6.0 COLLOIDAL SILICA LABORATORY TESTING AND RESULTS

6.1 Introduction

The purpose of the colloidal silica testing program was to determine if colloidal silica meets the essential performance criteria discussed in Chapter 2. For solution grouts, the viscosity is the primary variable that will determine if a material can be injected into a formation. For passive site remediation, the gel time is also important. In Phase 1 of the testing program, gel time curves were developed for different grades and dilutions of colloidal silica to determine if extended gel times could be obtained. Viscosity testing was also done on different grades and dilutions of colloidal silica. Phase 2 of the testing program included strength testing of stabilized sands.

This chapter consists of a description of the colloidal silica testing program, followed by a presentation of the results. Summaries of the results are given in Sections 6.4.1 and 6.5.1 and are followed by detailed presentations. Viscosity data is presented in Table A2-1 of Appendix 2. Table A3-1 of Appendix 3 contains details on the stabilized sand samples and Table A3-2 of Appendix 3 is a list of the cyclic testing results.

6.2 Colloidal Silica Gel Time and Viscosity Testing

6.2.1 Properties Measured

In phase one of the colloidal silica testing program, gel time curves were developed for different concentrations of three types of colloidal silica sols. Qualitative viscosity observations were made for all grout concentrations. In addition, quantitative viscosity measurements were done for selected grout concentrations.

Colloidal silica sols can be gelled by adjusting the pH or increasing the ionic strength of the solution. The properties that affect gel time include silica concentration, ionic strength, pH, particle size and specific surface area. Increasing the silica content causes a decrease in gel time but results in a stronger gel. Increasing the ionic strength also causes gel time to decrease. The longest gel time obtainable for a given silica concentration occurs when no salt is added. With respect to pH, the tendency to gel is greatest at pH's between 5 and 6 for the reasons discussed in Section 3.6.1. Gel times are longer at pH's above and below this range. Gel time increases as the particle size increases and the specific surface area decreases. Therefore, at a given silica concentration, gel time will be longest for the solution with the largest average particle size. Gel time curves are presented in the results section.

One additional factor pertinent to the case of passive site remediation is the presence of ions in the soil to be stabilized. If there are exchangeable cations in the soil to be stabilized, there may be an effect on the gel time. Soils with exchangeable cations can change the ionic strength of the solution as it passes through the soil. This will cause a corresponding change in the gel time. Therefore, tests were also done to assess whether the addition of Monterey sand would affect the gel time

6.2.2 Materials

Three different sols were chosen for testing to find a range of viscosities and gel times that might be applicable for passive site remediation. The colloidal silica sols selected for testing were Ludox®-SM, Ludox®-HS-40 and Ludox®-TM. Some of the important properties of these formulations are shown in Table 6-1 (DuPont 1997).

Fisher Scientific (Product number S271) sodium chloride was used as the added salt. pH adjustments were made using 6 N hydrochloric acid. The hydrochloric acid was prepared by diluting concentrated hydrochloric acid with distilled water. The water used to dilute the grout was tap water. In the case where sand was added to the samples, the sand used was Monterey #0/30 sand. The properties of this sand are discussed in Section 6.4.2.

Table 6-1 Properties of Ludox Colloidal Silica Sols

	Ludox-SM	Ludox HS-40	Ludox TM
SiO_2/Na_2O (by weight)	50	95	225
Stabilizing counter ion	Sodium	Sodium	Sodium
Particle charge	Negative	Negative	Negative
Silica (as SiO_2), weight %	30	40	50
PH	10.0	9.7	9.0
Viscosity (cP)	5.5	16	40
Average Particle Size (nm)	7	12	22
Specific Surface Area (m^2/g)	345	220	140

6.2.3 Methods

6.2.3.1 Sample Preparation

For each type of colloidal silica tested, several combinations of silica and salt concentrations were considered. The different combinations of silica and salt concentrations are shown in Table 6-2. For each concentration of silica and salt, a series of samples was made at different pH's. The pH varied from about 9 to about 5 in half pH increments. The amount of colloidal silica sol, water, and salt for the entire batch of samples was calculated and measured. The salt was dissolved in the tap water and then mixed with the appropriate amount of concentrated colloidal silica sol.

The pH of the batch was measured using a Fisher Scientific Accumet AR10 pH meter. The pH was adjusted to the initial pH value using 6 N HCl. The acid was added a few drops at a time with a pipette and thoroughly mixed into the colloidal silica solution. The pH was measured again and additional acid was added as needed until the pH of the entire batch reached the first pH increment. At this point, a 55-ml sample was removed from the batch and placed in a 60-milliliter plastic test tube with a screw-on cap. The pH of the remainder of the solution was then adjusted to the next desired pH increment using the same process. The next 55-milliliter sample was removed and placed in a test tube with a glass marble. This process continued until the entire batch of samples was completed. The glass marbles were used to assist in making gel time and viscosity observations. Glass marbles were selected so they would not react with the colloidal silica and alter the gel times. Marbles were used in all samples except those to which Monterey sand was added. For the samples where Monterey sand was added, the colloidal silica solution was made in the same way described above. Individual samples were made by placing 20 grams of Monterey sand in the test tube with 30 milliliters of colloidal silica grout.

Table 6-2 Colloidal Silica Samples for Gel Time Curves

Type of Ludox	Silica Concentration (weight %)	NaCl Concentration (N)	pH Range
SM	5	0, 0.01, 0.03, 0.10	5 - 9
SM	7.5	0, 0.01, 0.03, 0.10	5 - 9
SM	10	0, 0.01, 0.03, 0.10	5 - 9
SM + Sand	5	0, 0.01, 0.03, 0.10	5.5 - 8.5
SM + Sand	7.5	0, 0.01, 0.03, 0.10	6 - 8.5
SM + Sand	10	0, 0.01, 0.03, 0.10	7 -9
HS	10	0.10	5 - 9
HS	15	0.10	5 - 9
HS + Sand	5	0.10	7 - 8
HS + Sand	10	0.10	6.5 - 8
TM	10	0, 0.01, 0.03, 0.10	5 - 9
TM	15	0.10	5 - 9
TM	20	0.10	5 - 9
TM + Sand	10	0.10	6 - 7.5
TM + Sand	15	0.10	5 - 6.5

6.2.3.2 Gel Time Testing

Gel state descriptions presented by Sydansk (1990) are reproduced in Table 6-3.

Table 6-3 Gel States of Colloidal Silica

Gel State	Description
1	No detectable gel formed. Gel appears to have same viscosity (fluidity) as original polymer solution and no gel is visually detectable.
2	Highly flowing gel. Gel appears only slightly more viscous than original polymer solution.
3	Flowing gel. Most of obviously detectable gel flows to bottle cap upon inversion.
4	Moderately flowing gel. Small portion (5-15%) of gel does not readily flow to bottle cap upon inversion.
5	Barely flowing gel. Gel slowly flows to bottle cap and/or significant portion (>15%) of gel does not flow upon inversion.
6	Highly deformable non-flowing gel. Gel does not flow to bottle cap upon inversion (gel flows to just short of reaching bottle cap.
7	Moderately deformable non-flowing gel. Gel flows about halfway down bottle upon inversion.
8	Slightly deformable non-flowing gel. Only gel surface deforms slightly during inversion.
9	Rigid gel. There is no gel-surface deformation upon inversion.
10	Rigid ringing gel. Tuning-fork-like mechanical vibration can be felt or heard after bottle is tapped.
11	Rigid gel no longer ringing. No tone or vibration can be felt or heard, because natural frequency of gel has increased.

The gel time was checked by inverting the samples and watching the marble drop from one end of the tube to the other. The degree of gelling could be observed by the speed with which the marble would drop from the top to the bottom of the tube. Initially, it would take less than one second for the marble to drop from one end of the tube to the other (Gel State 1). As the colloidal silica started to thicken, the marble would stick to the bottom of the tube for a few seconds after the tube was inverted before dropping from the bottom to the top of the tube (Gel State 2). During this initial thickening period, the travel time remained less than one second after the marble stopped sticking to the tube. As the thickening continued, the marble would take longer to drop through the solution. For the purposes of this study, the colloidal silica was considered to be gelled when it took longer than 15 seconds for the marble to drop through the gel (Gel State 4 or 5). The gelling process would continue through the remaining gel states until it became a firm, resonating gel (Gel State 10). In this state, when a tube is tapped against a firm surfaces, it vibrates. When extremely low concentrations or very long gel times were used, the tests were terminated before Gel State 10 was reached. In cases where sand was added to the test tubes, gel time observations were made by shaking the tubes and watching how long it took for the sand grains to settle.

6.2.3.3 Viscosity Testing

Qualitative observations of viscosity were also made during the gel time testing. The length of time it took for the marble to drop through the grout gave an indication of the viscosity. These observations indicate that the viscosity of the sol remains fairly low until just prior to gelling.

Quantitative viscosity measurements were made using a Brookfield rotating viscometer (Model DV-II+). Generally, the Brookfield viscometer was set at 200 revolutions per minute and the test was run for 30 seconds. As the viscosity increased, the revolutions per minute were decreased to stay in the range of the instrument. In these cases, the duration of the test was increased to about 2 minutes.

6.3 Strength Testing of Stabilized Sands

The purpose of strength testing of stabilized sands is to determine if the stabilized sands will perform adequately under the proposed earthquake loading. Cyclic laboratory tests can not reproduce the stress conditions that exist in actual seismic events, but can give us an idea of how the stabilized formation might behave if it were subjected to an earthquake loading. Earthquakes have a random loading pattern that apply stresses in three dimensions. The loading experienced by a soil formation in the field depends on many factors, some of which include the magnitude of the earthquake, the distance from the site, and the depth of the earthquake. It is not practical to reproduce an actual earthquake loading in the laboratory. Even if it were, earthquake events have unique time histories that are not likely to be representative of the next earthquake loading. Therefore, standardized tests are performed in the laboratory under controlled conditions, where the components of the load applied to the sample and the boundary conditions of the test are known. Predictions of the behavior in the field are extrapolated from the test results.

The cyclic triaxial test is one method that can be used to determine the liquefaction resistance or cyclic strength of a soil. In this test, a cylindrical sample is placed between platens, surrounded by a latex membrane, placed within a triaxial chamber, and subjected to a confining pressure. During the test, the sample is first saturated, then consolidated to the desired stress condition, and finally loaded with a pulsating deviator load. The deviator load cycles between compression and extension. Drainage is permitted during consolidation, but prevented during the cyclic loading. During the cyclic loading, the pore pressure in the sample increases, causing the effective stress to decrease. As this occurs, the sample strains axially.

Liquefaction may be defined as the point when the pore pressure equals the initial effective confining stress or when a certain amount of axial strain is reached. Often, more than one criterion for liquefaction is used. “Initial” liquefaction may be considered to be the point at which the excess pore pressure equals the initial effective confining pressure. Additional degrees of liquefaction will be reported for development of one percent, two percent, or five percent axial strain. In cyclic triaxial tests, strain is often measured in terms of double amplitude axial strain, which is the maximum strain that develops during an entire cycle of compression and extension. Grouting the soil will cause the permeability to decrease, making it difficult to measure the pore pressure response accurately. Therefore, for the purposes of this study, the strain was considered to be the more important factor.

Cyclic triaxial tests are often interpreted in terms of the cyclic stress ratio and number of cycles to initial liquefaction. The cyclic stress ratio is defined as the ratio of the maximum cyclic shear stress to the initial effective confining stress. When the cyclic stress ratio is used, samples that are subjected to different loading conditions can be compared. Typically, several tests are run at different cyclic stress ratios. The number of cycles of deviator stress required to cause liquefaction is plotted against the cyclic stress ratio to develop a cyclic resistance curve. A cyclic resistance curve for loose sand at a relative density of 22 percent is shown in Figure 6-1.

