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THE IMPORTANCE OF CHEMICAL GROUTING MATERIALS FOR OPTIMUM
MECHANICAL PERFORMANCE WITH DIFFERENT SOIL CONDITIONS

by

YUSUF ALPER CINAR

A THESIS

Presented to the Graduate Faculty of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

in

GEOLOGICAL ENGINEERING

2018

Approved by

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ABSTRACT

Grouting is a frequently used technique for controlling the water inflow and reinforcement of soil and rock. Even though cement-based grouting materials have been well characterized, ongoing improvements of chemical grouting materials create a need to better understand the characteristics of these materials in order to increase the efficiency of grouting applications. The purpose of this study is to characterize three common chemical grouting materials by exploring their mechanical performance under varying initial soil conditions. Performance decision criteria consist of the Unconfined Compressive Strength (UCS) and slake durability test results, observation of penetration ability, and comparison of the findings. The three chemicals used were acrylate, colloidal silica, and polyurethane. Test specimens were prepared with two different sand gradations and two different initial moisture contents, which were compacted to the same constant density. Cylindrical test specimens were injected using a constant and predetermined injection pressure. Injected specimens were moist-, air- and wet-cured for 28 days. Thereafter, the specimens were tested and the stress-strain relationships were developed. Slake durability tests were conducted to characterize the durability of chemically grouted sands subjected to wetting-drying cycles. The results of this study showed that initial grain size and fine content of the soil influenced the resultant strength for acrylate and colloidal silica grouting materials. On the other hand, initial moisture content of soil was solely effective on UCS of acrylate grouted sand. This study found that the effect of wetting-drying cycles on durability was minimum for the polyurethane grouted sands. It may be concluded that use of polyurethane in medium sands and use of acrylate in fine sands can be more effective than the use of acrylate, and colloidal silica for medium sands and the use of polyurethane, and colloidal silica for fine sands.

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1. INTRODUCTION

1.1. CHEMICAL GROUTING

Cement-based material is the most common and the oldest material used in many grouting applications. The particle size of Portland cement allows it to penetrate into soils that are coarse sands and gravels. However, Portland cement has some deficiencies regarding groutability. The sophisticated versions use ultrafine and microfine cements, which can compensate the difficulty of penetrating into soils that are finer than coarse sand. Although low toxicity, low cost, and good penetration ability makes cement-based materials preferable, chemical grouting materials are used instead when the performance of the cement-based materials is not adequate.

Chemical grouting materials were developed in the early 1950s and are specialized with a high penetration ability compared to the cementitious grouting materials. While many of them are in use, some types have been withdrawn from the market due to performance and toxicity issues. Chemical grouts can be differentiated with their chemical content, strength, viscosity, durability, gel time, and toxicity. Chemical grouts may be separated into the groups silicates, urethanes, acrylates, lignins and resins (American Society of Civil Engineers and United States Army Corps of Engineers, 1997). Even though new combinations and advancements continue to broaden the material range, the five types mentioned above can be used for a general overview.

An early form of silicates were the sodium silicates. Nowadays, a revised form of silicates generally named as colloidal silica are used, which refers to a stable dispersion of silica particles (Iller, 1979). While the size of the silica particles can be as small as 2 nm, it is possible to come across silica particles with particle sizes up to 100 nm (Persoff et al., 1999). In terms of fracture behavior, colloidal silica-based grouts show a ductile behavior

and become stiffer after about two days of setting time. Hardened colloidal silica act as an elastic-plastic material. Therefore, the failing risk caused by the blasting vibration in tunnel construction is eliminated (Butrón et al., 2009). On the other hand, use of silica with mechanical excavation also has some advantages. A recent study shows that use of sodium silicate instead of polyurethanes to stop a flowing granular material during a TBM excavation was successful due to the controllable gelling time of sodium silicate (Harkins and Parmantier, 2012).

Urethanes are another chemical grouting material used in many fields. The material has excellent water stopping ability, but it may not be used for soils finer than medium sand (Robinson et al., 2012). Although polyurethanes are expansive materials as much as colloidal silica, they may be considered as economical solutions because of their foaming ability of up to 20 times its initial volume. Injection of the polyurethane can be done by reshaping the rock with high grouting pressures or by not reshaping the rock and letting the grout penetrate into cracks and voids of the rock (Sharmin and Zafar, 2012). The moisture condition of the grouted media has an effect on the density of the foam, which is important for stopping water flow and developing mechanical properties of the surrounding rock of an underground structure. The volume increase of this material may cause new openings or cracks in the rock. Therefore, expansive behavior of the grout must be well characterized when designing the grouting program. However, deficiency of test procedures for determining the expansion-pressure-temperature relations of polyurethane put it into the background while specifying the grout material for grouting applications (Vipulanandan et al., 2012).

The use of many of the chemical grouts were discontinued because of the environmental limitations. One of them was acrylamide, which is considered highly toxic. Acrylamide could be used only between 1953 and 1978 in the United States. Thus, acrylates were introduced as a less toxic form of acrylamides (American Society of Civil Engineers and United States. Army. Corps of Engineers, 1997). Acrylates are mostly preferred for

tunneling applications because of their ability to penetrate into soils with low permeability, as low as 10^{-4} cm/s (0.2834 ft/d), and because of their infiltration-reducing ability (Ozgurel and Vipulanandan, 2005). Even though the strength of acrylates is slightly lower than the acrylamide and the difficulty of adjusting the controlling time as opposed to acrylamides, acrylates become a preferable alternative. Later on, the usage of acrylamides was allowed by the EPA on condition of ensuring that the required protection for the workers was used. Both acrylate and acrylamide are currently in use for grouting applications. The third member of this family is acrylic that is a different form falling between acrylamide and acrylate. Acrylics include less acrylamides and can be used where the EPA limitations do not allow the use of acrylamides.

Resins include epoxy grouts and are sometimes used with urethanes which are slightly different from epoxies. Even though the polymerization of both epoxy and urethanes are similar, resultant properties differentiate them depending on the purpose of grouting application. While the higher early strength and fast curing characteristics of epoxy make it a good candidate for structural repair, better penetration ability, adjustable set time, and more flexible characteristic of urethane is considered more applicable for water-proofing grouting applications. Epoxies are mostly used for repairing the concrete because of their corrosion protection and water stopping abilities (Issa and Debs, 2007). In recent years, cement-based grouts were modified with various chemicals other than common supplementary materials or admixtures. A recent study shows that the use of epoxy as an additive in cement-based grout design develops the rheological properties through increasing the setting time, increasing the resistance to acid erosion, and reducing the bleeding (Anagnostopoulos et al., 2016).

1.2. STATEMENT OF THE PROBLEM

Water inflow is a major problem that causes important stability issues in tunnels and other underground structure constructions. Grouting is a very common application to overcome this problem. When the conventional grouting materials are insufficient to perform as desired, chemical grouting becomes the most favorable option. However, there is not enough information because of the limited application of chemical grouting, which arises from the expensiveness of the materials (Faramarzi et al., 2016). In this regard, deciding the suitable chemical grouting material plays a crucial role. Considering the limited understanding of chemical grouting applications, deciding criteria is based on trying materials respectively starting with the cheapest one in many field applications. However, the efficiency of the grouting is controlled by several factors. Thus, knowing the effect of these factors helps to optimize the effectiveness of grouting.

Although the primary purpose of chemical grouting is stopping the water inflows by decreasing the hydraulic conductivity of soil or rock, increasing the strength is the secondary purpose of the application. If movement is expected around the grouted area, the strength-improving characteristics of the material is important. On the other hand, the water shut-off ends up with the increase in strength. Therefore, the strength-gaining and water-stopping properties of the chemical grouting should be considered as interrelated (Karol, 2003).

The effectiveness of grouts is observed as the improvements in mechanical properties of the grouted soil. Hence, researchers concentrate on investigating the mechanical behavior of grouted sands. The material properties of grout and sand and the bonding properties between the grout and sand particles adjust the mechanical behavior (Vipulanandan and Krizek, 1986). Penetrability, which is interrelated with grout and sand properties, is the other key factor that affects effectiveness. Viscosity of a chemical grout is a property that controls the penetration ability. Besides, the permeability of a soil is another property that is the indicator of ability of a fluid to flow through a particular porous medium. Hence,

the combination of the permeability and the viscosity affect on the penetrability. Grout properties are generally given by the manufacturers in detail. Usually these properties can be used in the deciding process. However, other factors must be considered for the success of the application. Some of these factors are grain size, density, effective grain size, grain distribution, and initial soil moisture conditions (Ata and Vipulanandan, 1999; Karol, 2003; Ozgurel and Vipulanandan, 2005). Although there are studies to investigate the effect of these conditions on the mechanical behavior of grouted sands, current studies are not sufficient to make a comparison between different types of chemical grouting materials in this context.

For the best representation of in situ soil conditions, triaxial compression tests may be a better choice to test the grouted soil specimens when conducting an experimental study. This is because the triaxial test allows us to simulate confining stresses, which always exist in deep underground conditions. On the other hand, for the studies that have no specific depth interval or are not devoted to investigating the strength of a specific area, a triaxial test would not be required. Therefore, a uniaxial compressive strength test is a very useful component to compare the mechanical behavior change of grouted soil specimens (Karol, 2003). Additionally, increasing compressive strength can be related with a decrease in permeability of grouted sand (Zebovitz et al., 1989). Hence, compressive strength tests become more practical than triaxial tests to evaluate the overall performance of grouting chemicals.

Many of the chemical grouting applications can be applied below the water table. In such conditions, soil might be saturated or partially saturated. Therefore, curing conditions might be humid or wet depending on where the grouting application takes place. While some studies take this into consideration, others only test the dry compressive strength, which may not be able to simulate the under-water curing conditions. Hence, unconfined compressive test results belonging to both humid and wet cured materials must be taken into consideration when exploring the mechanical behavior of chemically grouted soils.

Additionally, the permanence of the grouting materials can be determinant depending on the project needs. While sometimes grouting is a temporary solution, it may be considered as a permanent solution. A chemical grout might be required to be durable solely during the construction of an underground structure for seepage control or during the entire structure life of a derivation tunnel, which is typically about 50 years. In this case, freeze-thaw and wet-dry cycle tests become important tools to get an idea about the permanence of chemical grouting material. Therefore, determination of the mechanical behavior requires the consideration of durability, which can be defined as resistance to physical abrasion caused by wet-dry cycles or freeze-thaw cycles happening naturally in the soil or rock medium where the underground constructions take place (Anagnostopoulos, 2007; Xing et al., 2014). Considering the importance of this phenomenon, one study clearly shows that the slake durability test is a good method to investigate the effect of wet-dry cycle on durability (Anagnostopoulos, 2006). Thus, the slake durability index I_d can be used as an indicator of durability, which is an important part of overall mechanical performance.

From the literature review, it can be understood that the effect of some of the conditions stated above were investigated by different researchers for one particular material. However, considering the difficulty of determining chemical grouting material in field applications, more than one material should be compared under the same conditions.

1.3. OBJECTIVES OF STUDY

The objective of the research is to characterize the mechanical behavior of chemically grouted sand with different chemical grouting materials. The study was based on a comparison of the resultant strength and durability of grouted sand columns by using three common chemical grouting materials. The tasks include observing the effects of the following:

- 1- Changes in the mechanical properties with different soil grain sizes.
- 2- Effects of the curing conditions on the resulted strength.

3- Observation and implicitly testing the penetrability of grouting materials.

4- Comparison of the strength gain of grouted sand columns by three different chemical grouting materials.

5- Durability of grouted sand samples subjected to wet-dry cycles.

6- Based on the first five objective results, evaluation of the general mechanical behavior of common chemical grouting materials exposed to the same conditions.

Identification of the objectives stated above will help determine material type with respect to the soil conditions in the field.

2. METHODOLOGY

2.1. MATERIALS

2.1.1. Sand. Chemical grouting materials are highly capable compared with cement-based materials' low penetration performance. But even so, the minimum particle size of porous media is limited for applicable grouting. Therefore, the fine content of sand plays an important role to estimate penetration performance of grouting materials. Fine content of a soil is measured by the particle amount that passes through a #200 sieve. Soils can be considered as easily, moderately, and marginally groutable, which range as less than 12%, 12 to 20%, and 20-25%, respectively (Baker, 1982). The grain size distribution of this consideration is presented on Figure 2.1.

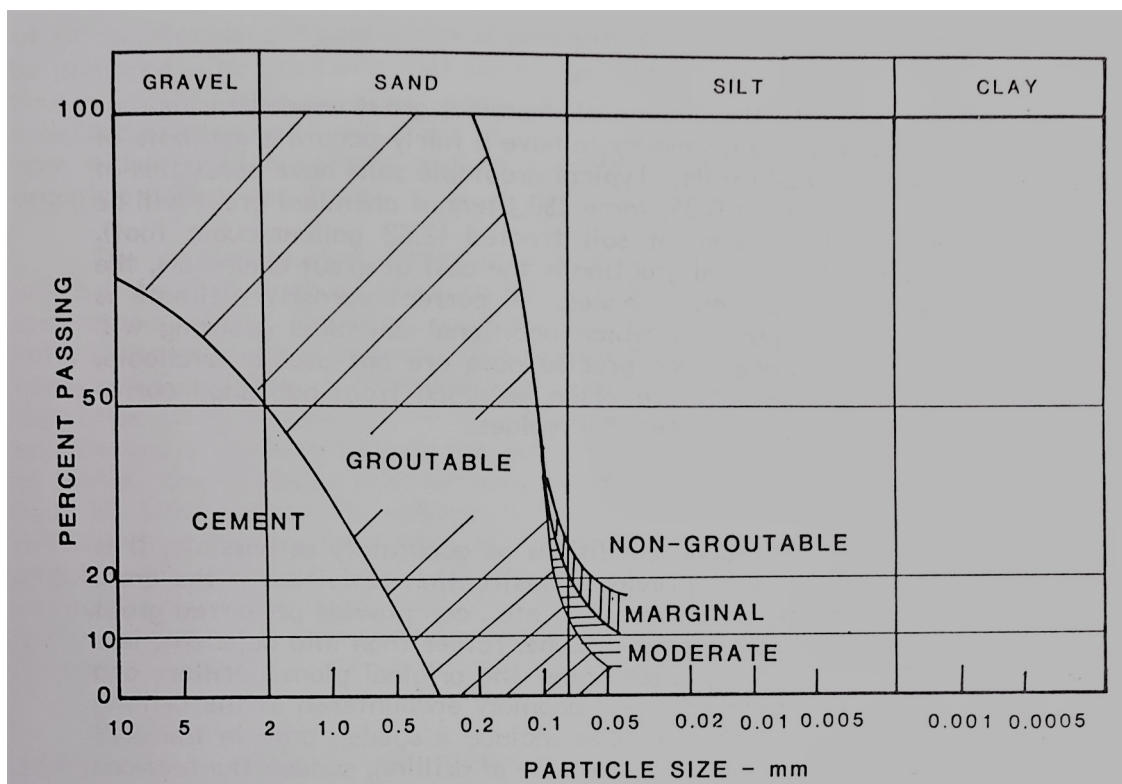


Figure 2.1. Grain Size Relationship for Grouting (Baker, 1982).

