a relative density 40 % grouted with 11 weight % colloidal silica cured for 7 days has been analyzed. The sample is initially exposed to high temperatures so that no moisture is left in the sample. Images have been taken from resolution ranging from ×100 to ×10000.

6 Results and Discussion

6.1 Optimum Colloidal Silica Amount from Triaxial Test Results

From the analysis of cohesion and internal friction angle test results obtained from triaxial tests, optimum colloidal silica wt. % was obtained as 12.5, 11 and 10 wt. % for 30, 40 and 60 % relative densities respectively. The optimum percentages were used to prepare samples for all the tests mentioned in this research work is shown in Figure 4.

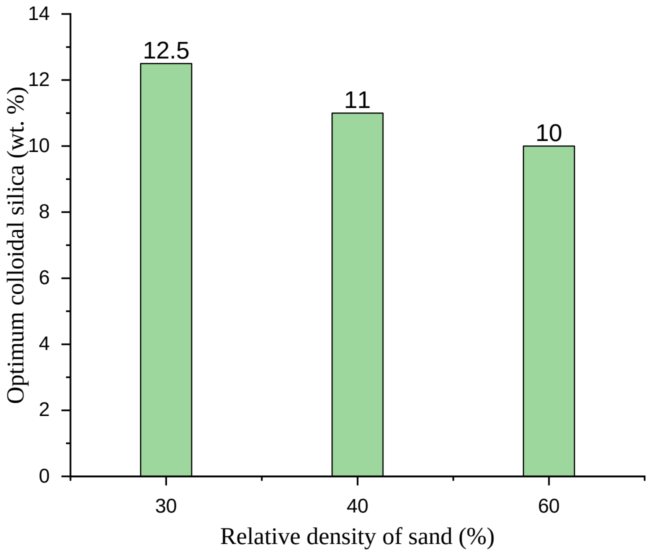

Fig 4. Optimum colloidal silica content for sand samples at three different densities

6.2 Variation of Hydraulic Conductivity with Normal Stress

Development of saturated hydraulic conductivity of colloidal silica treated sand as functions of loading pressures are shown in Figures 5-9. The effect of applied loading pressures on hydraulic conductivity is less significant, once become more than 500 kPa in all the colloidal silica treated sand. Based on the experimental investigations the addition of colloidal silica reduces the permeability in colloidal silica stabilized samples. The reduction in permeability can make use as an insulation barrier for waste disposal management. The hydraulic conductivity of the colloidal silica treated sand changes inversely with the applied loading pressures.

Hydraulic conductivity of colloidal silica treated sand at different relative densities is in the range of 10^{-9} to 10^{-12} m/s. Also, an exponential decrement in hydraulic conductivity was seen with the increase in colloidal silica particles with an increase in curing days. Thus this sand-colloidal silica matrix having the range of hydraulic conductivity mentioned above is suitable for a barrier material. Reduction in hydraulic conductivity is the main benefit of colloidal silica grout which forms chemical bonds among sand grains. This property can be utilized in preventing leakage of water through dam foundations, underground facilities and retaining walls.

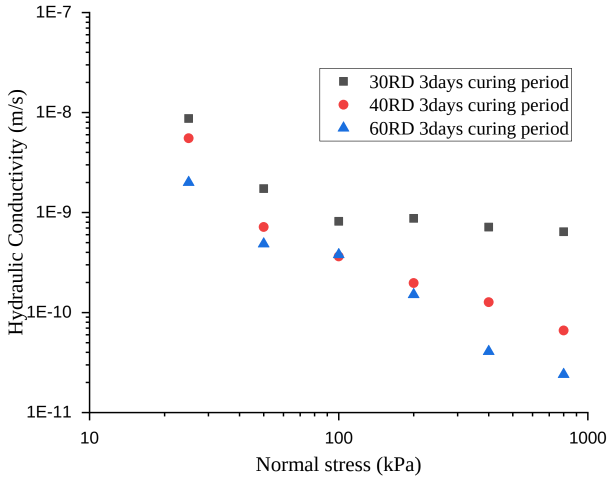

Fig 5. Hydraulic conductivity of colloidal silica treated samples at three different relative densities: Curing period of three days