One way to determine if treatment is successful is to develop a cyclic resistance curve for untreated sands and stabilized sands to compare the improvement due to treatment. If the stabilized sands require more cycles to liquefy, then the treatment may be considered successful. Treatment could also be considered successful if the strain that develops during cyclic loading is limited. As shown in Figure 2-3, loose sands and dense sands behave differently during cyclic loading. Loose strains accumulate very little strain until just prior to liquefaction. At the onset of liquefaction, strain accumulates very quickly and can cause rapid collapse of the sample. In contrast, dense sands accumulate a small amount of strain early in the cyclic loading, but that level of strain increases very slowly or not at all.

There have been many liquefaction studies done on untreated sands, but very few have been done on sands treated with cement or chemical grouts. Some dynamic testing studies have been done on sands treated with chemical grouts to determine dynamic properties or fatigue life for design of machine foundations (Maher et al. 1994b, Rosenfarb and Hackman 1981, Vipulanandan et al. 2000). Several liquefaction studies have been done on naturally and artificially cemented sands (Clough et al. 1989, Saxena et al. 1988) and silicate-grouted sands (Maher et al. 1994a).

Clough et al. (1989) considered the effect of weak cementation on the liquefaction resistance of sand. They drew the following conclusions relating to liquefaction resistance. First, the behavior of a loose cemented sand is similar to the behavior of a denser, uncemented sand. Second, the liquefaction resistance increases as the degree of cementation increases. Additionally, if there are weak lenses in cemented sand, these lenses lower the liquefaction resistance. This effect is more pronounced at higher stress levels. Finally, after a certain level of cementation is reached, the soil is essentially not liquefiable.

Saxena et al. (1988) found that even a small amount of cement significantly increases the cyclic strength compared to uncemented sands. Like Clough et al. (1989), Saxena et al. (1988) noted that cemented loose sands behave similarly to dense uncemented sands. They also noted that when cemented sands were tested cyclically, the axial strains were “often more asymmetrical about the zero strain axis” than for untreated sands. In addition, they found that the cyclic stress of treated sands increased with relative density and with curing period.

Maher et al. (1994a) did monotonic and cyclic testing on Ottawa sand treated with sodium silicate, acrylate polymer, or microfine cement grout. The sands were at relative densities of 41 and 65 percent. The sands were saturated prior to testing using the method of vacuum saturation (Rad and Clough 1984). Maher et al. (1994a) found that treatment with sodium silicate in concentrations between 20 and 60 percent increased the liquefaction resistance of sand from three to six times over untreated sand. Similarly, treatment with acrylate polymer grout increased the liquefaction resistance from two to four times over untreated sands. Finally, sands treated with microfine cement grout and tested at cyclic stress ratios between 0.3 and 1.0 did not liquefy at all.

6.3.1 Properties Measured

The goal of the strength testing of stabilized sands was to determine how much the stabilizer improved the strength or decreased the strain in the soil during cyclic loading. A second goal was to determine the minimum amount of stabilizer required to adequately stabilize the soil. A third goal was to determine if different grades of colloidal silica produced different results. Finally, the static strength properties of stabilized soils were determined for comparison with cyclic data and with published data.

The initial intent of the cyclic testing program was to attempt to make and test the samples in a manner representative of field conditions. With passive site remediation, the soil formation will be treated by permeation grouting at low pressures with stabilizers that have long set times. The formation will be saturated before, during, and after treatment. Therefore, the samples were made by tamping loose sand in a mold and permeation grouting the samples under fairly low gradients. Grouts with gel times of up to 30 days were used. The samples were cured for three times the gel time and then tested cyclically. The technique of back pressure saturation was used to increase the degree of saturation of the samples. High back pressures were required to saturate the samples. The results of these tests were very erratic.

Therefore, the testing program was modified in an attempt to obtain more reproducible results. First of all, the method of making samples was changed from tamping and permeation grouting to pluviating dry sand into the grout. This procedure ensured that the sand particles would be coated with grout. The method is not representative of field conditions, but it is very reproducible. Next, the samples were cured for a minimum of ten times the gel time. Numerous samples were cured for as long as 40 times the gel time. The back pressure saturation procedure was eliminated.

The purpose of back pressure saturation was to use the effective stress criterion for determining the onset of initial liquefaction. However, the pore pressure is measured at the ends of the samples, so accurate pore pressure measurements require free draining samples. Unless a sample is free draining, the pore pressures measurements at the ends of the sample probably do not reflect the pore pressures in the middle of the sample. The treated samples are not free draining. Therefore, it is likely that the pore pressures measured in the samples that were back pressure saturated do not accurately reflect the pore pressures in the middle of the samples. In addition, it is possible that the process of back pressure saturation weakened or damaged the bonds in the colloidal silica grout. Therefore, the back pressure saturation process was eliminated from the testing procedure.

In subsequent cyclic triaxial tests, the effective stress criterion for onset of liquefaction was not used. The effectiveness of treatment was evaluated based on the development of axial strain during cyclic loading and the residual static strength of the sample after testing.

The static properties measured were the unconfined compressive strength and the unconsolidated undrained strength using unconfined compression (UC) and unconsolidated undrained (UU) tests, respectively. Unconfined compression tests were chosen so the results could be compared with published results (Persoff et al. 1999, Yonekura and Miwa 1993). Additionally, these tests are often done on chemically stabilized sands and have the advantage of being fast and easy. UU tests were chosen because they are more representative of the stress state of the soil formation in the field, so they might give a better idea of the strength of the grouted mass prior to earthquake loading. Baseline UC and UU strength tests were done to determine the maximum strength of treated samples prior to cyclic loading. After cyclic testing, most of the samples were tested statically to determine the residual strength.

Samples were made with concentrations that varied from 5 to 20 percent by weight of colloidal silica. Three different grades of Ludox colloidal silica were used.

6.3.2 Materials

The sand used in the testing program was Monterey No. 0/30 sand, which is a commercially available sand from California. Monterey No. 0/30 sand is a light brown, poorly graded, medium to fine sand, with sub-angular to sub-rounded grains. Over 98 percent passes the No. 20 sieve (0.84 mm) and is retained on the No. 100 sieve (0.15 mm). A gradation curve is shown in Figure 6-2.

The index properties of the Monterey No. 0/30 sand are presented in Table 6-3. The grain size distribution was determined in general accordance with ASTM D422, Standard Test Method for Particle Size Analysis of Soils. The mean grain size D_{50}, the coefficient of uniformity, C_u, and the coefficient of curvature, C_c, were determined from the results of the particle size analysis and are shown in Table 5.1. The maximum and minimum densities were determined using the Standard Test Method for Maximum Index Density of Soils using a Vibrating Table (ASTM D4253) and the Standard Test Method for Minimum Index Density of Soils and Calculation of Relative Density (ASTM D4254), respectively. The specific gravity was determined in general accordance with ASTM D854, Standard Test Method for Specific Gravity of Soil by Polito (1999).

The grades of colloidal silica used for strength testing of stabilized sands were Ludox-SM, Ludox-HS-40 and Ludox-TM. The properties of these materials were summarized in Section 6.2.2.

Table 6-4 Index Properties for Monterey Sand

USCS Classification Symbol	SP
D_{60} (mm)	0.46
D_{50} (mm)	0.44
D_{30} (mm)	0.36
D_{10} (mm)	0.28
Coefficient of Uniformity, C_u	1.64
Coefficient of Curvature, C_c	1.01
Specific Gravity, G_s	2.65
Minimum Index Density (pcf)	90.8
Maximum Index Void Ratio, e_{max}	0.821
Maximum Index Density (pcf)	112.7
Minimum Index Void Ratio, e_{min}	0.464

6.3.3 Methods

6.3.3.1 Preparation of Molds and Platens

Two different types of molds were used. Stainless steel molds were made from Shelby tubes. The tubes were cut to a length of 6.5 inches and split longitudinally so the samples could be removed from the mold without using a jacking force. The molds were clamped together using hose clamps. Electrical tape and vacuum grease were used to seal the seam of the mold to prevent leakage during grouting. WD-40 was used to lubricate the molds prior to sample preparation. However, the grouted samples tended to stick to the sides of the molds, making it difficult to remove the specimens from the molds without damaging them. Therefore, additional molds were made from 3-inch-diamter PVC pipe. The molds were 7.5 inches long and split longitudinally in thirds or quarters. The molds were glued together with silicone glue to prevent leakage during grouting and held together using hose clamps. A picture of the molds is shown in Figure 6-3.

Grouting platens were made for the tops and bottoms of the molds from 1-inch-thick PVC. A picture of a platen is shown in Figure 6-3. The platens were cut to a diameter of 2.9 inches to fit the molds. Grooves were cut into the platens in a star shape to facilitate the movement of grout through the sample.

6.3.3.2 Sample Preparation

Samples were made in one of two ways. The first method used was the undercompaction technique (Ladd 1978), after which the samples were permeation grouted under hydraulic gradients between one and three. The second method of sample preparation was by pluviation of dry sand into the grout.

The undercompaction technique used is described in Ladd (1978) with modifications suggested by Chan (1985). It involves placing the soil in layers and compacting each layer to a slightly higher relative density. The first layer placed will be compacted more and more as each successive layer is placed. Therefore, the first layer should be placed at a lower density than successive layers to compensate for the additional energy it will receive from the compaction of subsequent layers. Similarly, the top layers will be compacted less than the underlying layers and should be placed at a higher relative density. Chan (1985) recommends that the soil be placed in seven layers, with the target relative density assigned to the middle layer. The first three layers are placed at lower relative densities, while the upper layers are placed at higher relative densities. Therefore, if the target relative density is 35%, the layers one through seven will be placed at relative densities of 32, 33, 34, 35, 36, 37 and 38 percent, respectively.

For this study, a relative density of 22 percent was selected, which corresponds to a void ratio of 0.75. The samples were prepared by placing the soil in the molds in lifts and tamping each lift to the appropriate height. The amount of soil required for each lift was determined for the appropriate relative density and water was added to get a saturation of 50%. A total of seven lifts were used for each sample.

Prior to grouting, the samples made by moist tamping were flushed with three pore volumes of distilled, deaired water under a hydraulic gradient of between one and three. After three pore volumes of water were run through the sample, three pore volumes of grout were permeated through the sample under a hydraulic gradient of between two and three. After the grout was finished flowing through the sample, the platen was plugged to prevent the grout from draining out of the mold. The top platen was also plugged to prevent air from getting into the mold during the curing period. If the top platen was needed for another sample, it was removed from the top of the mold after grouting and the mold was sealed to prevent air and water from getting into or out of the sample. The samples were placed in a constant temperature room at a temperature of 23° C to cure.

It was sometimes difficult to remove the samples from the Shelby tube molds because they tended to stick to the sides of the molds. Therefore, a wire trimming tool was used to release the sample from the side of the mold. The wire was placed between the edge of the mold and the sample and gently sawed around the outside of the mold. This was done two or three times to thoroughly loosen the sample so it could be removed from the mold without being damaged.

For samples made by pluviation, the amount of dry sand necessary for a sample 6.25 inches in height at a relative density of 22 percent was measured. The amount of grout required to fill all the pores at the target relative density was placed in the mold. The sand was pluviated through air into the pore fluid from a height of 8 inches. The sides of the mold were tapped very gently until the sample was at the appropriate height and the sand particles were saturated with grout. The mold was then sealed and left to cure.

Prior to testing, the top and bottom of each sample was leveled. A straight edge was used to trim the samples so that each sample had flat ends perpendicular to the longitudinal axis. The dimensions of the sample were measured and recorded. A schedule showing sample details, including colloidal silica concentration, gel time, cure time, method of sample preparation, and type of testing is shown in Appendix 3.

6.3.3.3 Testing

The unconfined compression strength was measured in general accordance with ASTM D2166 Standard Test Method for Unconfined Compressive Strength of Cohesive Soil and ASTM D4609 Standard Guide for Evaluating Effectiveness of Chemicals for Soil Stabilization. A strain rate of 0.3 percent per minute was used for all of the unconfined compression tests. The following procedure was used.