In order to simulate equal underground soil conditions, sand samples were compacted at a predetermined density. Two different grain sizes were used: fine and coarse sand. Fine content of the sand sample was mechanically adjusted to 13% for fine sand and 3% for medium sand. Also, soil samples were compacted at two different initial moisture contents. Water content was determined to generate partially saturated conditions. Taking into consideration this aim, two different initial water contents were used for each sand: 5% and 10% were used for fine sand, and 2% and 4% were used for medium sand. All soil samples were mechanically mixed in laboratory with Missouri River Sand. Soil gradation and unit weight values are presented in Table 2.1. Detailed grain size distributions are presented in Appendix A(A.1, A.2). The difference of grain size distribution between fine and medium sand can be seen in Figure 2.2.

Table 2.1. Gradation and Unit Weight of Sand Samples

Sample Code	Medium Sand-1	Medium Sand-2	Fine Sand-1	Fine Sand-2
Passing #4 (%)	100	100	100	100
Passing #10 (%)	95.22	95.22	100	100
Passing #40 (%)	50.76	50.76	65.3	65.3
Passing #200 (%)	3	3	13	13
Initial Moisture Content (%)	2	4	5	10
Dry Unit Weight of Compacted Sand (kN/m ³)	16.5	16.5	16.5	16.5

Conversion: 1 kN/m³ = 6.37 lb/ft³

2.1.2. Chemical Grouting Materials. Polyurethane, acrylate gel, and colloidal silica were the three different chemical grouting materials used in this study for comparison purposes. These grouting materials have similar characteristics in terms of gelling process, penetration ability, strength, and sensitivity. Since the uniaxial strength of the grouted sand



Figure 2.2. Graded Missouri River Sand

is the main component of the comparison process, other properties of grouts were kept similar as much as possible. In order to evaluate the resulting mechanical performance of these materials, similar gelling time, injection, and curing process were applied for all samples injected with the three chemicals. One of the most important concerns of grouting applications is deciding the injection pressure for optimum penetrability without hydrofracturing the soil and rock. Therefore, injection pressures in these experiments were constant and a predetermined injection pressure was used to avoid fracturing of sand samples.

2.1.2.1. Colloidal silica. Colloidal silica is an aqueous solution consisting of dissolved nano silica particles made by subtracting the alkali in the sodium silicate (Gallagher et al., 2007; Liao et al., 2003; Persoff et al., 1999). The gelling process of the colloidal silica starts by reducing the pH of the solution with a neutralizing agent. For the neutralization of colloidal silica dispersion, an accelerator solution is used (NaCl). The ionic strength and pH level of colloidal silica solution is modified with this neutralization agent. This process controls the gelling time and resulting properties of the grout. The colloidal silica ratio used in grouting applications can be found in the range of 6% through 40% in various experimental studies (Gallagher et al., 2007; Pan et al., 2016; Persoff et al., 1999; Shen et al.,

2017). These studies reveal different mechanical characteristics of colloidal silica injected sand and rocks. Since the performance criteria compares the resulting compressive stress of the grouted sand columns in this study, relatively high silica concentration was chosen. The product was the commercially available Ludox SM that has 30% SiO₂ concentration by weight (Appendix C.5). Technical details of the product are presented in Appendix C.1. The accelerator was prepared in the laboratory using pure crystallized NaCl and distilled water. The accelerator ratio was determined to have a gelling time that of about 1 hour, allowing enough time to complete a successful injection process. The colloidal silica used in this study has a specific gravity of 1.22 and viscosity of 6 mPa.s (6 cps), which is very close to that of water. The chemical was in the liquid form and had a cloudy white color. Hence, these properties make this grouting material highly capable of penetrating into fine-grained soils. The mixing details of colloidal silica and the accelerator are presented in Table 2.2.

Table 2.2. Mix Design of Colloidal Silica

Colloidal Silica	Ludox SM (Product of Sigma-Aldrich)
SiO ₂ Concentration (% Weight)	30
Added NaCl Solution (M)	1.1
Final SiO ₂ Concentration (% Weight)	27
Final NaCl Concentration (M)	0.1
Colloidal Silica to Accelerator Ratio (Volume:Volume)	10:1
Gel Time (minutes)	60

2.1.2.2. Acrylate gel. Acrylate grouts are developed as a less toxic alternative to acrylamide grouts. Acrylates basically consist of acrylate salts with a cross-linking monomer and a redox catalyst system (Karol, 2003). Even though gelling time control of

acrylate is less effective than its predecessor, potassium ferricyanide is used as an inhibitor for retarding gelling time. A redox catalyst system of acrylates includes an initiator and triethanolamine accelerator (Whang et al., 1995). Depending on the choice of different manufacturers, ammonium persulfate or sodium persulfate may be used as an initiator. Both controllable gelling time and very low viscosity values of acrylates make them preferable options for chemical grouting. Therefore, two different commercially available acrylate gels were used for testing. One was the De Neef AC-400 and the other was the SealBoss 2400 Seal Gel (Appendix C.6, C.7). Viscosity values for AC-400 and Seal Gel 2400 are 5-7 mPa.s (5-7 cps) and 1-3 mPa.s (1-3 cps), respectively. Both systems use sodium persulfate initiators. Other technical details of the products are presented in Appendix C C.2, C.3. In addition, potassium ferricyanide was used to control the gelling time for both acrylate kits. In order to test mechanical performance of acrylate grouts, mixing designs were created depending on the information given by manufacturers. Mixing details of acrylates are presented in Table 2.3.

Table 2.3. Mix Design of Acrylates

Acrylate Grout	Seal Boss 2400 Seal Gel	De Neef AC-400
Acrylate Monomers in Final Solution (% Volume)	47	26.5
Accelerator in Final Solution (% Volume)	3	0.45
Initiator Ratio in Water (% Weight)	1.5	1
KFe in Final Solution (% Weight)	0.1	0.5
Initiator in Final Solution (% Weight)	0.7	0.5
Gelling Time (minutes)	30-40	30-40

2.1.2.3. Polyurethane. Polyurethane grouts are mainly grouped as water reactive and two components. While water reactive polyurethane grouts can be found in the form of hydrophilic and hydrophobics, two component polyurethane grouts are divided as organic and organic-mineral resins (Bodi et al., 2012; Robinson et al., 2012). Basically, the reaction of polyol and diisocyanate creates the polyurethane (Anderson and Crosby; Komurlu and Kesimal, 2015; Robinson et al., 2012; Vipulanandan et al., 2012). Additionally, depending on the formulation of manufacturers, certain amounts of catalyst and additives are added with the polyols (Bodi et al., 2012; Robinson et al., 2012). After an exothermic reaction, urea and CO₂ are formed. CO₂ acts as a pressurizing agent helping the movement of grout along the voids of sand and cracks of rock medium. The commercially available Seal Boss 1510 was selected for this study, which is a methylene diphenyl diisocyanate (MDI) based one component, water-reactive (hydrophobic) polyurethane (Appendix C.8). Technical details of the product are presented in Appendix C.4. In order to have maximum gelling time, the lowest amount of accelerator allowed by the manufacturer was used. Mixing details are presented in Table 2.4.

Table 2.4. Mix Design of Polyurethane

PU Grout	Seal Boss 1510 WaterStopFoam
Polyurethane (% Volume)	98
Catalyst Ratio (% Volume)	2

The viscosity of Seal Boss 1510 varies between 160-250 mPa.s (160-250 cps) depending on the temperature and accelerator ratio. Although some polyurethane grouts have lower viscosity values, Seal Boss 1510 can be considered among the advanced and low viscosity polyurethane grouts. Gelling time and application period of polyurethanes are differentiated from other chemical grouts. Even though gelling time can be controlled by changing the accelerator ratio, induction time, or the moment where the foaming starts,

happens much sooner. Therefore, gelling time is not a good indicator to define application time for polyurethane, as opposed to acrylate and colloidal silica. Because time is needed for removal and for sealing of molds, induction time in this study was considered to finish the injection process instead of gelling time.

2.1.3. Capping Materials. A capping material is expected to have enough bonding capability and minimum strength for stable testing (Trejo et al., 2003). According to ASTM standards C 617 and C 1231, a gypsum cement or a sulfur compound can be used as a bonded capping material, while neoprene pads can also be used as unbonded capping compounds. A study reveals that gypsum plaster is more capable of filling the voids caused by irregularities on the surface of samples (Trejo et al., 2003). Specific to this study, the characteristic of gypsum paste was distinctive because of the difficulty of grinding a flat surface with the friable ends of grouted specimens. In order to transfer the load correctly to the specimen, the application of capping becomes as important as the capping material. Therefore, high-strength gypsum cement, glass plates, and bull's-eye levels were used in accordance with ASTM C 617. Since the standard requires specific thickness and dimensions, glass plates that are 0.25 mm (0.001 in.) in thickness, 3 x 3 in. (76.2 x 76.2 mm) in dimension were produced (Figure 2.3). Commercially available Hydrocal white gypsum cement was used, which has a compressive strength of 5000 psi (34473.8 kPa) in dry conditions.

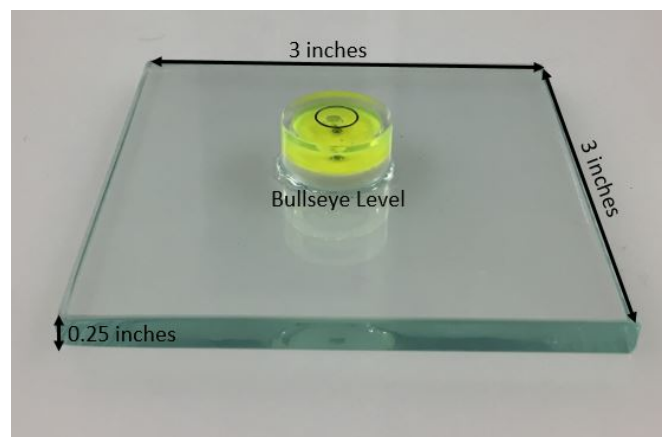


Figure 2.3. Glass Plate for Gypsum Capping.

2.2. SAMPLE PREPERATION

2.2.1. Injection Apparatus. Grouting of the sand specimens must simulate the field applications. In order to ensure that the grouting material spread out properly in-between the pores of the sand, a proper setup of injection system plays an important role. Previous studies use similar laboratory setups inspired by the same principle (Dano et al., 2004; Ortiz, 2015; Ozgurel and Vipulanandan, 2005; Schwarz and Krizek, 1994; Zebovitz et al., 1989). In addition, there is an ASTM standard for laboratory testing of grouted sand, which is ASTM D4320. In this study, a laboratory apparatus was designed by considering the essentials of the standard. A constant and continuous injection pressure was provided to inject the grout into sand columns. Sand was compacted in clear acrylic tubes that had an influent in the bottom and effluent on the top of the cylindrical column. Steel mesh and filter papers were used both at the bottom and at the top surface of the material to avoid any possible clogging in the system. The schematic design of the laboratory injection system is presented in Figure 2.4.

2.2.2. Injection Procedures and Curing Conditions. Injection pressures and the curing process were designed with taking into consideration the field conditions. As aforementioned, the injection pressures were constant at a predetermined value to prevent disturbance of the compacted soil samples. Considering various penetration abilities of three different chemical grouting materials, the highest possible injection pressure was selected and the same injection pressure was applied during the injection process. Even though higher injection pressures than those predetermined might help the full saturation of some samples, it could cause an unpredictable mechanical performance variation (Christopher et al., 1989). Depending on the information above and the recommended pressures by ASTM D4320, injection pressure was specified as 8 psi (55.2 kPa). The reason for choosing the 8 psi (55.2 kPa) injection pressure instead of the maximum value given by the standard, which is 10 psi (68.9 kPa), was to stay to conservative preventing any over pressure arising from a poor pressure calibration. Since the analog pressure gauge was able to measure

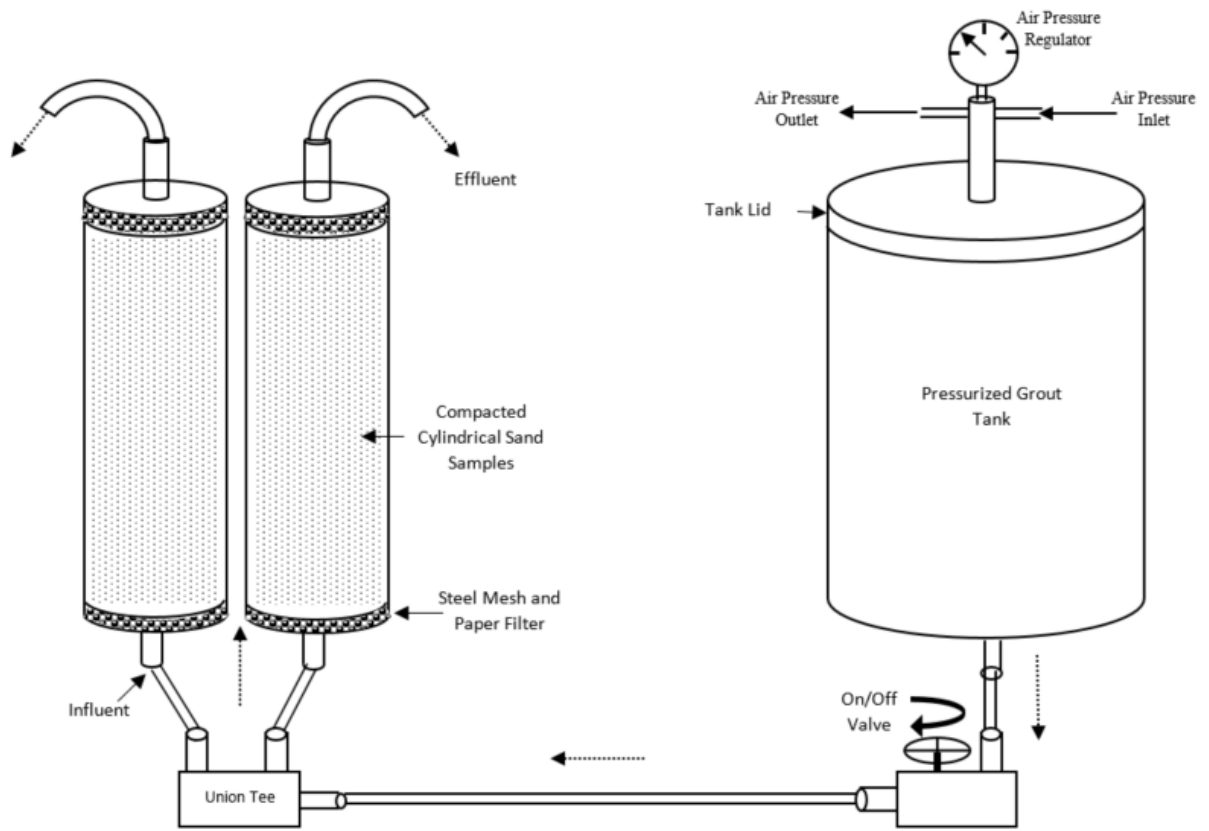


Figure 2.4. Laboratory Injection Setup.