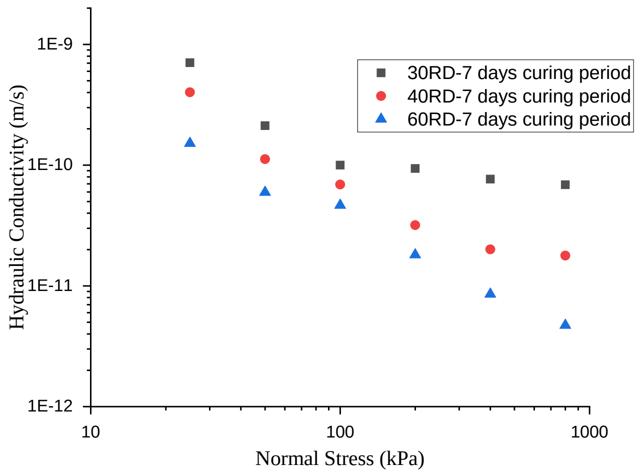

Fig 6. Hydraulic conductivity of colloidal silica treated samples at three different relative densities: Curing period of seven days

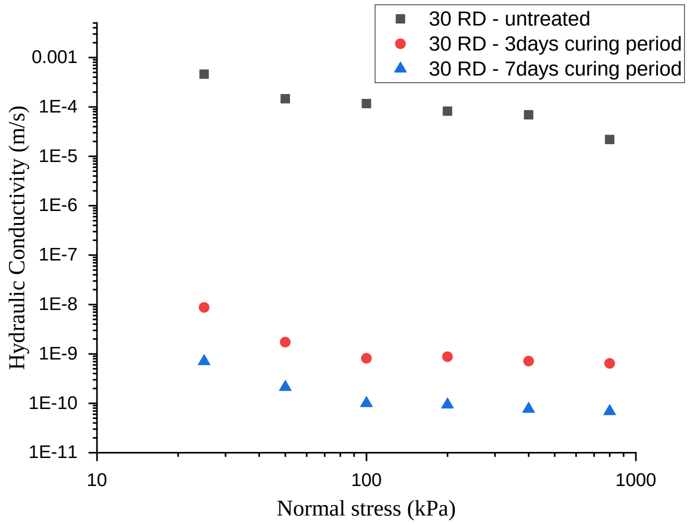

Fig 7. Hydraulic conductivity of untreated as well as colloidal silica treated samples at a relative density of 30 RD: Curing periods of three days and seven days

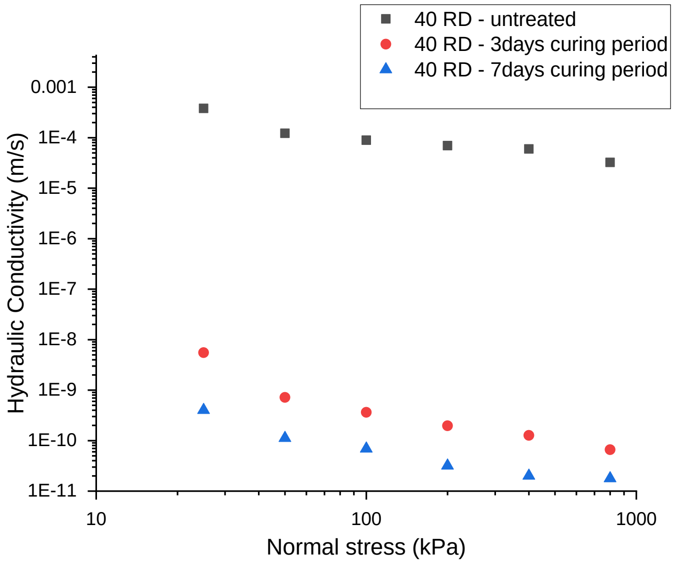

Fig 8. Hydraulic conductivity of untreated as well as colloidal silica treated samples at a relative density of 40 RD: Curing periods of three days and seven days

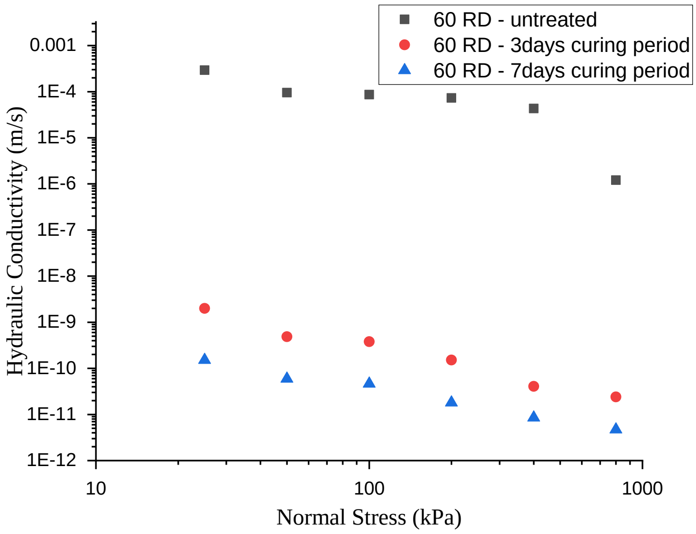

Fig 9. Hydraulic conductivity of untreated as well as colloidal silica treated samples at a relative density of 60 RD: Curing periods of three days and seven days