1. The sample was centered on the bottom platen and the loading device was adjusted so the top platen was in contact with the sample. The dial gage indicator was zeroed.
2. The axial load was applied at a strain rate of 0.3 percent per minute.
3. The load was recorded at intervals of 0.005 inches of deformation.
4. The loading was continued until load values decreased 20 percent below the peak value or until 15 percent strain was reached.
5. A sketch of the sample showing the failure plane was drawn.

The undrained strength was measured in general accordance with ASTM D2850 Standard Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression. A strain rate of 0.3 percent per minute was used for all of the UU tests. The following procedure was used.

1. The sample was centered on the bottom platen. The top platen was place on top of the sample. A latex membrane was expanded using a membrane expander and placed around the sample. The membrane was secured to the platens using an O-ring. The sides of the platens were covered with a thin film of water soluble lubricant to improve the seal between the platens and the membrane.

2. The top of the cell frame was attached to the bottom of the frame and the loading piston was threaded onto the top platen. The triaxial cell was assembled, filled with water, and centered in the load frame. The cell pressure was applied. The dial gage indicator was zeroed.
3. The axial load was applied at a strain rate of 0.3 percent per minute. The load was recorded every 0.005 inches of deformation.
4. The loading was continued until 15 percent axial strain was reached or until the deviator stress dropped 20 percent below the peak value.
5. A sketch was drawn of the sample at failure.

The equipment used for the cyclic triaxial testing was an automated triaxial testing system from the Soil Engineering Equipment Company. The loading is controlled using closed-loop feedback systems. The closed-loop feedback system and the data acquisition system are controlled using a five-channel signal processor from Paul Gross Associates. A personal computer is used to run the software that controls the equipment. During each test, axial load, axial displacement, cell pressure, effective pressure, and pore pressure are measured by the system and recorded on the computer. The cell, effective, and pore pressures are measured using pore pressure transducers. An LVDT is used to measure the axial displacement and a load cell is used to measure the axial load. A picture of the triaxial cell is shown in Figure 6-4.

The cyclic tests were run in general accordance with ASTM D5311 <u>Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil</u>. Certain modifications to the test procedure were required because the stabilized samples had a low permeability. The tests on stabilized were set up using the following procedure.

1. Filter paper was placed on the bottom platen of the triaxial cell. The sample was centered on the filter paper and another piece of filter paper was placed on the top of the sample. The top platen was centered on top of the sample. The sides of the platens were covered with a thin coat of water soluble lubricant to improve the seal between the latex membrane and the platens. The membrane was expanded using a membrane expander and placed around the sample.

O-rings were used to secure the membrane to the platens. The volume change device was filled with deaired water.

2. The top of the cell frame was attached and the loading piston was threaded into the top platen. The pore pressure line was attached to the top platen and tightened.
3. The triaxial cell was assembled and filled with water. The cell was placed in the load frame and the load cell, pressure line and drainage lines were attached.
4. The test was initiated using the computer software. Since the triaxial setup is automated, the test was run by following the directions provided in the menu for each segment of the test as described below.
5. The same procedure was used on untreated sands except the samples were formed in the cell using a forming jacket.

During the first phase of the strength testing program, each sample was saturated. The purpose of saturating the sample is to fill all of the voids of the sample with water. The technique of back pressure saturation is typically used to increase the degree of saturation of the specimen. In this method, a back pressure is applied to the pore water in the specimen to force the air in the pores into solution. The cell pressure and back pressure are increase simultaneously in small increments (generally less than 20 kPa) so that the effective stress on the sample remains constant and the sample does not become overconsolidated. During back pressure saturation, the cell pressure was kept at 50 kPa above the back pressure.

If the specimen has a low degree of saturation initially, it can be very difficult to achieve adequate saturation, even with high back pressures. The initial degree of saturation can be improved by allowing carbon dioxide to flow through the sample prior to introducing deaired water to the sample. CO_2 displaces air in the pore spaces and is much more soluble in water than air is. Allowing deaired water to flow through the sample prior to application of back pressure also increases the initial degree of saturation. CO_2 and deaired water were permeated through the untreated samples prior to testing.

The grouted samples were not free draining, so it was not possible to introduce either CO_2 or deaired water to the sample prior to back pressure saturation. It was also difficult to remove air bubbles from the drainage lines, even with a vacuum applied to the sample. Therefore, very high back pressures were required to saturate the samples (in excess of 500 kPa).

The degree of saturation is measured using the pore pressure parameter B, where $B = \Delta u/\Delta\sigma_3$; Δu is the change in pore water pressure that results from the increase in confining pressure; and, $\Delta\sigma_3$ is the change in confining pressure. A B value of 1 indicates complete saturation. Specimens are considered to be saturated if the B value exceeds 0.95. In the case of treated samples, it was difficult achieve a B value greater than 0.8. Reaching a B value of 0.8 required the use of high back pressures for a period of hours or overnight. Therefore, when treated samples achieved a B value above 0.8, cyclic testing was initiated. As discussed previously, back pressure saturation was performed only during the initial phase of strength testing of stabilized sands.

When the sample had reached a B value above 0.8, the sample was isotropically consolidated to an effective stress of 100 kPa (14.7 psi). The values of the LVDT and the volume change transducers were recorded before and after the consolidation phase so that the final specimen void ratios could be calculated. The consolidation segment was run for 2 minutes.

Following consolidation, the sample was cyclically loaded. The desired CSR was specified using the appropriate peak-to-peak deviator stress for the effective confining pressure. A sinusoidal loading function with a period of 2 seconds was used for all of the tests. Each test was run for a maximum of 100 cycles or to a maximum double amplitude strain of 11 percent. The maximum of 100 continuous cycles per test was dictated by the constraints of the software, while the maximum strain was dictated based on the range of the LVDT. In some cases, if the sample did not reach the limiting strain in 100 cycles, up to nine additional series of 100 cycles were run for a total of 1000 cycles. Between tests, drainage from the sample was prevented by closing the valve between the volume change device and the drainage line. Some cyclic tests were terminated at axial strains between one and five percent so UC or UU tests could be done on samples that had been tested cyclically to different strain levels.

6.4 Colloidal Silica Gel Time and Viscosity Testing Results

6.4.1 Summary

The goal of the colloidal silica gel time and viscosity testing program was to develop gel time and viscosity curves for different concentrations and different grades of colloidal silica. It was expected that colloidal silica solutions with gel times in excess of 50 days could be found, however, the specific formulations required to obtain those gel times were not known.

Three types of colloidal silica were tested. Different types of colloidal silica have different average particle sizes. Solutions with smaller average particle sizes have shorter gel times. Ludox-SM, which has an average particle size of 7 nanometers, was selected because it has been used successfully in other soil stabilization experiments reported in the literature. These cases were discussed in Chapter 3. Ludox-SM has been used in field experiments in concentrations as low as five percent. Because of the small particle size, it requires a smaller concentration to form a firm, resonating gel.

Ludox-HS has an average particle size of 12 nanometers. The larger particle size causes two things to happen. First, a higher concentration is required to get a firm, resonating gel to form. Second, longer gel times are possible than with Ludox-SM at similar ionic strengths and pH's. Ludox-TM was also selected because it has a particle size of 22 nanometers, so it was expected that very long gel times could be obtained. However, it was also expected that higher concentrations of Ludox-TM would be required to form a firm, resonating gel.

Gel time curves were developed for different concentrations of three types of colloidal silica sols. Gel times of at least 50 days were obtained for all of the concentrations tested. Gel times of 100 days were obtained for most concentrations tested. Concentrations of 10 percent Ludox-TM with very low ionic strengths did not gel. The viscosity of the samples was generally less than 2 cP for half to two-thirds of the gelling time. Formulations with longer gel times had lower viscosity values for more of the induction period. However, these formulations also took longer to form a firm gel. These results are discussed in detail below. Based on the results of the gel time and viscosity testing, colloidal silica was selected for additional testing. Sands were stabilized using colloidal silica grout and tested for strength under static and cyclic loading.

6.4.2 Colloidal Silica Gel Time Testing Results

Gel times of 50 to 100 days were obtained for 10 percent Ludox-SM concentrations at all of the ionic strengths tested for this study. The gel time curves are shown in Figure 6-5. When a 10 percent Ludox-SM concentration is used in conjunction with low ionic strengths, a small change in pH can cause a large change in gel time. This trend can be seen in Figure 6-5. When no salt is added to the solution, a gel time of 50 days occurs at a pH of about 7.2, while a gel time of 100 days occurs at a pH of about 7.3. When the solution has an ionic strength of 0.01 N, gel times of 50 and 100 days occur at pH's of 7.2 and 7.4, respectively. When the solution has an ionic strength of 0.03 N, gel times of 50 and 100 days occur at pH's of 7.6 and 7.8. For an ionic strength of 0.1 N, a gel time of 50 days occurred at a pH of 9. This was the longest gel time measured for this concentration of Ludox-SM at an ionic strength of 0.1N NaCl.

Similar trends were observed for concentrations of 7.5 and 5.0 percent Ludox-SM, although longer gel times were possible and occurred at lower pH values. These results are shown in Figures 6-6 and 6-7 for concentrations of 7.5 and 5 percent, respectively. When no salt was added to 7.5 percent Ludox-SM, gel times of 50 and 100 days occurred at pH's of 6.6 and 6.8, respectively. When no salt was added to 5 percent Ludox-SM, gel times of 50 and 100 days occurred at pH values of 6.1 and 6.3, respectively. At ionic strengths of 0.1 N, gel times of 50 and 100 days occurred at pH's of 8.4 and 8.7 for the 7.5 Ludox-SM solution, respectively, and at pH's of 7.8 and 8.2 for the 5 percent Ludox-SM solution, respectively.

The testing of Ludox-HS and Ludox-TM was more limited. Gel time curves for Ludox-HS at concentrations of 10 and 15 percent are shown in Figure 6-8. Gel times of 50 and 100 days were obtained at pH's in the range of 7.5 to 8.5. Gel time curves for Ludox-TM at concentrations of 10, 15, and 20 percent are shown in Figure 6-12. Gel times in the range of 50 to 100 days were obtained at pH's in the range of 6 to 7.5. Solutions of 10 percent Ludox-TM with ionic strengths less than 0.08 N did not gel in more than 450 days.

6.4.3 Colloidal Silica Viscosity Testing Results

Formulations of 10 and 15 percent Ludox-HS and 15 percent Ludox-TM were tested using a Brookfield viscometer to determine the evolution of viscosity with time. The viscosity results are included as Table A2-1 in Appendix 2. The results indicate that the viscosity should remain less than about 5 cP for most of the gel time and then increase rapidly once gelation starts. A representative plot is shown in Figure 6-10. This figure shows three samples of 15 percent Ludox-HS with different gel times. The sample with a pH of 7 has a gel time of about 10 days. The viscosity stays below a value of 5 cP for 5 days and then increases rapidly until a gel is formed at about 10 days. The sample with a pH of 7.5 has a gel time of about 26 days. The viscosity increases to a value of about 60 after 21 days and continues to increase until the sample gels at about 26 days. The sample with the pH of 7.8 has a gel time of about 105 days. At 79 days, the viscosity was at a value of 5.5 cP. Over the next 16 days the viscosity increased to 435 cP and a firm gel was formed by 105 days.

Based on these results, it appears that the colloidal silica solution maintains a fairly low viscosity until just prior to gelling. At shorter gel times, the transition through the gel states shown in Table 6-3 is more rapid than with longer gel times. At longer gel times, the viscosity stays fairly low for a large portion of the gel time, but it also takes longer for a firm gel to form once gelation has started.

6.5 Results of Strength Testing of Stabilized Sands

6.5.1 Summary

The primary goal of testing stabilized sands was to determine if colloidal silica grout could successfully stabilize loose sands to prevent excessive deformation during cyclic loading. A second goal was to determine the minimum concentration of colloidal silica that could be used to provide adequate strength to stabilize the soil. The smaller the concentration required, the less expensive the technology will be. Different grades of colloidal silica were used in various concentrations to determine the minimum concentration necessary to adequately stabilize the soil.