every 2 psi (13.8 kPa), 8 psi (55.2 kPa) was the as nearest possible to that of maximum. The sand sample was compacted immediately before the injection process to avoid moisture loss. The compaction process was completed in four steps. The sand was divided into four equal parts and compacted in the clear acrylic tubes. In order to achieve desirable dry unit weight, number of taps for medium sand-1, medium sand-2, fine sand-1, and fine sand-2 were 5, #3, #8 and 2, respectively. Then the sample and mold weight were measured with an electronic scale with an accuracy of 0.1 g (0.0002 lb). The compaction process was repeated until the desired weight was reached. Hence, an undesired dry unit weight of compacted samples was prevented. These steps were completed precisely to have the exact dry unit weight value. After compaction of sand in the clear acrylic tubes, steel meshes and filter papers were used for both the influent and the effluent (Figure 2.5).

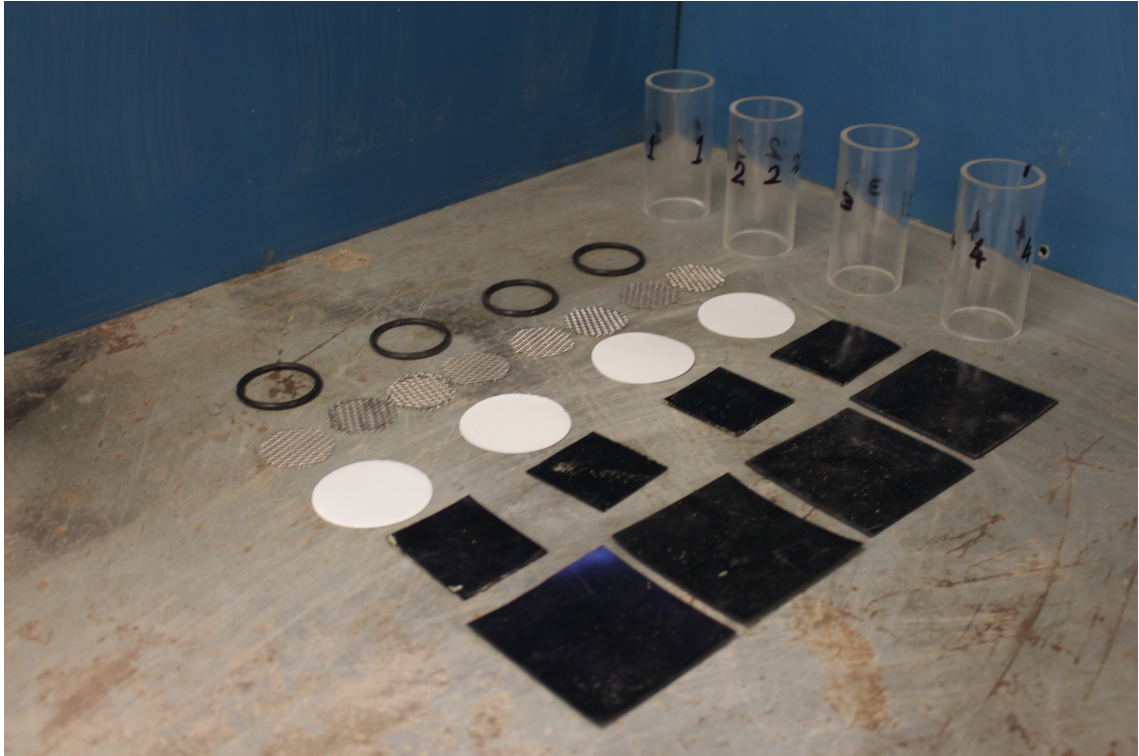
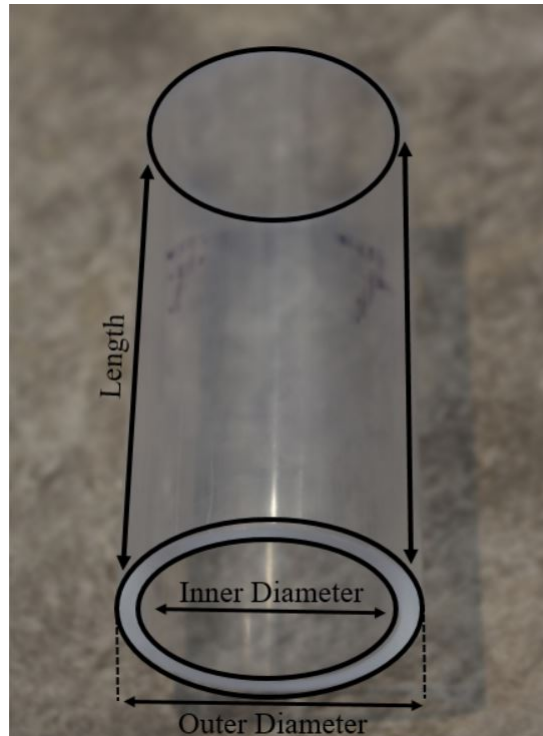


Figure 2.5. Equipments Used for Mounting.

Figure 2.6 below shows the acrylic tubes dimensions. Acrylic tubes were mounted to bottom and top plates. In order to provide a leakproof connection, nests were drilled in the acrylic plates using special drilling equipment and precise fitting of the acrylic tubes were ensured. The use of clear cast acrylic sheets simplified the production process. Technical details of top and bottom plates are presented in Figure 2.7.

Four male connector fittings were used in both influent and effluent. Also, a union tee fitting was used to separate the flow into two equal channels. A clear vinyl tubing was used for the connections between the grout tank and influent. Technical details of connection materials are presented in Figure 2.8. Steel meshe covers were cut from a #10 mesh. Qualitative filter papers, which are 55 mm (2.17 in.) in diameter, were selected considering the diameter of acrylic tubes (Figure 2.9).



Inner Diameter: 1.5 in.

Outer Diameter: 1.75 in.

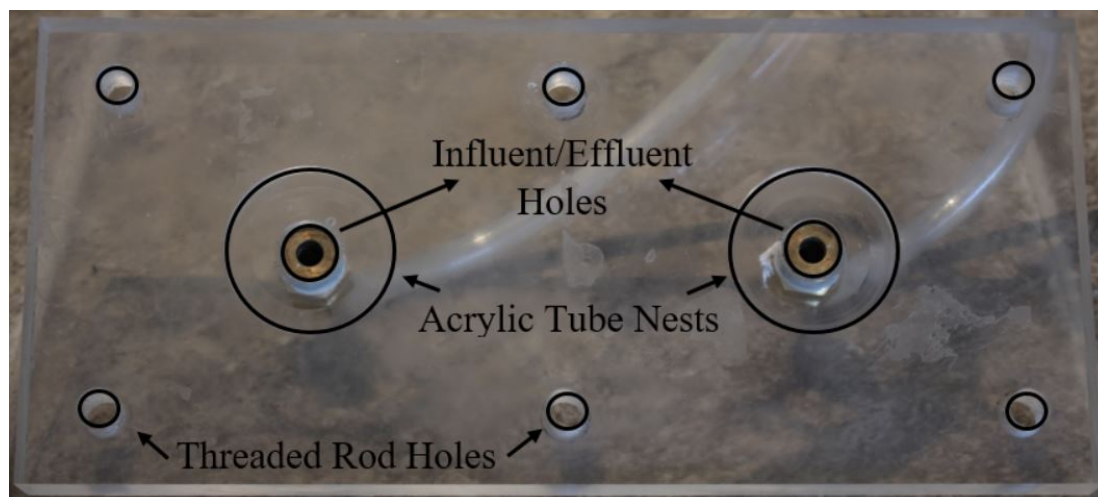
Length: 3.5 in.

Conversion Factor: 1 in. = 25.4 mm

Figure 2.6. Clear Acrylic Tube.

While the filter paper helped to keep the fines from being flushed out, the steel mesh was necessary to support the sample along the contact area. For every injection process, two compacted sand samples with the same initial conditions and the same gradations were mounted to the injection system (Figure 2.10).

Thereafter, the grout tank was filled with a sufficient amount of grout mix and pressurized to 8 psi (55.2 kPa). Injection was initiated and maintained through 5 minutes by opening the on/off valve between the tank and union tee (Figure 2.11). For some of the chemical grouting materials, the injection process was ended under 5 minutes after seeing enough liquid flowing from the effluent. A quantity of flowed chemical as much as the volume of the cylindrical mold was considered sufficient to fill the all pores of the



Diameter of Influent/Effluent Holes: 0.375 in.

Diameter of Nests: 1.75 in.

Diameter of Threaded Rod Holes: 0.25 in.

Conversion Factor: 1 in. = 25.4 mm

Figure 2.7. Top and Bottom Plates.



Tube Fitting Diameter of Male Connector: 0.375 in.

Male Connection Diameter: 0.375 in.

Tube Fitting Diameter of Union Tee: 0.375 in.

Vinyl Tubing Inner/Outer Diameter: 0.25/0.375 in.

Conversion Factor: 1 in. = 25.4 mm

Figure 2.8. Male Connector (left), Union Tee (center), and Vinyl Tubing (right).

compacted sand. In order to control the amount of liquid, injection material coming out from the effluent was collected in a graduated beaker as seen in the Figure 2.10. A detailed explanation of injection times of each material is presented in the next sections.

Upon completion of injection process, the acrylic tubes were removed from the bottom and top plates. Injected sand columns were left in the acrylic tubes for 24 ± 4 hours to harden. This waiting time was adequate to remove samples from acrylic tubes.



Figure 2.9. Filter Paper (left) and Steel Mesh (right).

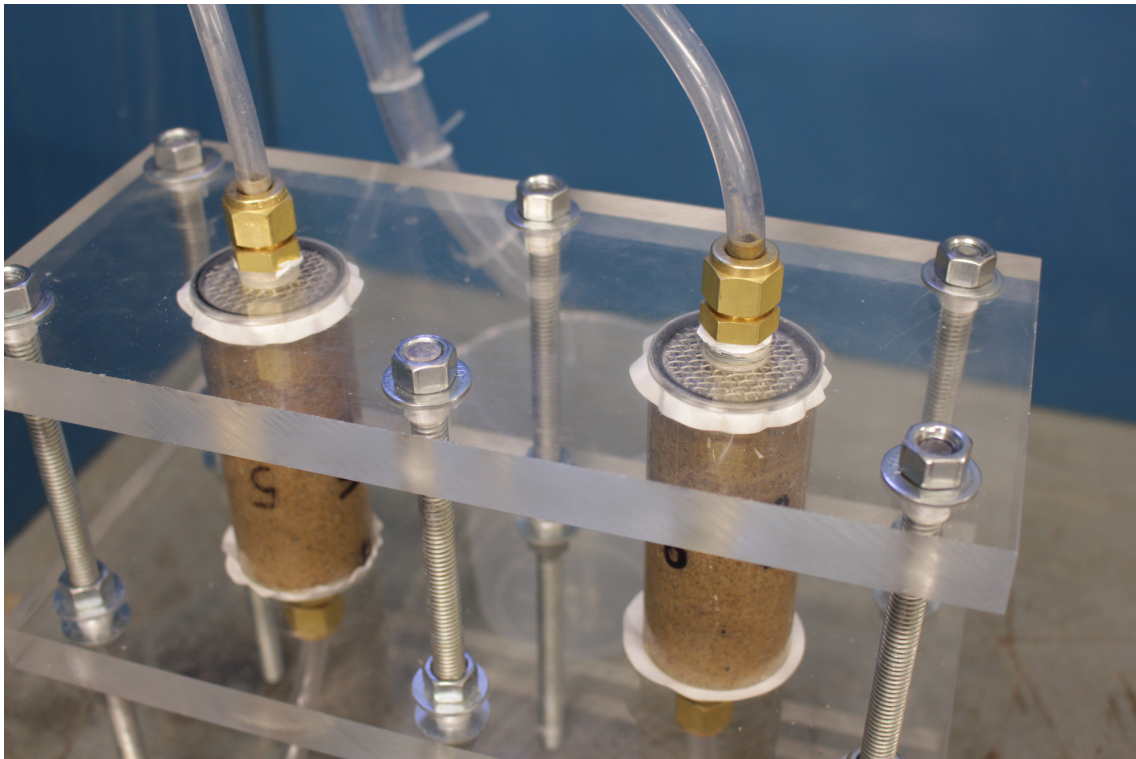


Figure 2.10. Mounted Sand Columns Before Testing.

Even though this period is sufficient for moist and dry-air curing of specimens, specimens needed to gain more stability before being immersed in the water for illustration of wet



Figure 2.11. Injection of Sand Columns.

curing conditions. Therefore, all removed samples were stored in ambient room conditions for another 24 ± 4 hours prior to let them cure within specified curing conditions (Figure 2.12).