6.3 Microstructural Investigation of Sand Treated with Colloidal Silica

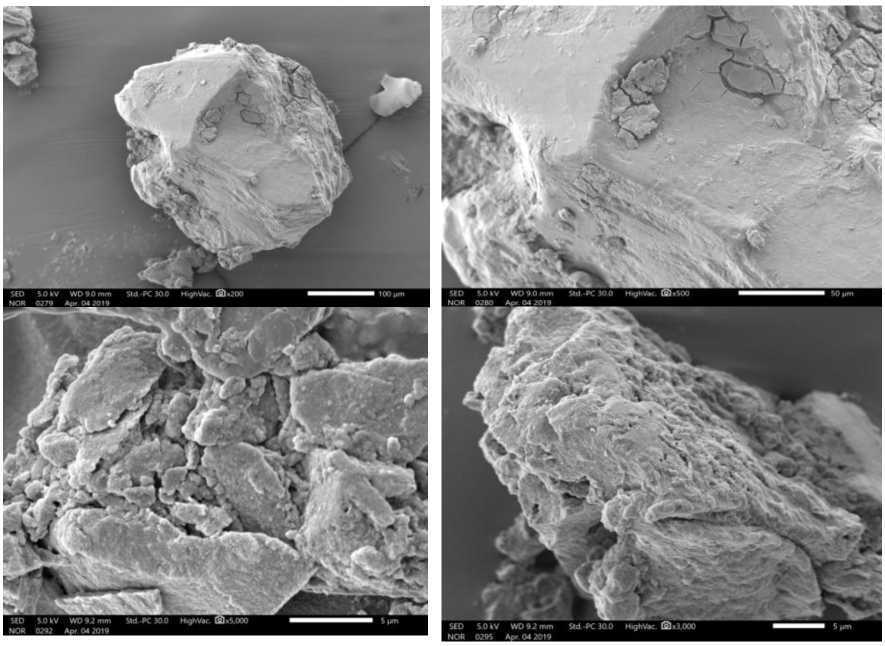

Fig 10. SEM images of Sand treated with colloidal silica

SEM analysis revealed that the colloidal silica and sand particles create a continuum of soil and silica particles. In Figure 10a, it can be seen that no distinction can be made between colloidal silica and sand. Colloidal silica acts as a binder and holds the sand particles together along with creating a cover around the sand particles in order to create a siloxane bond (Figure 10). The cracks seen in Figure 10b are desiccation cracks which are formed while conducting the sample preparation for SEM analysis. SEM analysis is generally conducted in order to understand the failure mechanism of the sample. In SEM analysis failure patterns in a brittle failure are either transgranular or intergranular cleavages. Failure planes are obtained as a separation planes between the individual grain contact. Careful observation of Figure 10c and 10d reveals that the colloidal silica grouted sample in the present study undergoes a brittle failure. At ×1000 magnification, failure planes can be clearly observed. In the static triaxial tests results also it was observed that the failure which took place was a brittle failure. SEM analysis confirms those results as well.The void spaces are shown in Figure 10c. It can be concluded from the SEM analysis that colloidal silica works like a binder.

7 Conclusions

According to the results obtained from the present study, we can advance the following conclusions

1. The hydraulic conductivity of colloidal silica treated sand varies inversely with the loading pressures at different relative densities of soils.
2. Also, an exponential decrement in hydraulic conductivity was seen with the increase in colloidal silica particles with an increase in curing days.
3. The effect of applied loading pressures on hydraulic conductivity is less significant, once become more than 500 kPa in all the colloidal silica treated sand.
4. Hydraulic conductivity of colloidal silica treated sand at different relative densities is in the range of 10^{-9} to 10^{-12} m/s. Thus this sand-colloidal silica matrix having the range of hydraulic conductivity mentioned above is suitable for an insulation barrier material.
5. According to the SEM analysis test results, the colloidal silica and sand particles create a continuum of soil and silica particles. Colloidal silica acts as a binder and holds the sand particles together along with creating a cover around the sand particles in order to create a siloxane bond.

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