Loose sands were stabilized with different percentages of colloidal silica and subjected to both static and cyclic loading. In general, samples stabilized with higher concentrations of colloidal silica had higher static and cyclic strengths and experienced less strain during cyclic loading. Sands stabilized with lower concentrations tolerated cyclic loading well, but experienced slightly more strain. All of the stabilized sands remained intact during cyclic loading and were able to be tested statically after cyclic testing.

In addition, sands stabilized with colloidal silica grout behave more like dense sands that loose sands. The axial deformation for the untreated sand at a cyclic stress ratio of 0.27 is shown in Figure 6-11. As noted earlier, the cyclic stress ratio is defined as the ratio of the maximum cyclic shear stress to the initial effective confining pressure. The untreated sample experienced 1, 2, and 5 percent double amplitude (DA) strain in 11, 11, and 12 cycles, respectively and collapsed after 13 cycles. The axial deformation for sand at the same relative density and cyclic stress ratio, but treated with 10 percent Ludox-SM, is shown in Figure 6-12. The treated sample required 35, 159, and 276 cycles to reach 1, 2, and 5 percent DA strain, respectively. The sample never collapsed and had an undrained strength of 1.8 psi after 400 cycles of loading. For comparison, a magnitude 7.5 earthquake would be expected to generate 15 significant uniform stress cycles (Seed and Idriss 1982).

Cyclic triaxial tests were done on samples stabilized with Ludox-SM at concentrations of 10, 15, and 20 percent. When tested at a cyclic stress ratio of about 0.40, samples with the 15 and 20 percent of Ludox-SM showed very little deformation during 1000 cycles of loading, as shown in Figure 6-13. Samples stabilized with 10 percent Ludox-SM experienced up to five percent strain when loaded at the same cyclic stress ratio for 100 to 500 cycles of loading, but remained intact during and after loading. Therefore, a 10 percent concentration of Ludox-SM is expected to be able to adequately stabilize the soil. Some strain would likely be experienced during cyclic loading, but would probably be on the order of two to three percent and little permanent strain should result. Higher concentrations would limit the strain more, but are likely to be too expensive for this application.

Unconfined compression (UC) tests and unconsolidated undrained (UU) tests were done to determine baseline strengths for different concentrations of colloidal silica grout. UC and UU tests were also done on samples that had been subjected to cyclic loading to determine residual strengths. It was found that the degree of strain experienced during the cyclic testing affected the residual strength of the stabilized sands. Samples that experienced the most strain had the lowest residual strength.

The average UC baseline strength ranged from 6.6 psi at a concentration of 5 percent Ludox-SM to 32.4 psi at a concentration of 20 percent Ludox-SM, as shown in Figure 6-14. After cyclic loading, the strength varied according to the strain experienced during cyclic loading. The strength of samples as a function of the strain achieved during cyclic loading is shown in Figure 6-15. Samples that experienced less than about two percent strain had very little strength degradation. Samples that experienced more than two percent strain had residual strengths that were between half and two-thirds of the baseline strength. In general, samples with high strains experienced the largest strength degradation.

The UU tests were done on samples grouted with 10 percent Ludox-SM. Baseline undrained strengths averaged 7.4 psi. After cyclic loading, the strength varied according to the strain experienced during cyclic loading. Samples that experienced less than about two percent strain had no strength degradation. Samples that experienced more than two percent strain had residual strengths between one-third and three-quarters of the baseline strength. The undrained strength is shown as a function of strain achieved during cyclic loading in Figure 6-16.

6.5.2 Cyclic Triaxial Test Results

The results from the initial cyclic testing program were very erratic. As discussed in Section 6.4.1, it was thought that there could be three reasons for the erratic results: 1) curing times were not long enough, 2) channeling occurred in the samples during permeation grouting, resulting in inadequate grouting, or 3) the back pressure saturation procedure damaged or destroyed the colloidal silica bonds. Since the results were erratic, they will not be reported here. Instead, the results of the modified cyclic testing program will be presented and discussed. A list of the samples tested, including sample number, CSR at testing, number of cycles during testing, and the number of cycles to one, two, and five percent double amplitude axial strain is presented in Table A3-2 of Appendix 3.

A series of cyclic triaxial tests were done on untreated sand to develop a baseline cyclic resistance curve for comparison with the treated samples. Four samples were tested at cyclic stress ratios between 0.19 and 0.27. As discussed in the summary, the sample tested at a cyclic stress ratio of 0.27 withstood a total of 13 cycles before it collapsed. It experienced one, two, and five percent DA strain in 11, 11, and 12 cycles, respectively. The sample tested at a cyclic stress ratio of 0.19 withstood 31 cycles before collapsing. It experienced one, two, and five percent DA strain in 28, 28, and 29 cycles, respectively. The results for the other two points are shown in Table 2 of Appendix 3. The cyclic resistance curve is shown in Figure 6-1.

Thirty-four treated samples were tested cyclically during the modified testing program. Fifteen samples with gel times of 4 hours were made by pluviating dry sand into molds containing grout. Six each were made at concentrations of 20 and 10 percent Ludox-SM. Three were made at a concentration of 15 percent Ludox-SM.

Of the six samples treated with 20 percent Ludox-SM, three were back pressure saturated before cyclic loading and three were tested without back pressure saturation. The samples that were not back pressure saturated were loaded for 1000 cycles each at cyclic stress ratios of 0.44. They experienced between 0.19 and 0.28 percent strain after 1000 cycles. The samples that were back pressure saturated were tested for 100 to 600 cycles at CSR's of 0.44. These samples experienced from 0.26 to 0.50 percent strain in fewer cycles than the samples that were not back pressure saturated, but still performed well.

Based on these results, it is difficult to conclude with certainty that the back pressure saturation negatively affected the cyclic strength of the samples. However, the fact that the samples that were back pressure saturated experienced slightly more strain in fewer cycles makes it difficult to conclude that the back pressure saturation was not affecting the strength either. Therefore, no additional back pressure saturation was done during the modified testing program.

The three samples treated with 15% Ludox SM were tested at cyclic stress ratios between 0.41 and 0.43 for 1000 cycles. The samples experienced 0.33, 0.39 and 2.9 percent strain. It is not known why one sample accumulated so much more strain that the other two. However, even 2.9 percent strain would be acceptable, particularly if it were transient strain that occurred only during the earthquake loading.

The six samples treated with 10 percent Ludox-SM were tested at cyclic stress ratios between 0.23 and 0.40 for up to 1200 cycles, as shown in Table 2 of Appendix 3. Of these samples, all reached one percent double amplitude strain, but the number of cycles required to reach that level varied widely. Sample SM10-10B reached one percent DA strain in just three cycles at a cyclic stress ratio of 0.40. Sample SM10-10D required 101 cycles at a cyclic stress ratio of 0.25 to reach 1 percent DA strain. Sample SM10-11D ran for 1000 cycles at a cyclic stress ratio of 0.27 without reaching 1 percent DA strain, but reached it in just 4 cycles when the cyclic stress ratio was increased to 0.40. The results for two percent DA strain were similar. While all six samples reached two percent DA strain, it took Sample SM10-10B just 10 cycles to reach it at a cyclic stress ratio of 0.40, but Sample SM10-11F required 159 cycles at a CSR of 0.27 to reach it. Only two of the samples reached five percent double amplitude strain. Samples SM10-10C and SM10-11F reached five percent DA strain in 261 cycles and 276 cycles, respectively at cyclic stress ratios of 0.23 and 0.27, respectively.

6.5.2.1 Results for Samples Made by Permeation Grouting

Samples SM10-13A and SM10-13B were made by moist tamping followed by permeation grouting with 10 percent Ludox-SM. These samples were tested at cyclic stress ratios of 0.30 and 0.37 for 1000 and 400 cycles, respectively. Sample SM10-13A reached one percent DA strain in 992 cycles and never achieved two or five percent DA strain. Sample SM10-13B strained less than one-half percent in 400 cycles at a cyclic stress ratio of 0.37.

6.5.2.2 Effect of Curing Time on Cyclic Resistance

To investigate the effect of curing period on cyclic resistance, twelve samples with gel times of about 1 day were made with 10 percent Ludox-SM. Three samples each were cured for periods of 11, 21, 32, and 56 days. The samples were then tested cyclically. Figure 6-17 is a plot of strain achieved during cyclic testing versus the cyclic stress ratio. Samples of the same age are plotted in the same symbol. In general, as the curing time increased, the level of strain reached during cyclic testing decreased. Therefore, it is likely that the cyclic resistance will continue to improve with time after treatment. The cyclic testing results are tabulated in Table A3-2 of Appendix 3 and explained in detail below.

Samples SM10-15A and SM10-15B were tested at 11 days at cyclic stress ratios of 0.29 and 0.25 for 300 and 400 cycles, respectively. Sample SM10-15A reached one percent DA strain in one cycle but required 220 cycles to reach two percent DA strain and never reached five percent DA strain. Sample SM10-15B reached one percent DA strain in 2 cycles, but never reached two or five percent DA strain. Samples SM10-16A, SM10-16B, and SM10-16C were tested after 21 days of curing at cyclic stress ratios of 0.30, 0.35, and 0.39, respectively for 200, 300, and 200 cycles, respectively. All three samples reached one percent DA strain in the first cycle. Sample SM10-16A required 24 cycles to reach two percent DA strain and never reached five percent DA strain. Sample SM10-16B reached two percent DA strain in 3 cycles but did not reach five percent DA strain. Sample SM10-16C required only 2 cycles to reach two percent DA strain, but did not reach five percent DA strain for 106 cycles.

Samples SM10-17A, SM10-17B, and SM10-17C were tested after 32 days of curing. They were tested at cyclic stress ratios of 0.41, 0.37, and 0.30, respectively for 100 cycles each. Sample SM10-17A reached one and two percent DA strain in one and two cycles, respectively, but did not reach five percent DA strain in 100 cycles. Sample SM10-17B reached one and two percent DA strain in one and three cycles, respectively, but did not reach five percent DA strain in 100 cycles. Sample SM10-17C did not reach one, two, or five percent DA strain in 100 cycles.

Samples SM10-18A, SM10-18B, and SM10-18C were tested after 56 days of curing. They were tested at cyclic stress ratios of 0.32, 0.41, and 0.37, respectively for 100 cycles each. Sample SM10-18A reached one DA strain in three cycles, respectively, but did not reach two or five percent DA strain in 100 cycles. Sample SM10-18B reached one and two percent DA strain in one and two cycles, respectively, but did not reach five percent DA strain in 100 cycles. Sample SM10-18C reached one percent DA strain in 3 cycles but did not reach two or five percent DA strain in 100 cycles.

6.5.2.3 Effect of Different Grades of Colloidal Silica on Cyclic Resistance

To investigate the ability of different types of colloidal silica to successfully treat sand, three samples with Ludox-HS and two samples were made with Ludox-TM at concentrations of 20 percent with a gel time of about 4 hours. The results were compared with the results from the samples stabilized with 20 percent Ludox-SM. These grades have different particle sizes and therefore require different minimum concentrations to form firm resonating gels. Ludox-SM requires the smallest concentration of silica by weight to form a firm gel and Ludox-TM requires the highest concentration. It was expected that when the same percentage of silica was used, samples treated with SM would have the highest resistance to cyclic loading and samples treated with TM would have the lowest resistance.

The Ludox-HS samples were cured for about two weeks while the Ludox-TM samples were cured for a period of one week before cyclic testing. As noted previously, the samples treated with 20 percent Ludox-SM experienced less than ½ percent strain after 1000 cycles a cyclic stress ratios of 0.44. The Ludox-HS samples were tested for 1000 cycles each at cyclic stress ratios between 0.41 and 0.43 and experienced from 0.32 to 1.24 percent DA strain. The Ludox-TM samples were tested for up to 200 cycles at a cyclic stress ratio of 0.41. Sample TM10-7A experienced one, two, and five percent DA strain in 2, 8, and 52 cycles, respectively. Sample TM20-7B experienced one percent DA strain in 102 cycles and did not achieve two or five percent DA strain in 200 cycles. As expected, the samples treated with Ludox-SM experienced less strain than those treated with Ludox-HS and Ludox-TM.