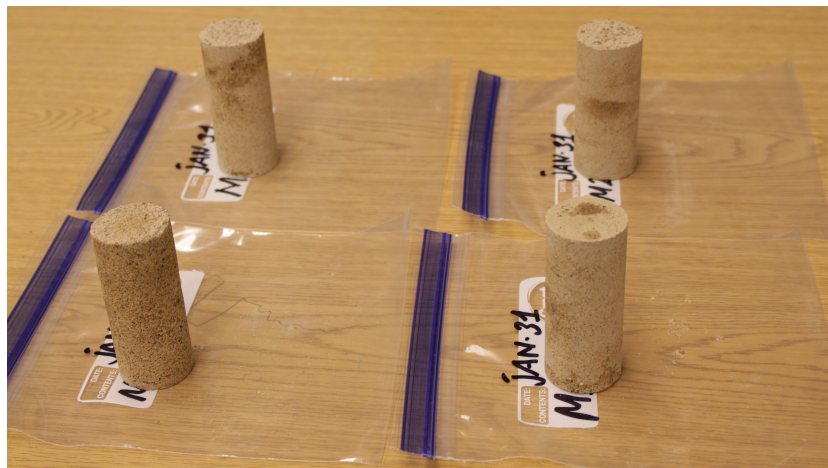


Figure 2.12. Injected Sand Columns Before Curing.

The second waiting period was important, especially for the samples that are cured while immersed in water. Samples were moist cured in ziplock bags, water cured by immersion in water, and air cured in laboratory room conditions. Curing of samples was conducted for 28 days from the injection day to testing day. Immediately after the curing period, samples were trimmed and capped with gypsum paste in accordance with ASTM C617. Because gypsum paste needs 30 minutes to harden, samples remained in room temperature for 1 hour throughout the capping process (Figure 2.13).

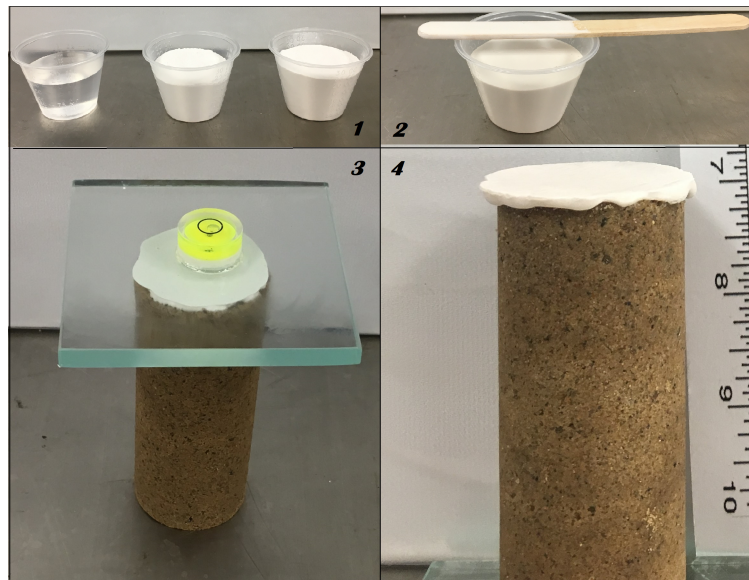


Figure 2.13. Gypsum Capping.

After completion of the compressive tests of the grouted sands which was prepared as described above, samples were retrieved for the wet-dry cycle test. Because there was not enough sample to test each grain size-initial moisture-chemical grouting material combination, three group of test samples were composed for three different materials. Only humid cured samples were retrieved when composing the test samples (Figure 2.14). Hence, the effect of the curing conditions was ignored during the determination of durability of grouted sand samples.

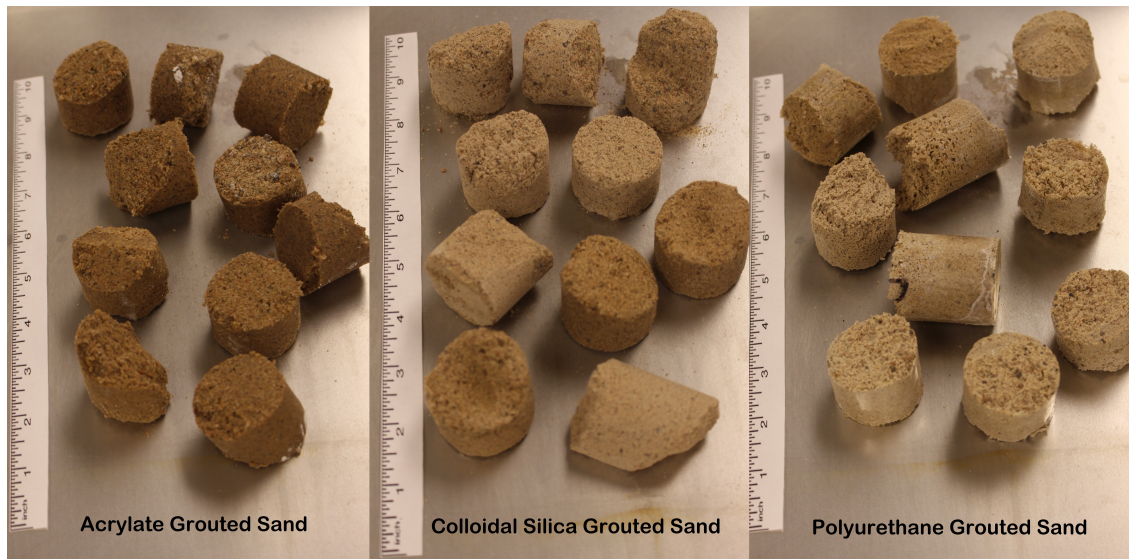


Figure 2.14. Retrieved Samples for Slake Durability Testing.

2.3. TESTING

2.3.1. Unconfined Compressive Test. The UCS is one of the most applied index test to determine the strength of soil and rock. This test basically is based on strain-controlled axial loading test samples. Thus, maximum resistance to axial compressive stress is detected without any confining stress that naturally affects to soil and rocks. UCS tests of grouted cylindrical samples were done with an Instron universal type machine that is static and fully automated and has a 5 kN (1124 lbf) loading capacity and is able to measure one thousandth of Newton. Also, the test machine was able to measure extension of specimens to an accuracy of 0.001 mm (0.00004 in.), and detect the load with an accuracy of 0.0001 Newton (0.00002 lbf). Tests were performed by using Bluehill 3 software, which allows the control of the extension rate and monitoring of the extension-load curves simultaneously. The testing setup is presented in Figure 2.15.

Since the standard test method for unconfined compressive strength of grouted sands was withdrawn by ASTM, tests were done in accordance with the ASTM D2166 which the withdrawn standard was originally based on. So, considering the requirements of this

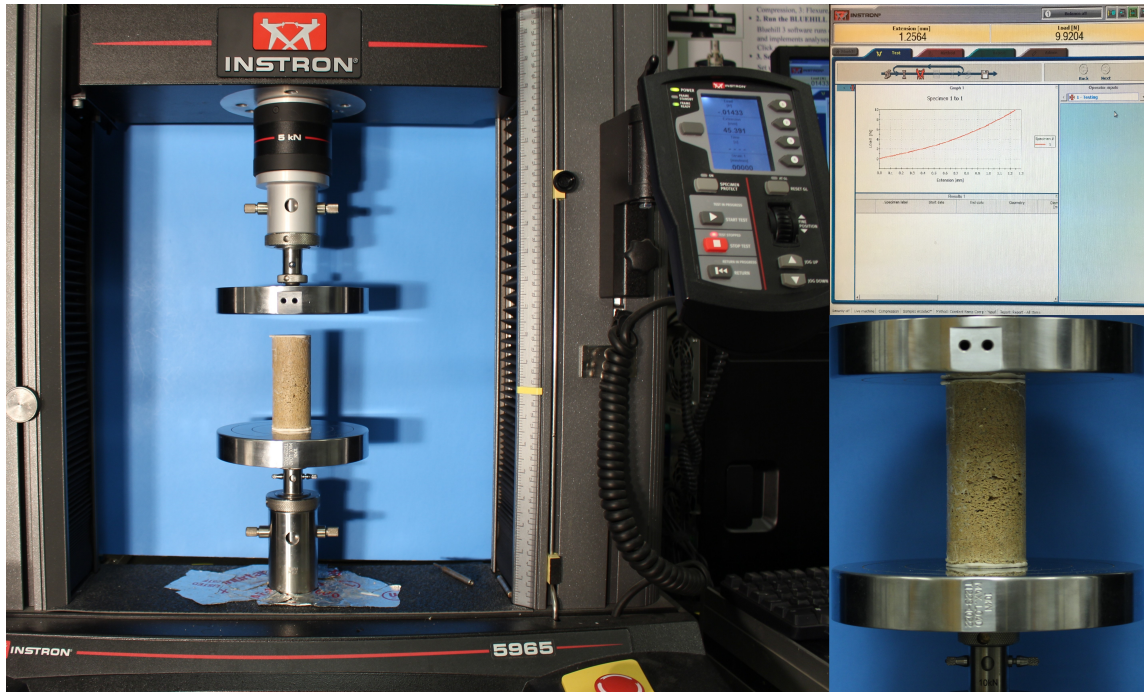


Figure 2.15. UCS Test Setup

standard, a strain rate of 1 mm/min (0.04 in/min) was used, which is proper for the sample length used in this study. Therefore, with this strain rate, axial loading was allowed until failure or 15% strain without exceeding the 15-minute maximum testing time specified by the standard. The same strain rate was used for all specimens to avoid variations in test results caused by the test procedure (Christopher et al., 1989).

2.3.2. Slake Durability Test. Slake durability testing is an accelerated method to observe the effect of wet-dry cycles on the durability of weak rock materials. Test samples are dried and slaked through successive wet-dry cycles. Even though the wet-dry cycles simulates only severe field conditions, this index test is very practical to compare durability of groted sand samples. The slake durability index was measured using a testing machine that meets the requirements of the relevant standard. The machine had a drum constructed with 2 mm (0.08 in.) square-mesh, which was 140 mm (5.51 in.) in diameter and 100 mm (3.94 in.) in height. Also, the drum was able to resist 110 ± 5 °C so that the samples could

be dried within the drum in the oven. The slake durability machine included a motor to rotate the drum for at least ten minutes with 20 rpm (Figure 2.16). For the oven-drying of the samples, a Humboldt digital temperature controlled bench oven was used.

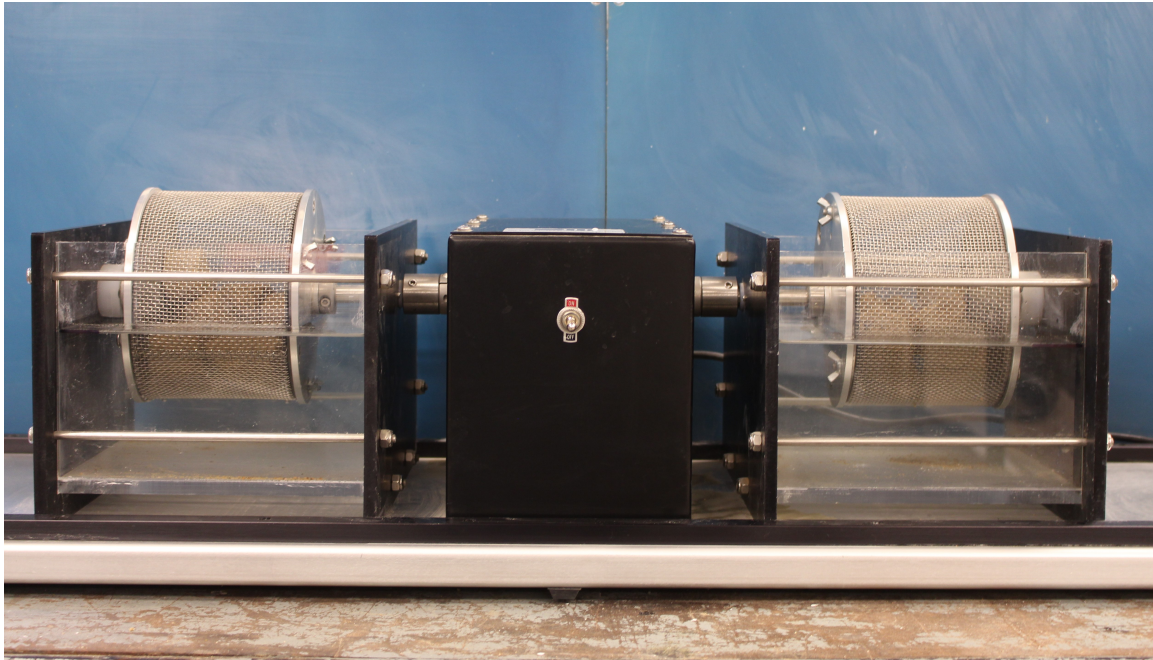


Figure 2.16. Slake Durability Test Setup.

This test was done in accordance with the requirements of ASTM D4644. Therefore, 10 representative samples ranging between 40 and 60 grams (0.09 and 0.13 lb) each were used for every test. First, the weight of drum (A) was recorded. Second, samples were placed in the drum and oven-dried for 24 hours. The oven-dried sample plus drum weight (B) was recorded. Immediately after weighing the drum with the sample, the drum was placed into the machine. Distilled water was used to fill the machine to 20 mm (0.8 in.) below the axis. Third, the motor was run for ten minutes at 20 rpm. Upon completion of cycling, the drum was removed and placed in the oven for another 24 hours. The same cycling process was applied for a second time. Finally, the oven-dried weight of the drum plus samples (C) was recorded. Hence, the slake durability index I_{d2} was calculated by using Equation 2.1:

$$I_{d2} = [(C - A) / (B - A)] \times 100 \quad (2.1)$$

Additional to the slake durability index, representative fragment types are photographed and stored after the test for the description of samples as it mentioned in the ASTM D4644.

3. LABORATORY TEST RESULTS

In this study, sixty-six compressive strength tests and three slake durability tests were performed to explore the mechanical behavior of chemically grouted sands with three common chemical grouting materials. Besides, the injection process of the materials was observed to understand the penetration ability of the chemicals. It should be noted that all test results and penetration times are based on chemical mix ratios, soil density, and injection pressures selected in this study and may show diversity under different combinations.

The elapsed time from starting propagation of chemicals in the injection system with opening of the on/off valve until the liquid first appears in the effluent was under 30 seconds for acrylate grouts for both fine and medium sands. This time was about a minute for the injection of colloidal silica into medium sands. The colloidal silica barely came from the effluent during the injection of fine sands within a 5-minute injection period. Nevertheless, the colloidal silica could penetrate into fine sands within a predetermined injection time. Different from these two materials, the polyurethane showed a specific penetration behavior. Although the polyurethane grout was not observed from the effluent within five minutes, grout was propagated into all voids of sample thanks to CO₂ gasses produced by the exothermic reaction. Because there are limitations regulated by the manufacturer, the selected catalyst ratio of polyurethane caused initiation of a foaming process without having enough time to remove molds from the injection system and seal them for curing. Therefore, the polyurethane can be considered as able to penetrate in 5 minutes like acrylate and colloidal silica even though the process is different. Besides, the propagation phase of polyurethane with medium sands was faster than that of the grouting of fine sands.

It has been shown that grain distribution and fine content of the grouted sand was effective on the resulting strength (Ozgurel and Vipulanandan, 2005; Zebovitz et al., 1989). In this study, in order to investigate the effect of grain size and fine content, two

different samples (fine sand and medium sand) were tested. The grain size distribution of these samples is presented in Appendix A. It can be seen from Figure 3.1 that the compressive strength of grouted sand is affected in different ways for different chemical grouting materials. As shown in Figure 3.1(a), Figure 3.1(b), and Figure 3.2(a), the higher the fine content of soil, the larger the observed increase in strength for acrylate and colloidal silica grouts. On the other hand, in Figure 3.2(b), an opposite relationship is observed for polyurethane grouts. Hence, an increase in the fine content of polyurethane grouted sand results in a decrease in the compressive strength. This may be due to the lower penetration ability of polyurethane in medium sand than in fine sand. It should be noted that most representative data, which is closest to mean UCS value of its particular chemical type-grains size-curing condition combination, was used to create the strain-stress curves. The mean UCS values are presented in Appendix B.1 and B.2.

Compressive test results of 28-day cured samples ranged between 60 kPa and 799 kPa (8.70 psi to 115.86 psi) for colloidal silica grouted sands (Figures B.7, B.8, and B.9). In addition, one sample could not be tested and was assumed to have zero strength. This is because the immersed-in-water sample of medium sand-2 could not have adequate strength to be tested and pulled apart after being taken out from the water. After 28 days of curing of colloidal silica grouted sand with different curing conditions, compressive test results showed considerable scatter. While the difference of average UCS values between air-cured and moist-cured samples is moderate, average UCS values of water-cured samples dramatically drop. This trend cannot be observed for only air-cured medium sand-1. However, the rest of the data supports the trend caused by the curing conditions. This relationship is illustrated in Figures 3.3 and 3.4. As shown in this figure, it can be concluded that colloidal silica is directly affected by the curing conditions.

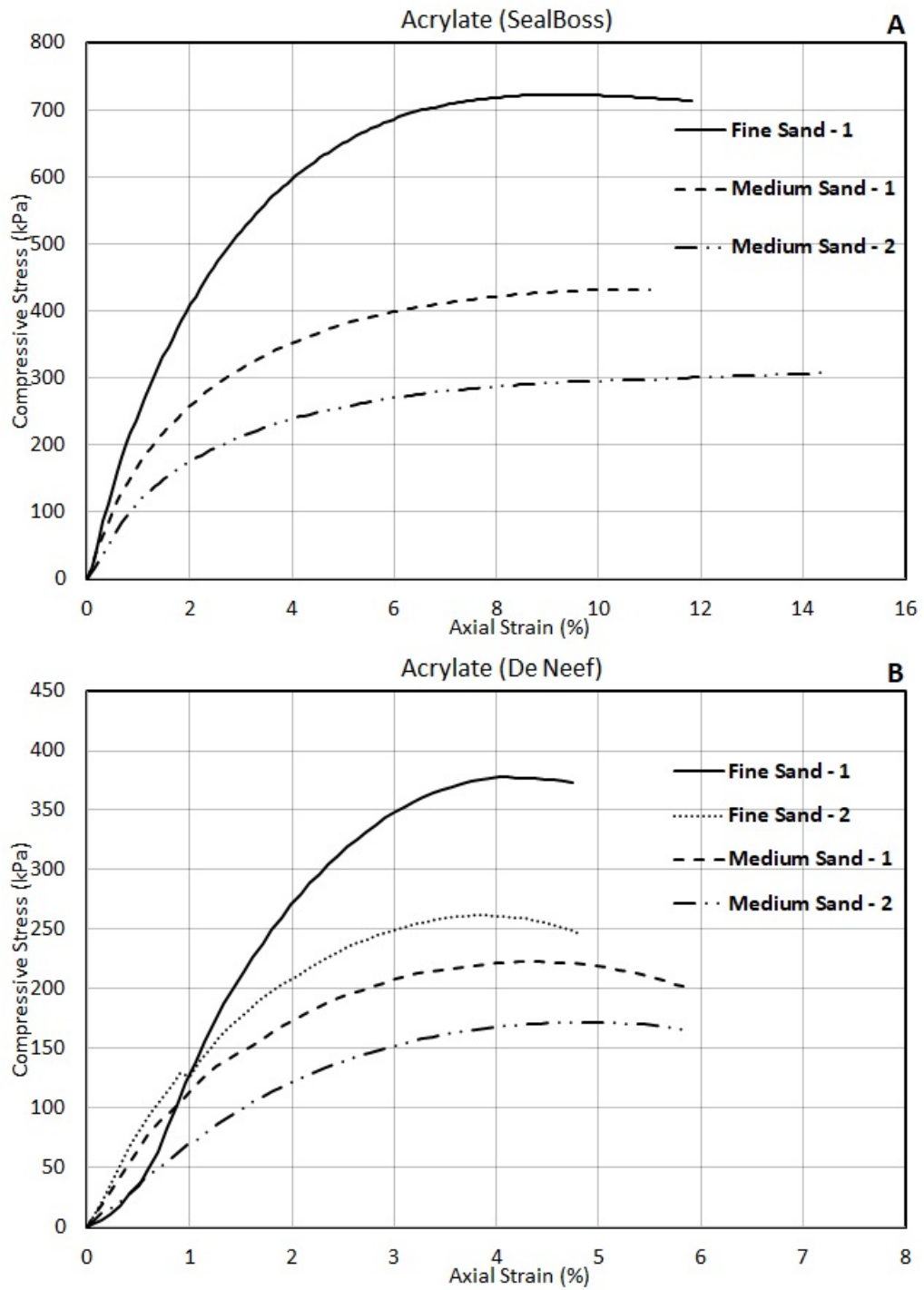
As seen in Figure 3.1, initial soil properties like grain distribution and fine content affect the resulting compressive strength. In addition to that, the effect of initial moisture content was also investigated. Samples of medium and fine sands were prepared with two

different initial water contents. The tendency of UCS values depended on initial moisture content shown in different ways for each chemical type. While a direct relationship is observed for acrylate, colloidal silica and polyurethane behave less correlated. As presented in Figure 3.5, by increasing the initial moisture content, the strength of acrylate grouted sands having the same grain size was decreased. Therefore, the results presented herein indicate that lower moisture content caused a stronger interconnection between sand and grout. On the other side, even though the UCS values varied with the increasing moisture content, data does not yield significant correlations for colloidal silica and polyurethane.

Unconfined compressive tests resulted in a manner which can be used for comparison purposes. The UCS test results of all three chemical grouts ranged from 60 kPa to 3954 kPa (8.70 psi to 573.48 psi) (from Figure B.3 to Figure B.11). The highest UCS values were reached with polyurethane grouted medium sand. On the other hand, the lowest UCS values were reached with colloidal silica grouted medium sand. While the UCS values of acrylate grouted medium sand were always higher than the colloidal silica grouted medium sands, colloidal silica grouted fine sand had more strength in some cases. Additionally, the acrylate grouted sand strength was varied in itself. In all cases, the acrylate grouted medium sand had higher UCS values than the colloidal silica grouted medium sand. However, for fine sands, the acrylate product of DeNeef AC-400 resulted in less strength than colloidal silica, while the acrylate product of the SealBoss 2400 Seal Gel resulted in more strength than colloidal silica. Therefore, it should be taken into consideration that depending on the mixing design of different manufacturers, the same type of chemical grouting materials might have different mechanical performance. Overall, polyurethane grouted sands give the highest UCS values with all curing conditions and the soil gradation. Colloidal silica grouted sands give the lowest strength except in some aforementioned cases. This relationship is illustrated in Figure 3.6. Reported compressive strength values in Figure 3.6 correspond to

the average values of all tested specimens for each particular combination of chemicals, sand type and curing condition. A detailed list of average compressive test results is presented in Appendix B.

The slake durability index of colloidal silica, acrylate, and polyurethane was 13%, 31%, and 94%, respectively (Table 3.1). Slake durability index values have been classified in a previous study (Franklin and Chandra, 1972). Depending on the classification system, durability index value of polyurethane grouted sand indicates that it has very high durability under wetting and drying conditions. In contrast, acrylate is classified as having low durability while the colloidal silica shows the weakest mechanical performance in terms of durability to wetting drying cycles. Thus, 13% of slake durability index puts the colloidal silica in a very low class. A representative photograph of fragment types that was retained at the end of the test is also presented in Figure 3.7.

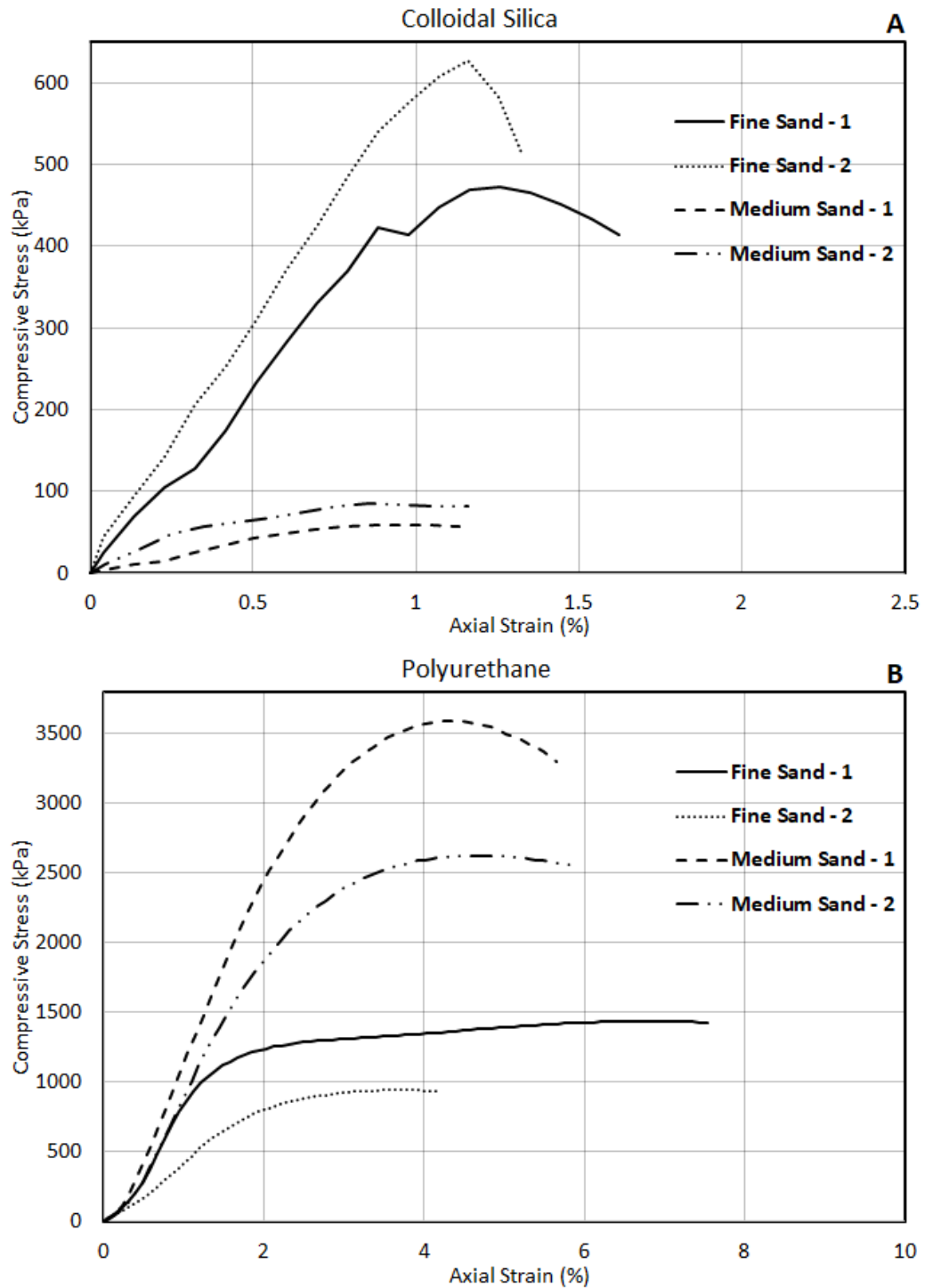


Graphic A: Moist cured samples of Acrylate Grouted Sands (SealBoss)

Graphic B: Moist cured samples of Acrylate Grouted Sands (De Neef)

Conversion Factor: 6.89 kPa = 1 psi

Figure 3.1. Stress-Strain and Grain Size Relationship.