6.5.3 Unconfined Compression Test Results

Unconfined compression tests were done on samples grouted with 5, 10, 15, and 20 percent Ludox-SM. The results of the tests are plotted in Figure 6-17 as a function of increasing silica content. Three samples each were tested at concentrations of 5, 10, and 15 percent Ludox-SM. The average strengths of the 3 samples at 5, 10, and 15 percent were 6.5, 12.9, and 16.0 psi, respectively. Unconfined compression tests were also run on 6 samples grouted with a concentration of 20 percent Ludox-SM. These samples were subjected to cyclic loading prior to the unconfined compression tests. These samples experienced less than ½ percent strain in 1000 cycles of cyclic loading. The average unconfined compressive strength of these samples was 32.2 psi.

Persoff et al. (1999) report that the unconfined compressive strength of Monterey sands grouted with colloidal silica increases linearly with increasing percentage of colloidal silica. They found that sands stabilized with 10 and 20 percent of Ludox-SM had unconfined compressive strengths of 23 and 46 psi, respectively. The results reported here are in general agreement with Persoff et al. (1999), although the magnitude of the unconfined compressive strength of these samples is about half that reported by Persoff et al. (1999). However, this sand was at a relative density of 22 percent. The relative density of the samples tested by Persoff et al. (1999) was not reported, but if the samples were denser than the samples tested for this study, it could explain some of the difference in magnitude of unconfined compressive strength.

Unconfined compression tests were also done on a series of samples stabilized with 10 percent Ludox-SM and subjected to cyclic loading. Figure 6-18 is a plot of unconfined compressive strength as a function of the strain experienced during cyclic loading. The general trend of this plot is that the strength decreases as the strain during cyclic loading increases. For samples that showed less than about two percent strain, the residual strength is almost as high as the baseline strength. In one case, the UC strength of a sample that experienced about one percent strain during cyclic testing was higher than the strengths of the samples tested for baseline strengths. This sample probably started out stronger than the samples tested for baseline strength; however, it probably did not lose much strength during the cyclic testing. As the strain experienced during cyclic loading increased above two percent, the residual strength decreased to about half to two-thirds of the baseline value. This suggests that the colloidal silica bonds are damaged or destroyed by straining during cyclic loading, causing the sample to weaken.

6.5.4 Unconsolidated Undrained Test Results

UU tests were done on a total of 11 samples grouted with 10 percent Ludox-SM. Three baseline strength tests were performed at confining pressure between 50 and 200 kPa. The undrained strengths ranged from 6.7 to 8.0 psi, with an average strength of 7.4 psi. UU tests were also done on eight samples that were subjected to cyclic loading first. The tests were done at confining pressures between 50 and 200 kPa. The results of these tests are shown in Figure 6-19 as a function of the strain experienced during cyclic loading.

The undrained strength after cyclic loading varied depending on the degree of strain experienced during cyclic loading. Samples that experienced less than about two percent strain had little strength degradation. Two samples with less than one percent strain had higher strengths after cyclic testing than the baseline samples had without cyclic testing. Samples S10-15B and S10-17C had less than one percent strain after 400 cycles at a CSR of 0.25 and 100 cycles at a CSR of 0.30, respectively. It is likely that these samples were stronger than the baseline samples to begin with; however, they probably experienced little or no strength degradation during cyclic loading.

Samples that experienced more than two percent strain had residual strengths of about one-third to three-quarters of the baseline strength.

6.6 Conclusion

Based on the results of the testing program, colloidal silica remains an excellent candidate for passive site remediation. The viscosity is very low for most of the induction period. Very long gel times are possible. Sands stabilized with 10 percent Ludox-SM experienced tolerable strains during cyclic loading. Even when strains of up to 5 percent were experienced, stabilized sand samples retained from half to two-thirds of their baseline strengths. Additional testing should be done to determine if smaller concentrations of Ludox-SM, i.e. 7.5 or 5 percent would provide adequate stabilization of loose sands. If smaller concentrations could be used, the material cost would be significantly less.

One issue that should be considered is the minimum curing time that will be required for sands stabilized with colloidal silica to reach adequate strength. At curing times of 10 times the gel time, all of the samples tested cyclically experienced acceptable levels of strain. Additional testing should be done to determine the minimum curing time necessary for stabilized sands to achieve adequate strength to withstand the expected loading conditions.

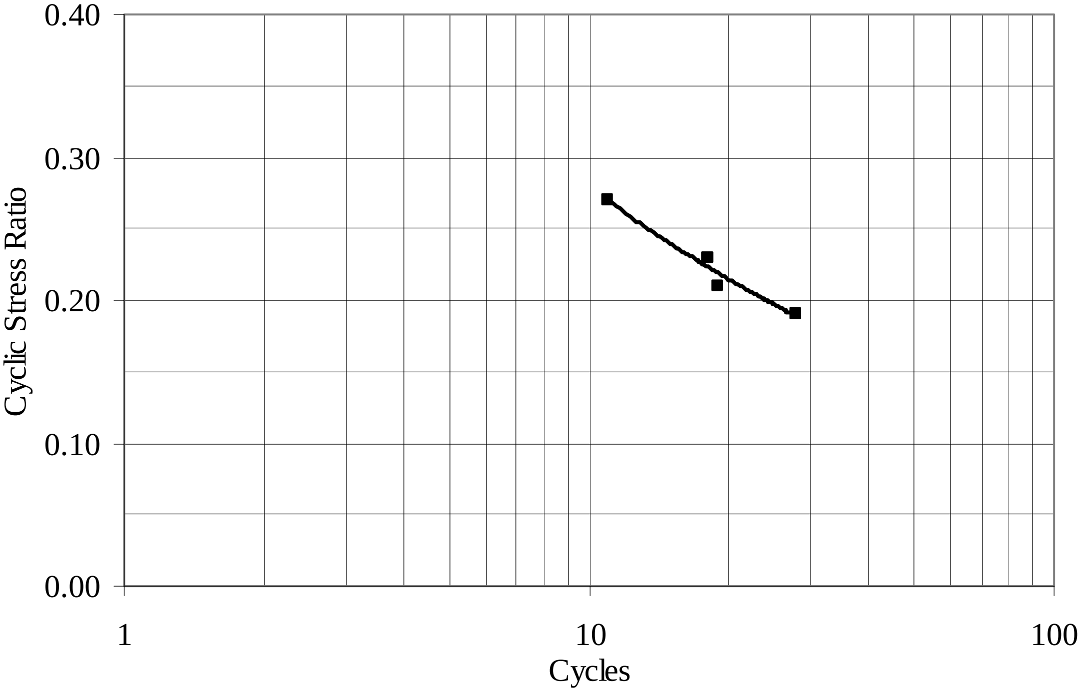


Figure 6-1 Cyclic resistance curve for untreated Monterey sand, Dr=22%
Cycles to reach 1% DA strain

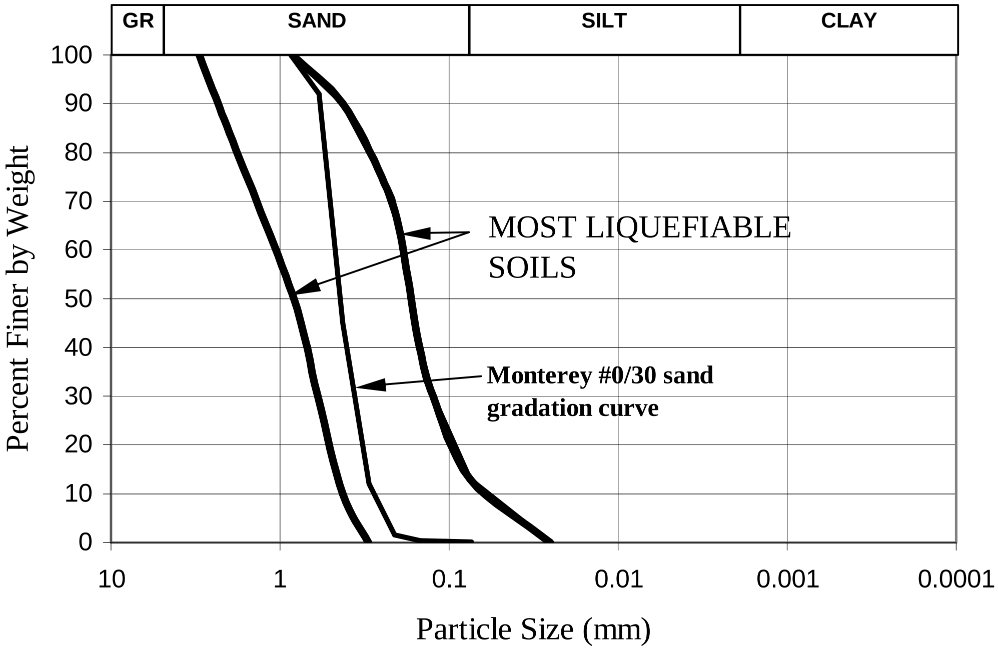


Figure 6-2 Grain size curve for Monterey #0/30 sand

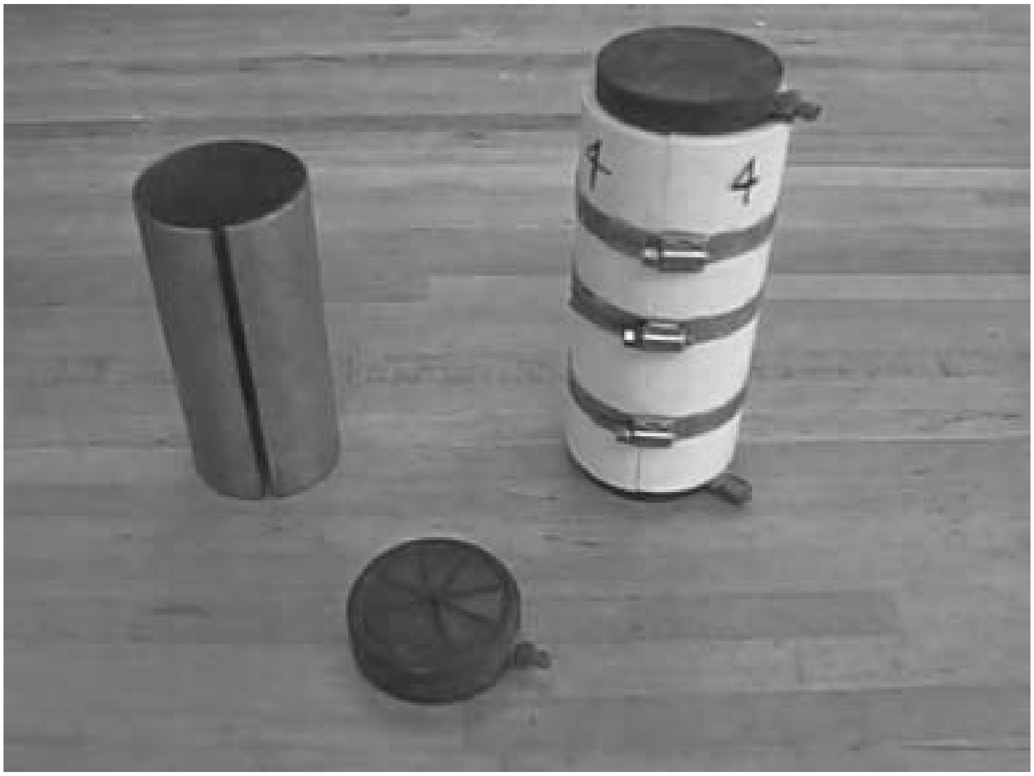


Figure 6-3 From left to right, stainless steel mold, platen, and PVC mold for forming stabilized sand samples