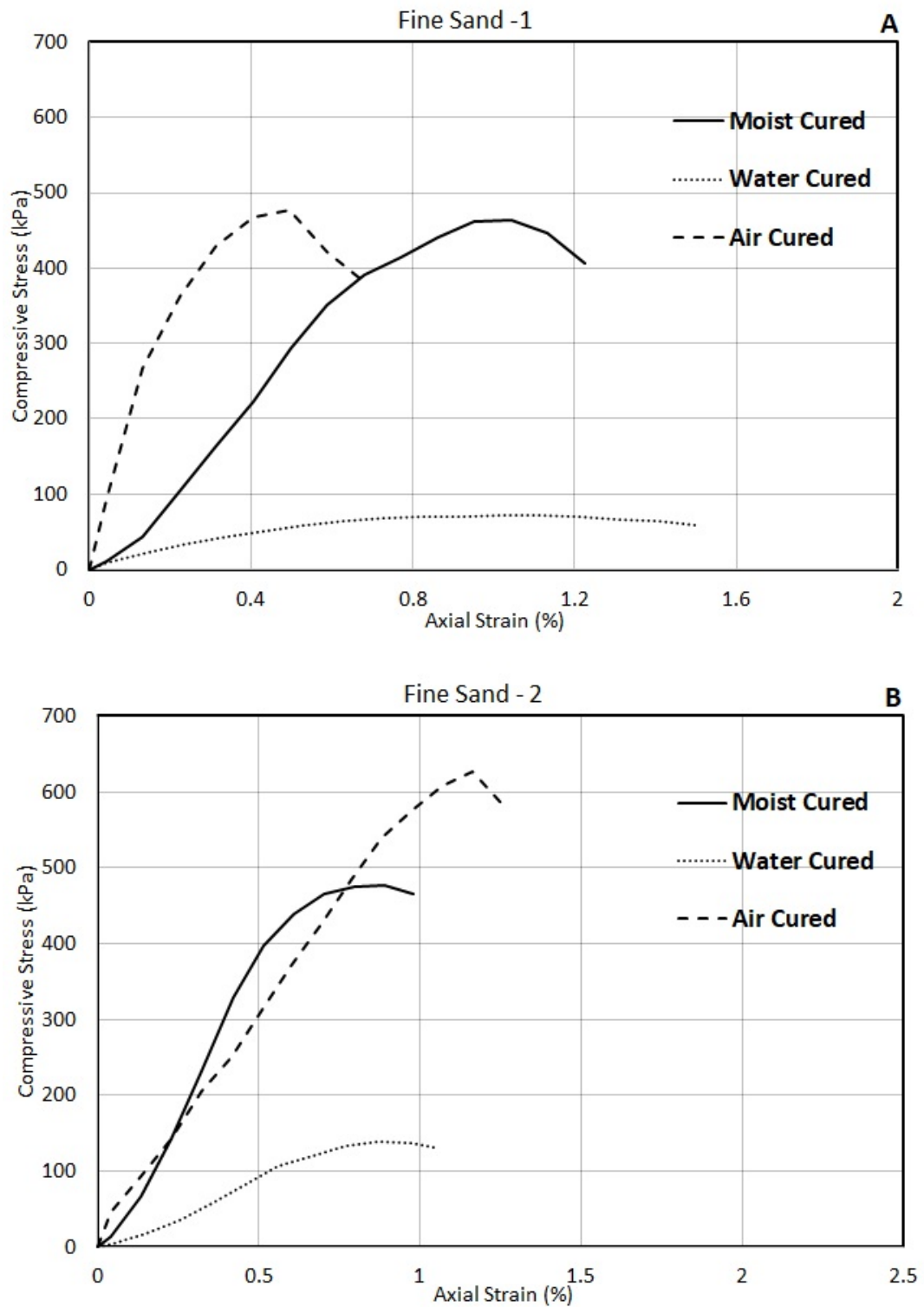


Graphic A: Moist cured samples of Colloidal Silica Grouted Sands

Graphic B: Air cured samples of Polyurethane Grouted Sands

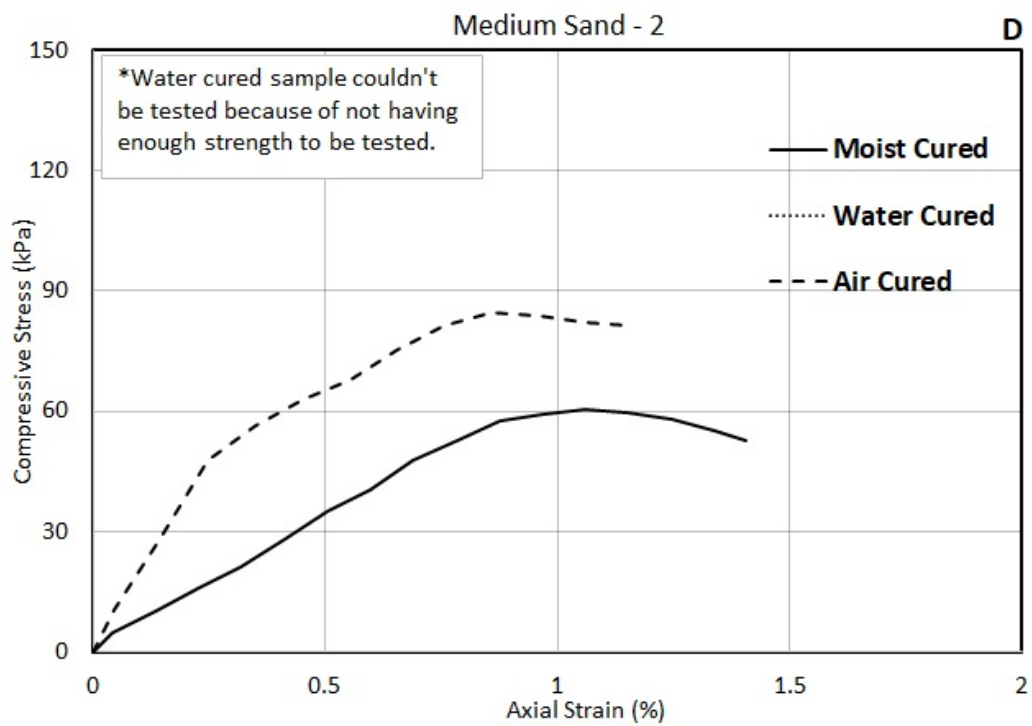
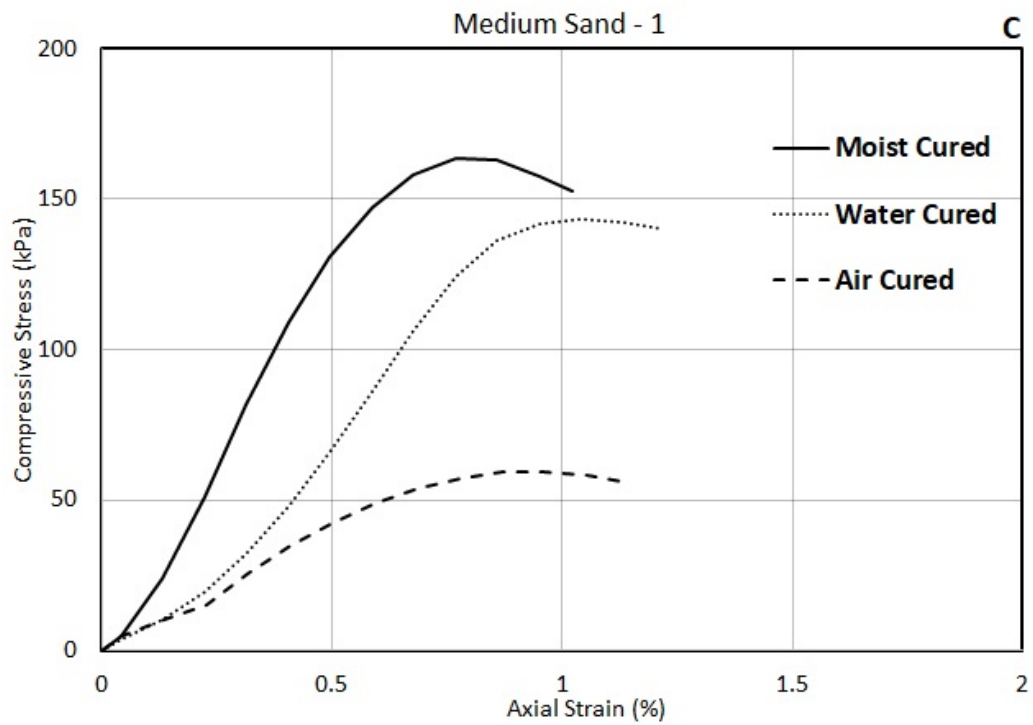
Conversion Factor: 6.89 kPa = 1 psi

Figure 3.2. Stress-Strain and Grain Size Relationship.



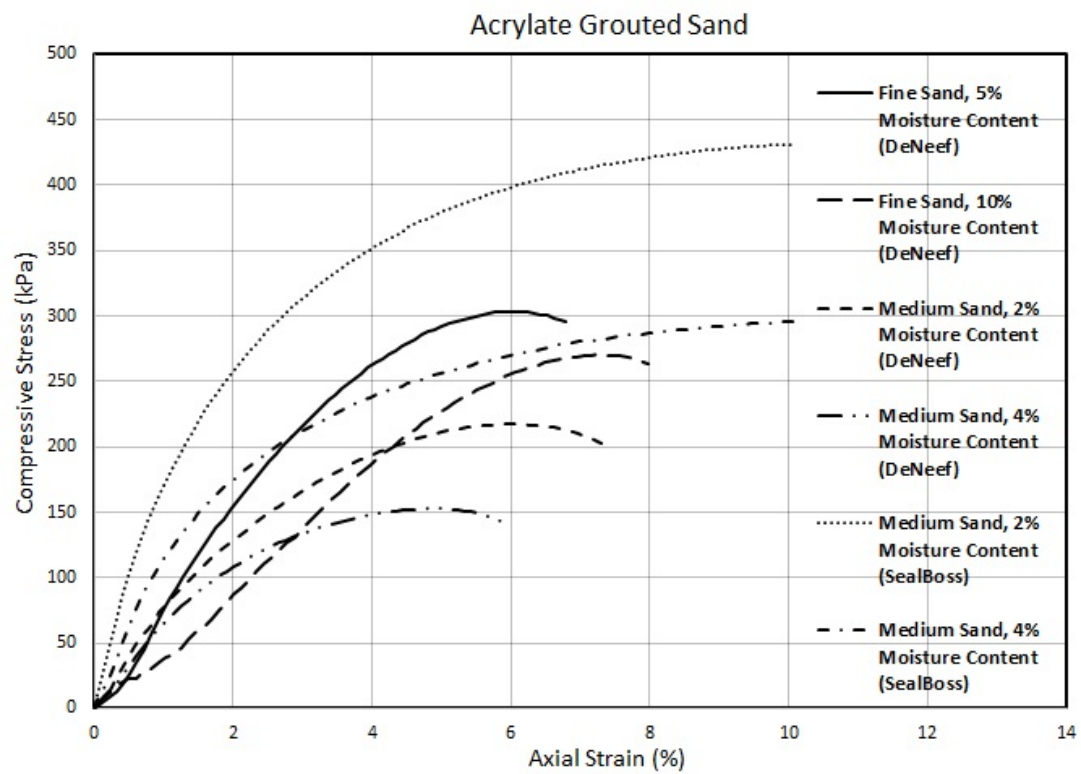
Conversion Factor: 6.89 kPa = 1 psi

Figure 3.3. Effect of Curing Conditions on Resulted Compressive Stress of Colloidal Silica Grouted Sand.



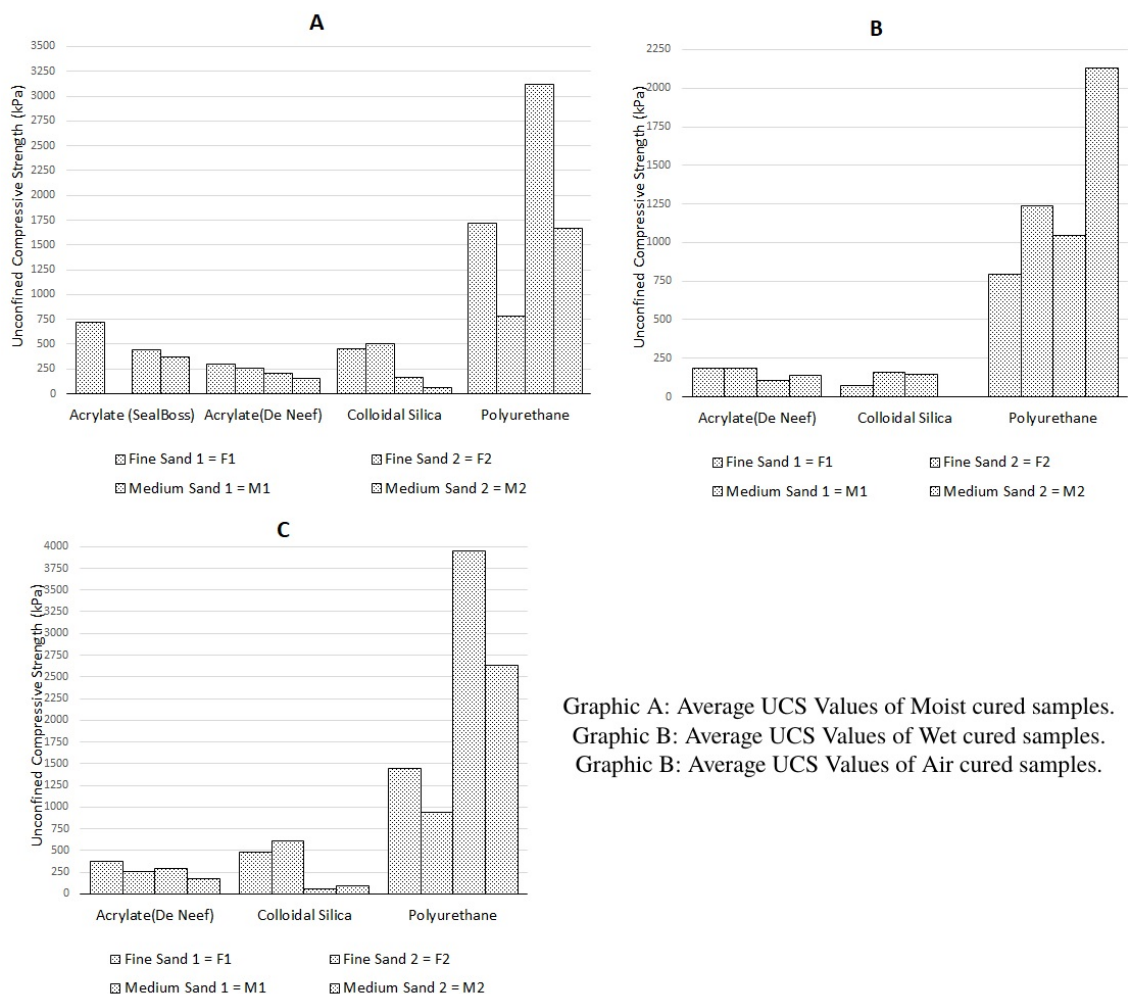
Conversion Factor: 6.89 kPa = 1 psi

Figure 3.4. Effect of Curing Conditions on Resulted Compressive Stress of Colloidal Silica Grouted Sand.



Conversion Factor: 6.89 kPa = 1 psi

Figure 3.5. Stress-Strain and Moisture Content Relationship of Acrylate Grouted Sand.



Graphic A: Average UCS Values of Moist cured samples.
 Graphic B: Average UCS Values of Wet cured samples.
 Graphic B: Average UCS Values of Air cured samples.