Figure 6-4 Triaxial testing system

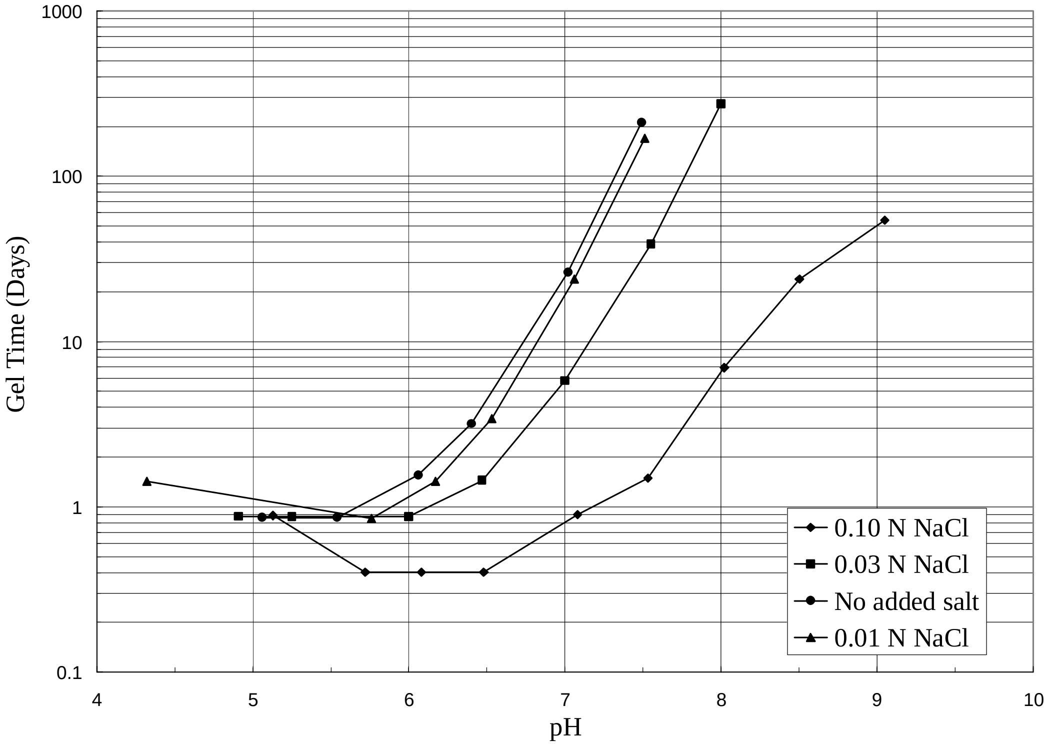


Figure 6-5 Ludox-SM 10% concentration gel time curves

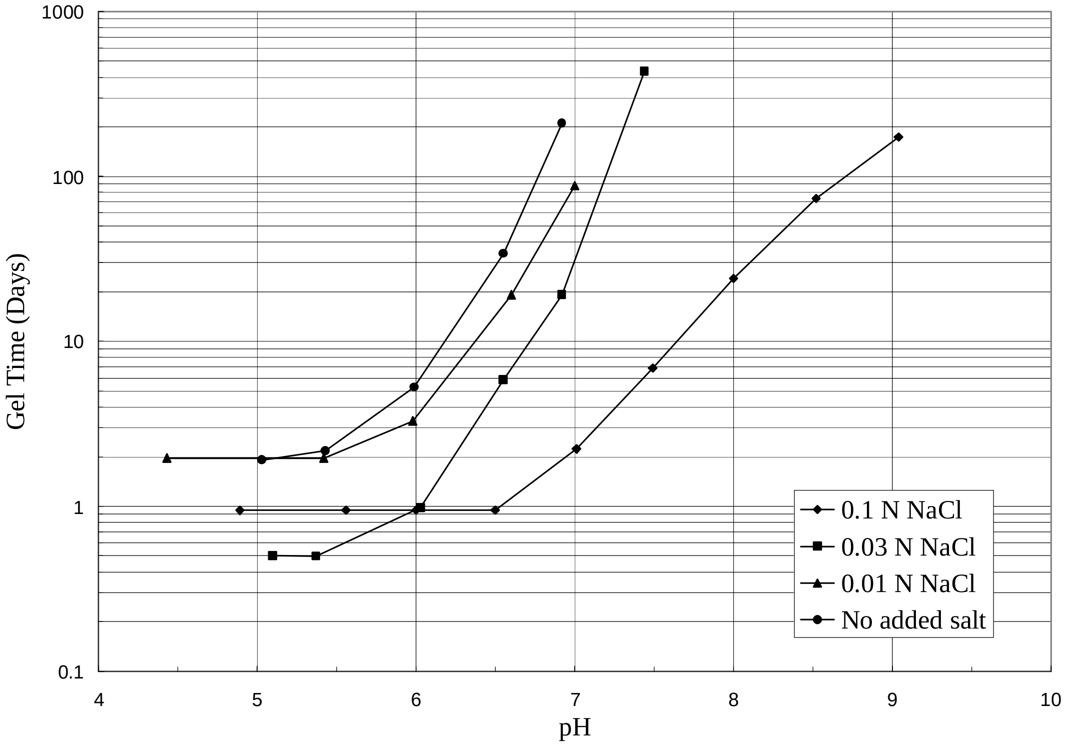


Figure 6-6 Ludox-SM 7.5% concentration gel time curves

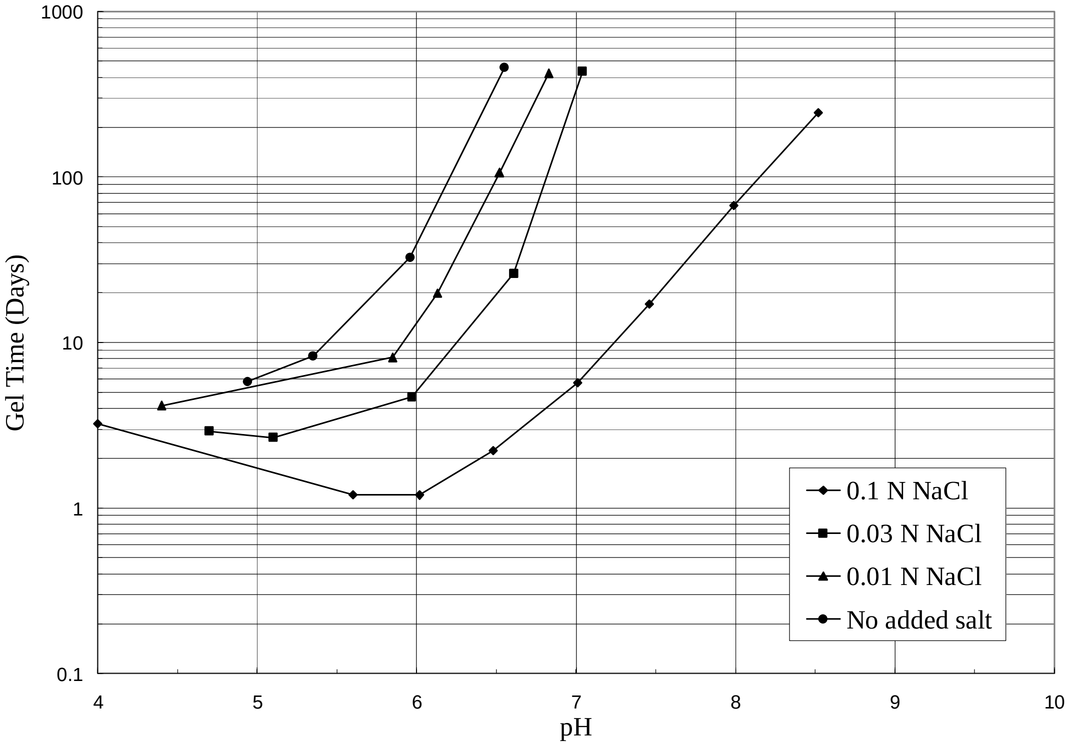


Figure 6-7 Ludox-SM 5% concentration gel time curves

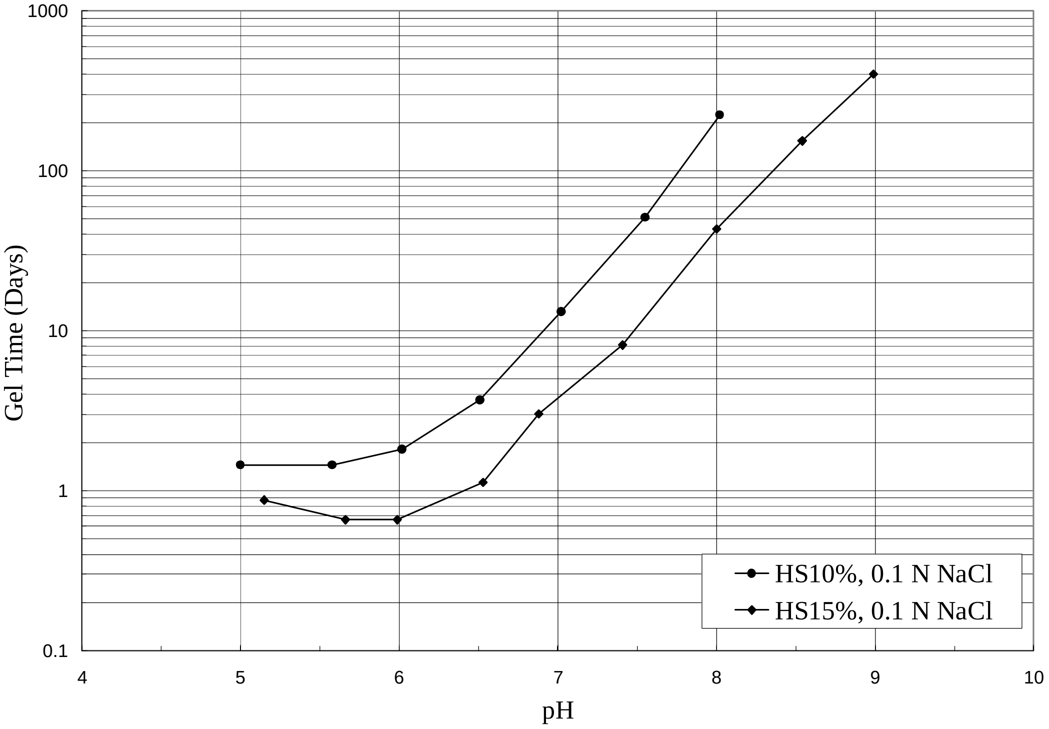


Figure 6-8 Ludox-HS concentration gel time curves

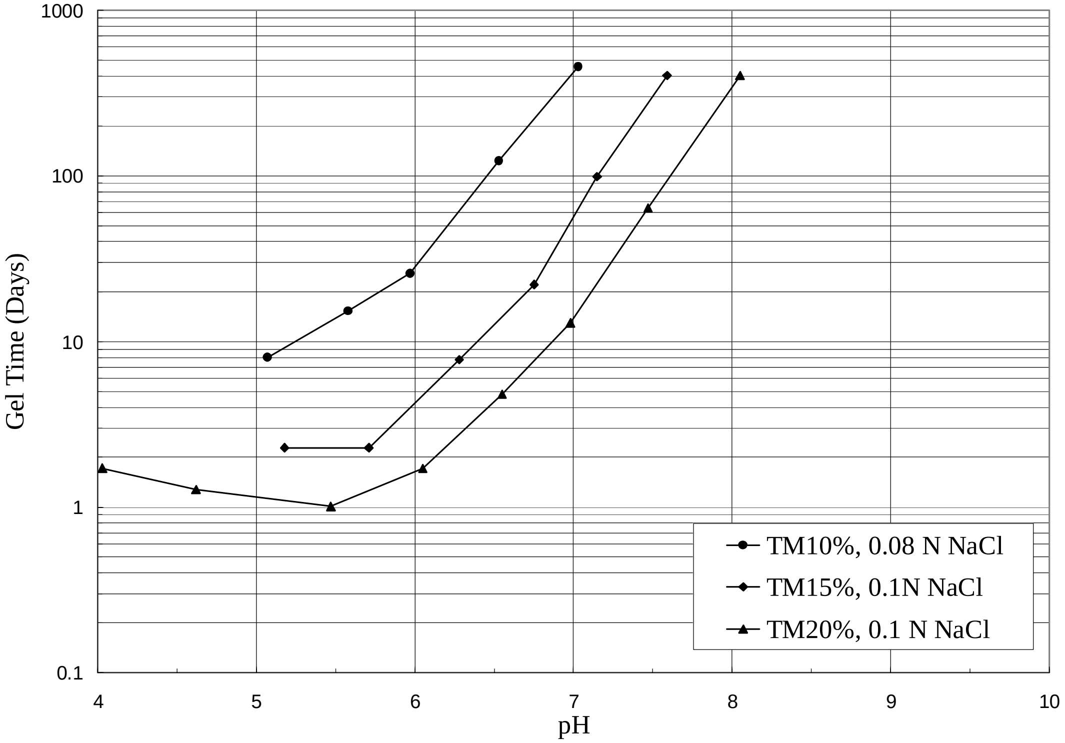


Figure 6-9 Ludox-TM concentration gel time curves

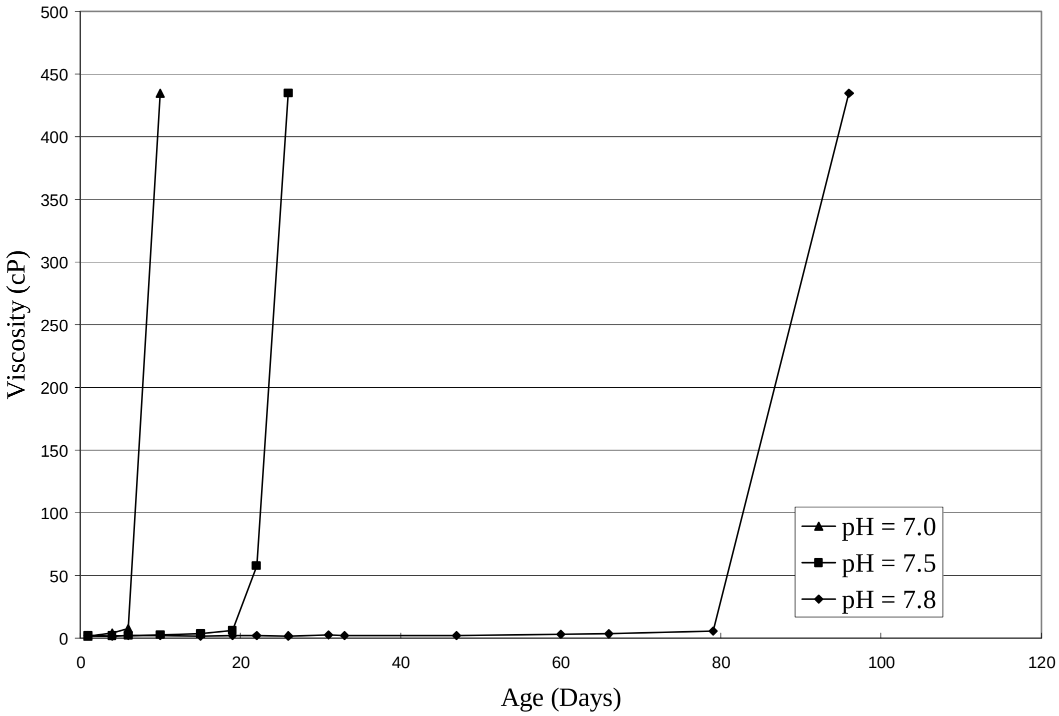
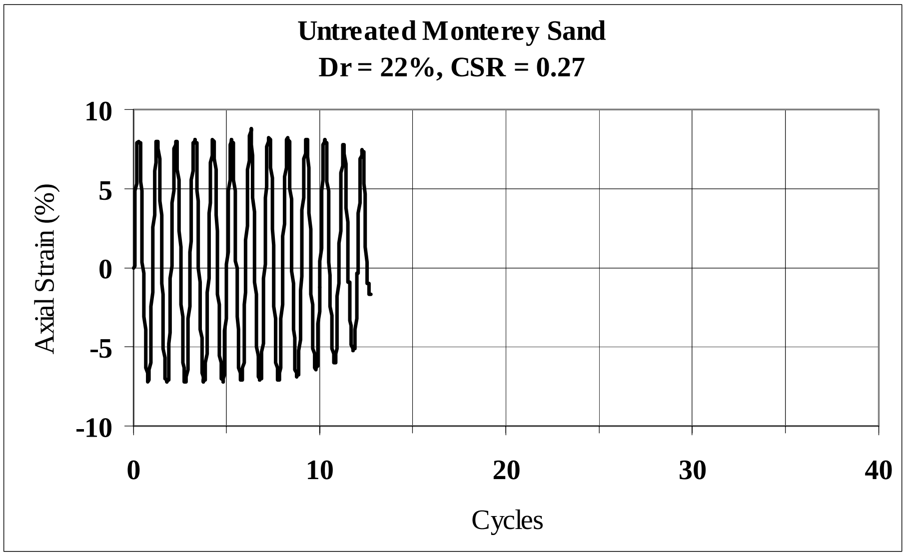


Figure 6-10 Evolution of viscosity
15% Ludox-HS



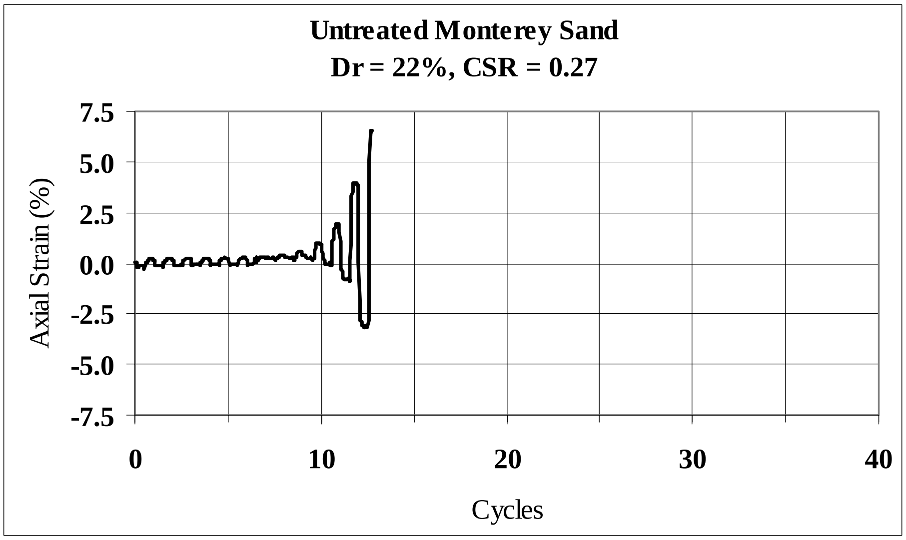


Figure 6-11 Cyclic stress-strain behavior of untreated Monterey sand
Dr=22%, CSR=0.27

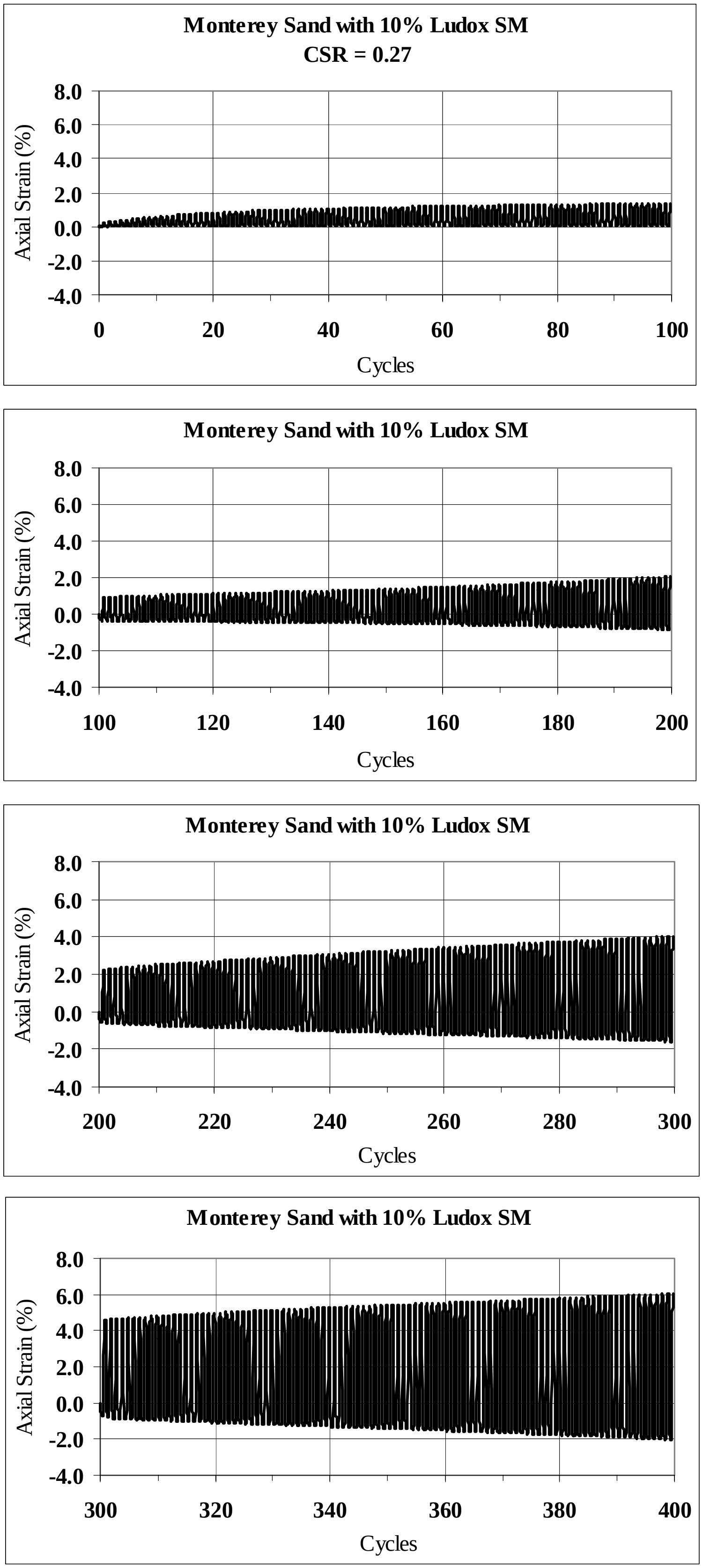


Figure 6-12 Cyclic stress-strain behavior of Monterey sand treated with 10% Ludox-SM, Dr=22%, CSR=0.27