Conversion Factor: 6.89 kPa = 1 psi

Figure 3.6. Average UCS Values of Grouted Sands.

Table 3.1. Slake Durability Test Results

Chemical Type	Colloidal Silica	Acrylate	Polyurethane
Weight of Drum (A) (g)	1229.6	1229.5	1460.9
Oven-Dried Sample + Drum Weight (Before Cycle) (B) (g)	1794.2	1752.9	1973.5
Oven-Dried Sample + Drum Weight (After First Cycle) (g)	1330.9	1366.4	1957.9
Oven-Dried Sample + Drum Weight (After Second Cycle) (C) (g)	1301.8	1389.8	1943.2
$Id_2 = [(C-A)/(B-A)] \times 100$ (%)	13	31	94

Conversion Factor: 1 g = 0.0022 lb

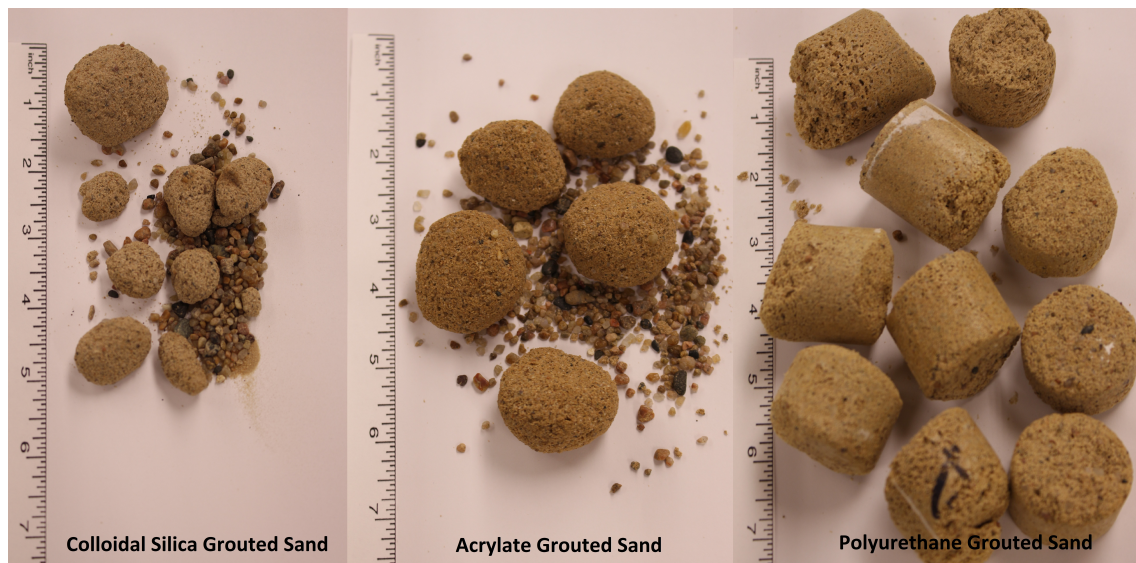


Figure 3.7. Fragment Type of Grouted Sand After Wet/Dry Cycles.

4. CONCLUSIONS

The effect of curing conditions, grain size distributions and initial moisture content on mechanical performance of chemically grouted sand was investigated by using the three chemical grouting materials. Also, the penetration ability of chemicals into different soils was evaluated based on observations during the injection process. However, the aim of this study is not giving design recommendations depending on the comparison, but somewhat to help in understanding the differences of behavior of the three chemicals. Sponsors of chemical grouting materials used in this experimental study are not responsible for the conclusions drawn herein. Based on the results, the conclusions below are as follows:

- Gel times of acrylate and colloidal silica were adequate for mixing and injection of the material. On the other hand, the foaming initiation time of polyurethane, which is about five minutes, was not desirable for controlling the gelling time. This restricts the time of grouting application and penetration time for polyurethane grouts. Penetration time into both fine and medium sand was lowest with acrylate grouts. Colloidal silica was similar to that of acrylate, but a little bit higher. Polyurethane had the highest penetration time. Since the gel times of acrylate and colloidal silica were controllable up to hours, penetration length could be increased greater than the length of tested specimens. However, the penetration ability of polyurethane can be considered limited because of its highest penetration time and its lowest gel time. Therefore, in terms of penetration ability, acrylate grouts are the best candidates for grouting applications.
- Decreases in particle size and increases in fine content caused an increase in UCS values for acrylate and colloidal silica grouts. This trend was not the same for polyurethanes. Because of low penetration ability of polyurethane with fine sands, an opposite trend was observed. The higher fines content and the smaller grain size caused a decrease in the UCS values for polyurethane grouts.

- The failure strains were affected by chemical type. The failure strain of colloidal silica grouted sands was about 1%. The strain values were varied for polyurethane grouted sand from 2.41% to 14.57% without showing a correlation. Acrylate grouted sand failure strains showed a trend depending on their curing conditions. While the failure strain of air-cured samples was as low as 2.84%, the failure strain of wet-cured samples was as high as 10.95%. This relationship could be observed for only De Neef AC-400 acrylate grout because there were not enough samples of SealBoss 2400 Seal Gel. Hence, colloidal silica was brittle compared to acrylate and polyurethane, which had more ductile characteristics.
- An increase in the initial soil moisture of sand led to a decrease in the UCS of acrylate grouted sand. The same trend for UCS values could not be obtained with the colloidal silica and polyurethane grouted sands.
- UCS was influenced by the chemical grouting type. Polyurethane grouts showed the highest strength. On the other hand, lowest UCS values belonged to colloidal silica grouted medium sands. Unconfined strength of grouted sands decreased by 98% when the colloidal silica was used instead of polyurethane. Under wetting-drying conditions, different durability characteristics were explored. The use of polyurethane caused the highest durability, while the use of colloidal silica brought the lowest durability. Also, acrylate grouted sands showed weaker performance in comparison with polyurethanes. However, durability of acrylate grouted sands was sufficient to put them in a better class than the colloidal silica.
- Polyurethane showed the highest durability and strength with the tested sample length. However, it can be expected that the lowest penetration ability of polyurethane may cause underperformance, especially for the fine sands, when the longer penetration length is needed. In this case, penetration ability of acrylate and colloidal silica make them more applicable candidates for fine sands. Even though the strength character-

istics are similar for these two, lower durability and brittle failure characteristics of colloidal silica make a difference. Therefore, acrylates may be a better solution for fine sands.

APPENDIX A

GRAIN SIZE DISTRIBUTION

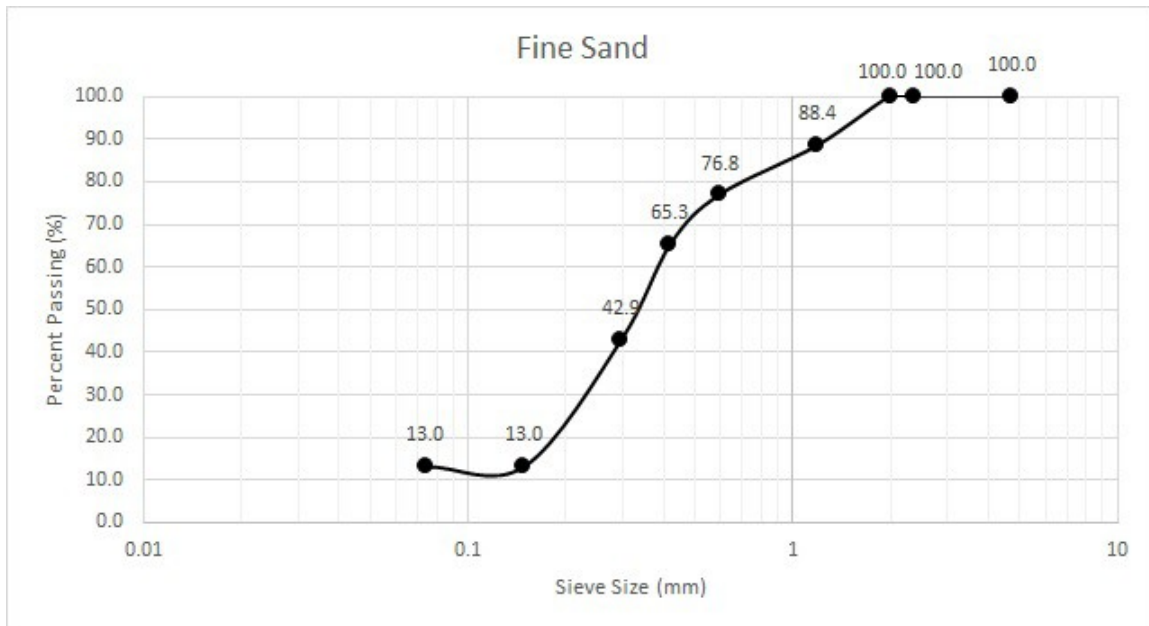


Figure A.1. Grain Distribution of Fine Sand

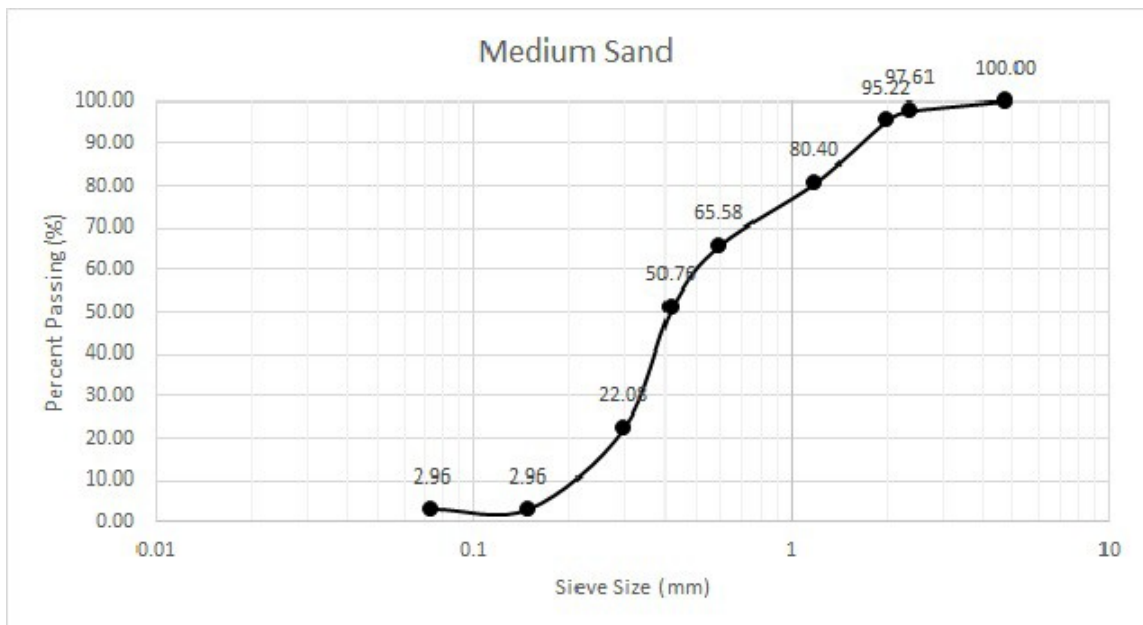


Figure A.2. Grain Distribution of Medium Sand

APPENDIX B

UCS TEST RESULTS

Specimen Label	Sand Code	Curing Condition	Type of Chemical
F1ADZ-1	Fine Sand - 1	Moist	Acrylate (De Neef)
F1ADZ-2	Fine Sand - 1	Moist	Acrylate (De Neef)
F1ADZ-3	Fine Sand - 1	Moist	Acrylate (De Neef)
F1ADW-1	Fine Sand - 1	Wet	Acrylate (De Neef)
F1ADW-4	Fine Sand - 1	Wet	Acrylate (De Neef)
F1ADW-2	Fine Sand - 1	Air	Acrylate (De Neef)
F1ADW-3	Fine Sand - 1	Air	Acrylate (De Neef)
F2ADZ-1	Fine Sand - 2	Moist	Acrylate (De Neef)
F2ADZ-2	Fine Sand - 2	Moist	Acrylate (De Neef)
F2ADZ-3	Fine Sand - 2	Moist	Acrylate (De Neef)
F2ADW-1	Fine Sand - 2	Wet	Acrylate (De Neef)
F2ADW3	Fine Sand - 2	Wet	Acrylate (De Neef)
F2ADW-2	Fine Sand - 2	Air	Acrylate (De Neef)
M1ADZ-1	Medium Sand - 1	Moist	Acrylate (De Neef)
M1ADZ-3	Medium Sand - 1	Moist	Acrylate (De Neef)
M1ADW-2	Medium Sand - 1	Wet	Acrylate (De Neef)
M1ADW-1	Medium Sand - 1	Air	Acrylate (De Neef)
M1ADW-3	Medium Sand - 1	Air	Acrylate (De Neef)
M1ADW-4	Medium Sand - 1	Air	Acrylate (De Neef)
M2ADZ-1	Medium Sand - 2	Moist	Acrylate (De Neef)
M2ADZ-2	Medium Sand - 2	Moist	Acrylate (De Neef)
M2ADZ-3	Medium Sand - 2	Moist	Acrylate (De Neef)
M2ADW-1	Medium Sand - 2	Wet	Acrylate (De Neef)
M2ADW-3	Medium Sand - 2	Wet	Acrylate (De Neef)
M2ADW-5	Medium Sand - 2	Air	Acrylate (De Neef)
F1ASZ-1	Fine Sand - 1	Moist	Acrylate (SealBoss)
M1ASZ-1	Medium Sand - 1	Moist	Acrylate (SealBoss)
M1ASZ-2	Medium Sand - 1	Moist	Acrylate (SealBoss)
M2ASZ-1	Medium Sand - 2	Moist	Acrylate (SealBoss)
M2ASZ-2	Medium Sand - 2	Moist	Acrylate (SealBoss)