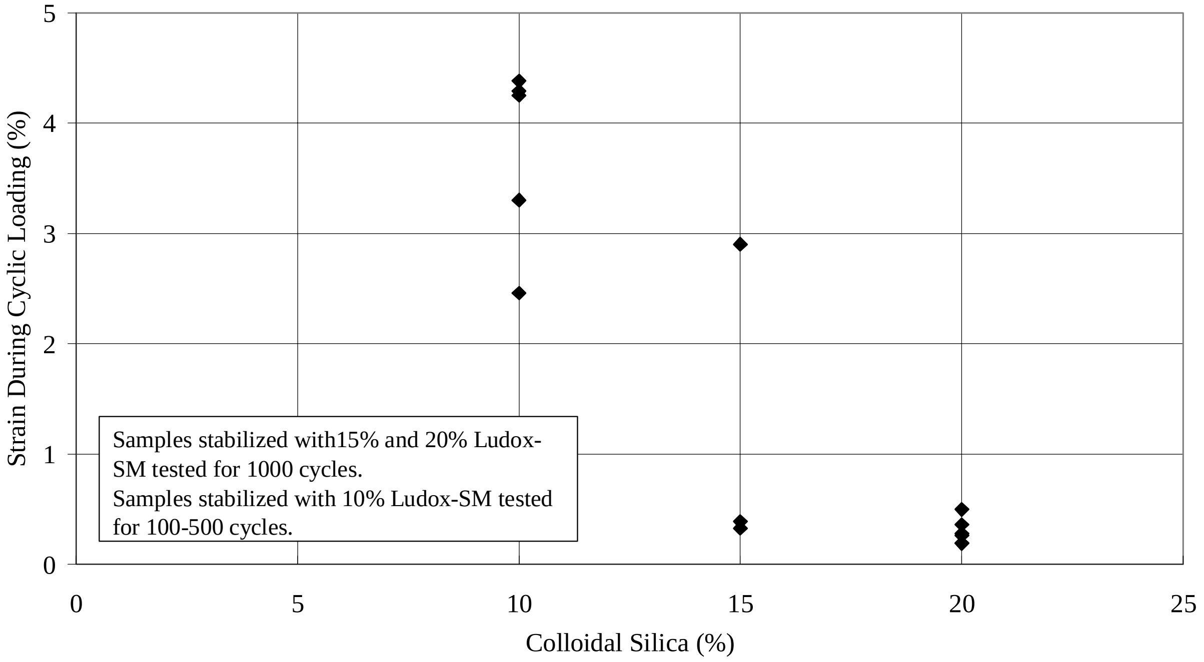


Figure 6-13 Percent Ludox-SM versus strain during cyclic loading at CSR = 0.40

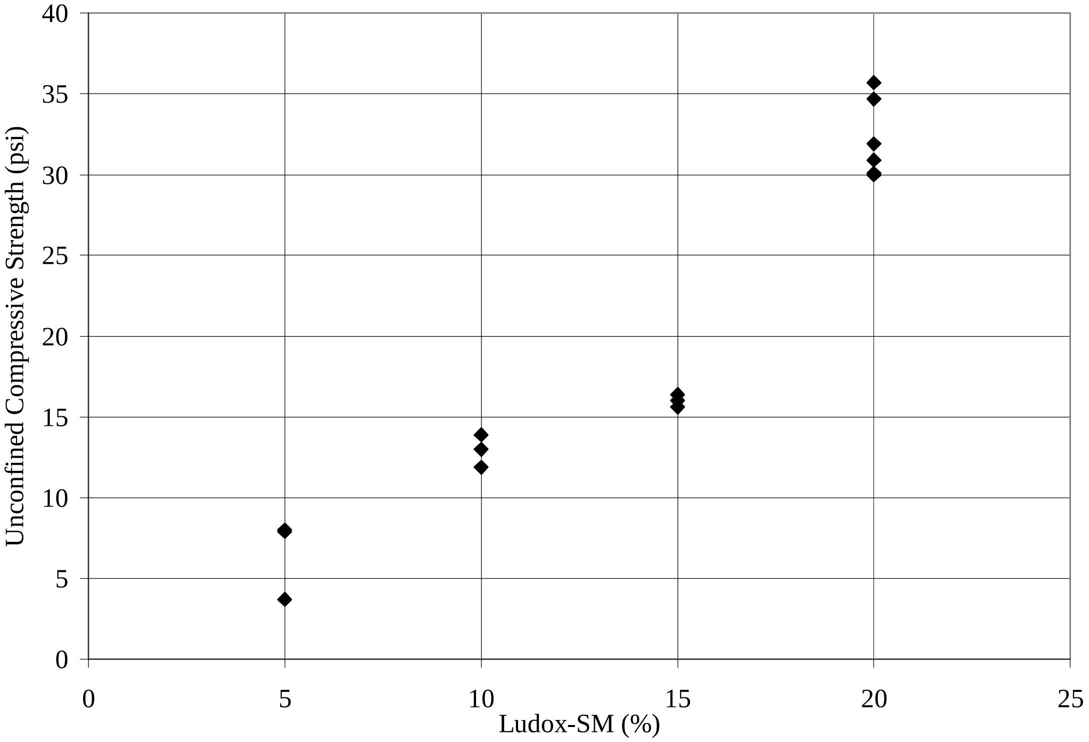


Figure 6-14 Unconfined compressive strength of stabilized sands

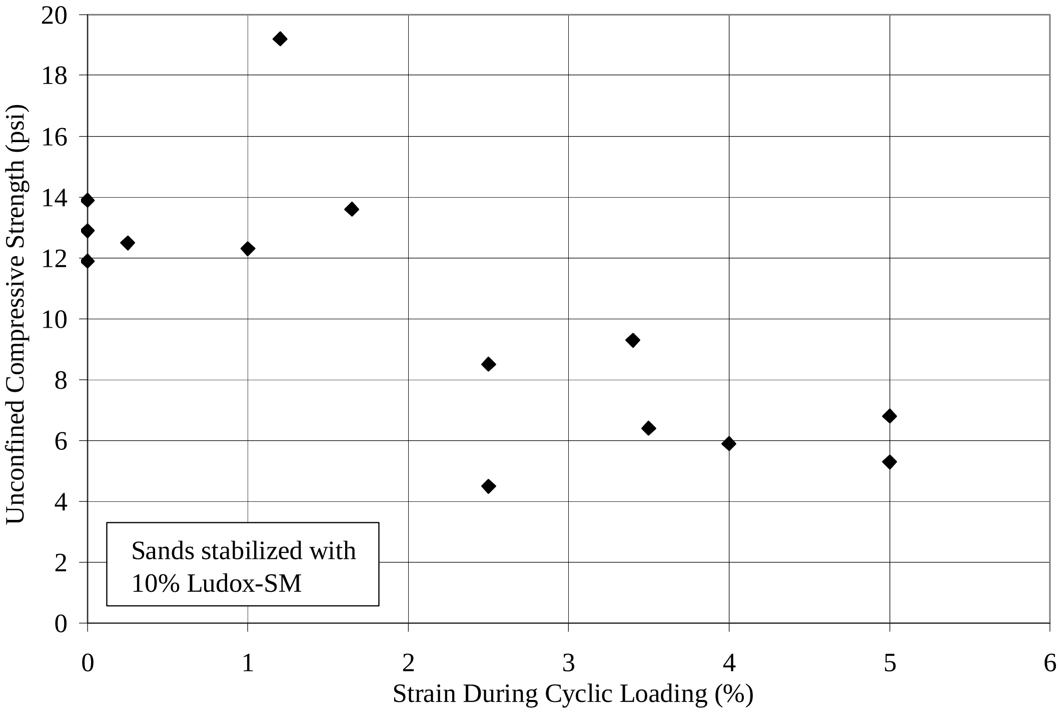


Figure 6-15 Unconfined compressive strength of stabilized sands after cyclic loading

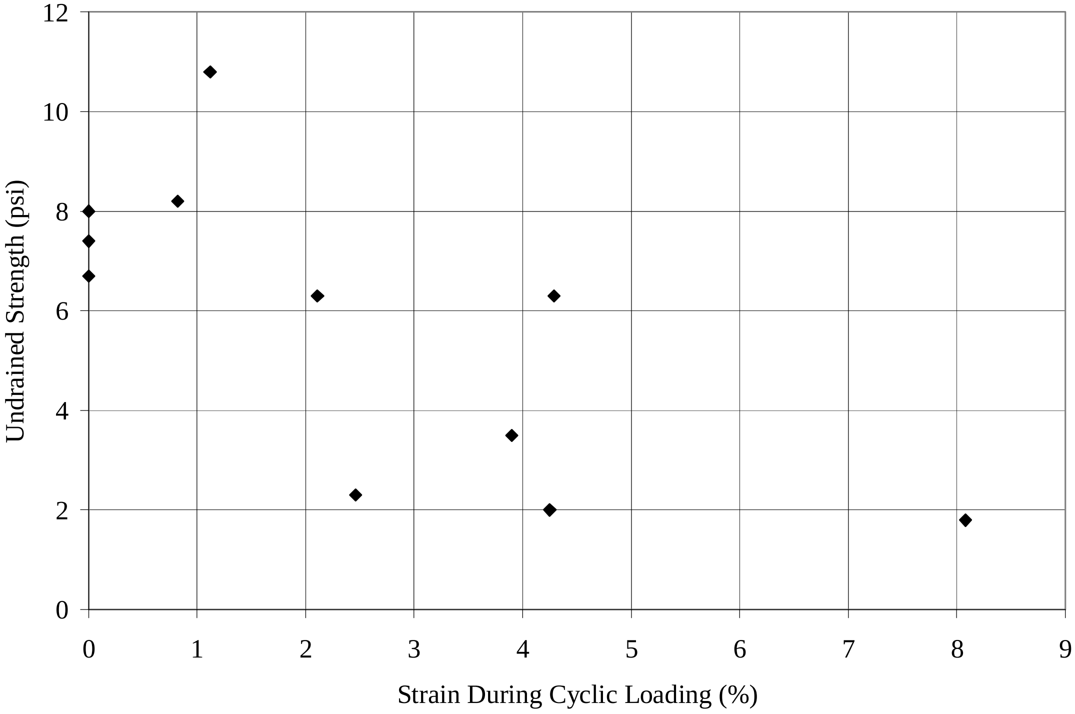


Figure 6-16 Undrained strength versus strain during cyclic loading

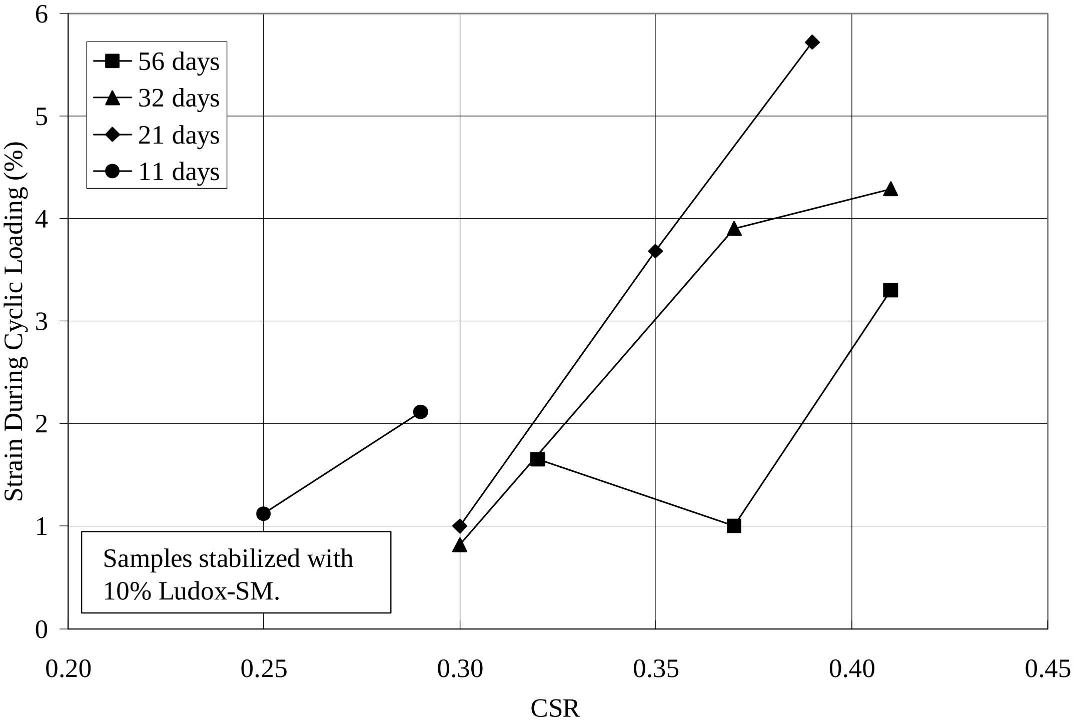


Figure 6-17 Strain during cyclic loading for samples of different ages