Table B.1. Specimen Labels of Acrylate Grouted Sands

Specimen Label	Sand Code	Curing Condition	Type of Chemical
F1CZ-1	Fine Sand - 1	Moist	Colloidal Silica
F1CZ-2	Fine Sand - 1	Moist	Colloidal Silica
F1CZ-3	Fine Sand - 1	Moist	Colloidal Silica
F1CW-1	Fine Sand - 1	Wet	Colloidal Silica
F1CW-2	Fine Sand - 1	Air	Colloidal Silica
F1CW-3	Fine Sand - 1	Air	Colloidal Silica
F2CZ-3	Fine Sand - 2	Moist	Colloidal Silica
F2CZ-4	Fine Sand - 2	Moist	Colloidal Silica
F2CW-1	Fine Sand - 2	Wet	Colloidal Silica
F2CW3	Fine Sand - 2	Wet	Colloidal Silica
F2CW6	Fine Sand - 2	Wet	Colloidal Silica
F2CW-2	Fine Sand - 2	Air	Colloidal Silica
F2CW4	Fine Sand - 2	Air	Colloidal Silica
F2CW5	Fine Sand - 2	Air	Colloidal Silica
M1CZ-2	Medium Sand - 1	Moist	Colloidal Silica
M1CW-1	Medium Sand - 1	Wet	Colloidal Silica
M1CW-2	Medium Sand - 1	Air	Colloidal Silica
M2CZ-1	Medium Sand - 2	Moist	Colloidal Silica
M2CZ-2	Medium Sand - 2	Moist	Colloidal Silica
M2CW-4	Medium Sand - 2	Wet	Colloidal Silica
M2CW-1	Medium Sand - 2	Air	Colloidal Silica
M2CW-3	Medium Sand - 2	Air	Colloidal Silica
F1PZ-2	Fine Sand - 1	Moist	Polyurethane
F1PW-1	Fine Sand - 1	Wet	Polyurethane
F1PW-2	Fine Sand - 1	Air	Polyurethane
F2PZ-1	Fine Sand - 2	Moist	Polyurethane
F2PZ-2	Fine Sand - 2	Moist	Polyurethane
F2PW-1	Fine Sand - 2	Wet	Polyurethane
F2PW-2	Fine Sand - 2	Air	Polyurethane
M1PZ-1	Medium Sand - 1	Moist	Polyurethane
M1PZ-2	Medium Sand - 1	Moist	Polyurethane
M1PW-1	Medium Sand - 1	Wet	Polyurethane
M1PW-2	Medium Sand - 1	Air	Polyurethane
M2PZ-1	Medium Sand - 2	Moist	Polyurethane
M2PW-1	Medium Sand - 2	Wet	Polyurethane
M2PW-2	Medium Sand - 2	Air	Polyurethane

Table B.2. Specimen Labels of Colloidal Silica and Polyurethane Grouted Sands

Acrylate Gel (Seal Boss)						Acrylate Gel (De Neef)							
Sand	Curing	Sample Code	UCS (kPa)	Average UCS (kPa)	Strain (%)	Sand	Curing	Sample Code	UCS (kPa)	Average UCS (kPa)	Strain (%)		
Fine Sand-1	Humid	F1ASZ-1	723.08	723.08	9.72	Fine Sand-1	Humid	F1ADZ-1	304.07	301.44	5.99		
		F1ADZ-2	322.53					6.26					
		F1ADZ-3	277.72					7.23					
	Water	F1ADW-1	206.34	188.27	5.94								
		F1ADW-4	170.19		8.57								
	Air Dry	F1ADW-2	378.12	378.12	3.97								
	Medium Sand-1	Humid	F2ASZ-1	270.85	260.45		7.37	Medium Sand-1	Humid	F2ADZ-1	270.85	260.45	7.37
			F2ASZ-2	281.04						7.17			
			F2ASZ-3	229.45						6.35			
Water		F2ADW-1	176.79	186.14	8.76								
		F2ADW-3	195.49		7.94								
Air Dry		F2ADW-2	262.10	262.10	3.84								
Medium Sand-2		Humid	M1ASZ-1	460.45	446.85	13.84	Medium Sand-2		Humid	M1ADZ-1	200.62	209.14	6.06
			M1ASZ-2	433.24						11.38			
			M1ADZ-3	217.65						6.05			
	Water	M1ADW-2	108.25	108.25	10.95								
		M1ADW-1	385.62		288.29	2.84							
	Air Dry	M1ADW-3	255.90	4.32									
		M1ADW-4	223.34	4.26									
	Medium Sand-2	Humid	M2ASZ-1	444.06	375.72	14.11		Medium Sand-2	Humid	M2ADZ-1	168.24	157.34	5.16
			M2ASZ-2	307.38						14.34			
M2ADZ-2			150.89	4.95									
Water		M2ADZ-3	152.90	141.75	4.92								
		M2ADW-1	149.52		7.21								
Air Dry		M2ADW-3	133.97	172.53	9.78								
		M2ADW-5	172.53		4.77								

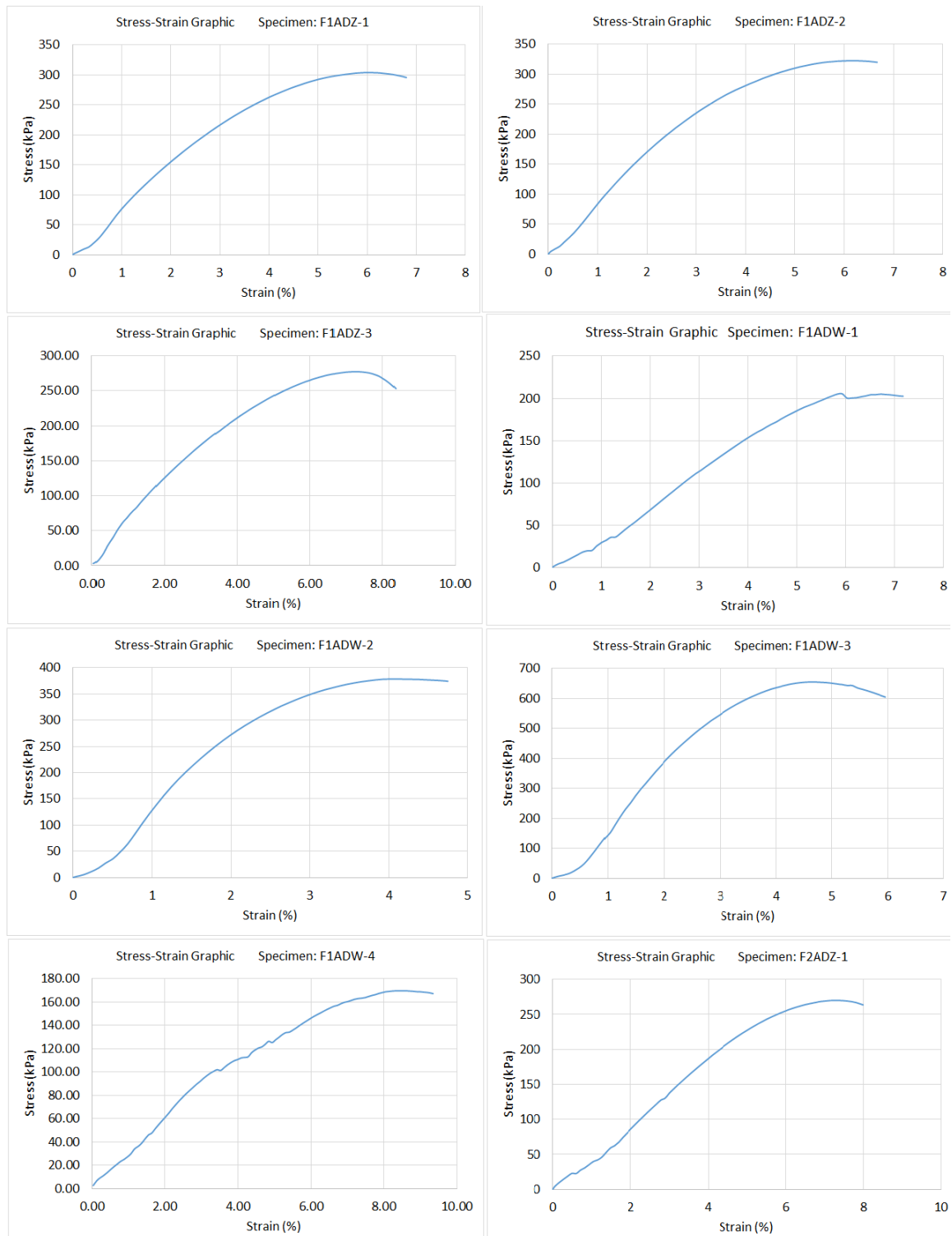
Conversion Factor: 6.89 kPa = 1 psi

Figure B.1. Mean UCS Values of Acrylate Grouted Sand

Colloidal Silica						Polyurethane							
Sand	Curing	Sample Code	UCS (kPa)	Average UCS (kPa)	Strain (%)	Sand	Curing	Sample Code	UCS (kPa)	Average UCS (kPa)	Strain (%)		
Fine Sand-1	Humid	F1CZ-1	336.90	451.07	0.57	Fine Sand-1	Humid	F1PZ-2	1714.41	1714.40	9.60		
		F1CZ-2	466.97		1.00								
		F1CZ-3	549.33		1.21								
	Water	F1CW-1	71.54	71.54	1.08		Water	F1PW-1	794.10	794.10	4.14		
		Air Dry	F1CW-2	484.03	479.62			0.47	Air Dry	F1PW-2	1439.07	1439.07	6.73
			F1CW-3	475.20				1.24					
Fine Sand-2	Humid	F2CZ-3	480.42	506.65	0.86	Fine Sand-2	Humid	F2PZ-1	774.23	777.69	4.73		
		F2CZ-4	532.88		0.77								
	Water	F2CW-1	118.51	156.37	0.71		Water	F2PW-1	1236.95	1236.95	8.63		
		F2CW3	212.10		0.37								
		F2CW6	138.50		0.89								
	Air Dry	F2CW-2	414.16	614.99	0.68		Air Dry	F2PW-2	944.69	944.69	3.71		
		F2CW4	631.55		1.19								
		F2CW5	799.27		1.05								
	Medium Sand-1	Humid			164.73			Medium Sand-1	Humid	M1PZ-1	3238.80	3117.22	5.19
M1CZ-2			164.73	0.85									
Water		M1CW-1	143.61	143.61	1.09	Water	M1PW-1		1048.90	1048.90	2.32		
Air Dry		M1CW-2	59.87	59.87	0.95	Air Dry	M1PW-2		3953.87	3953.87	4.37		
Medium Sand-2	Humid	M2CZ-1	73.07	67.32	0.73	Medium Sand-2	Humid	M2PZ-1	1777.99	1777.99	14.95		
		M2CZ-2	61.57		1.09								
	Water	M2CW-4	Could not be tested	zero strength	Could not be tested		Water	M2PW-1	2128.02	2128.02	14.57		
	Air D	M2CW-1	101.29	93.58	0.66		Air D	M2PW-2	2627.29	2627.29	4.57		
M2CW-3		85.86	0.90										

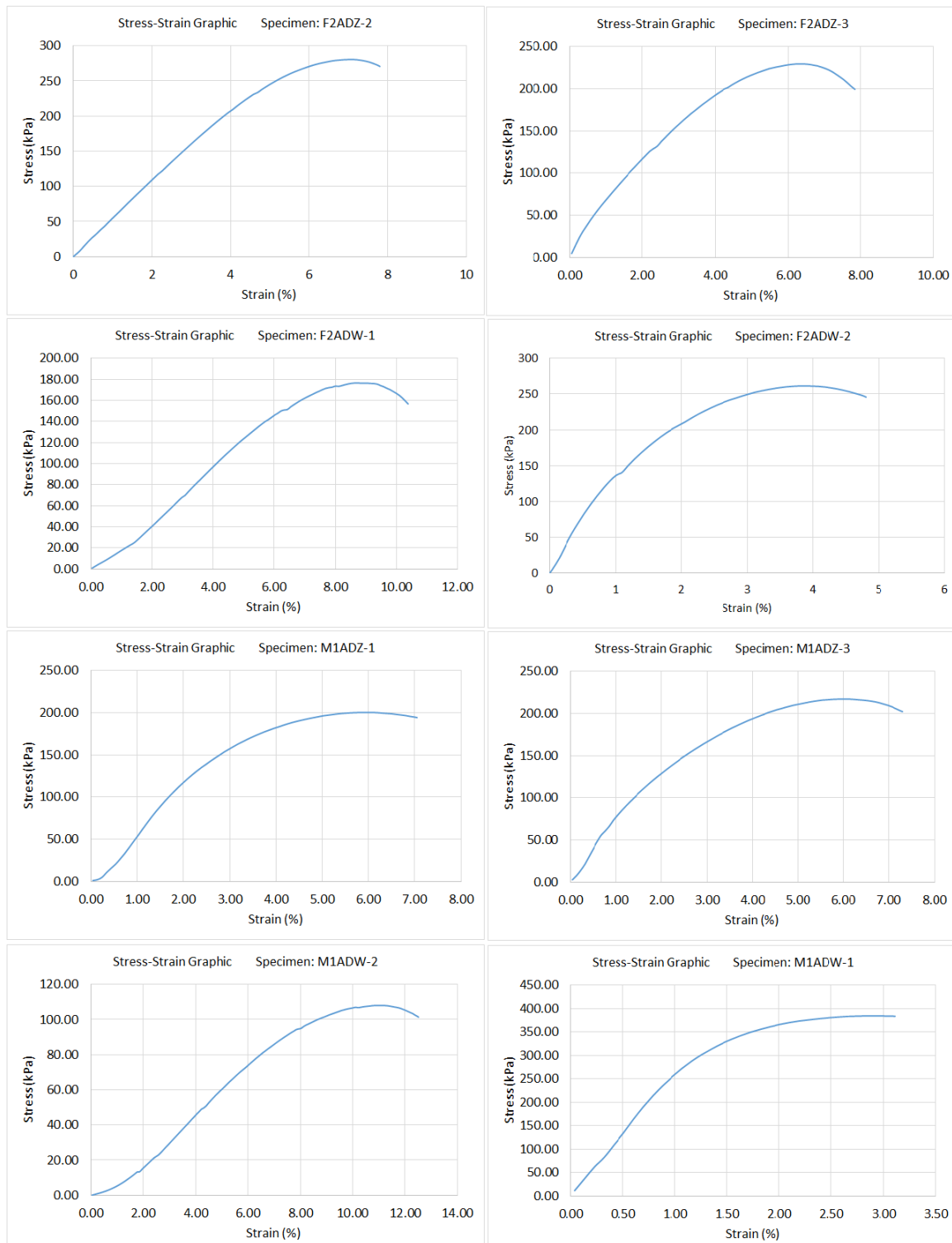
Conversion Factor: 6.89 kPa = 1 psi

Figure B.2. Mean UCS Values of Colloidal Silica and Polyurethane Grouted Sand



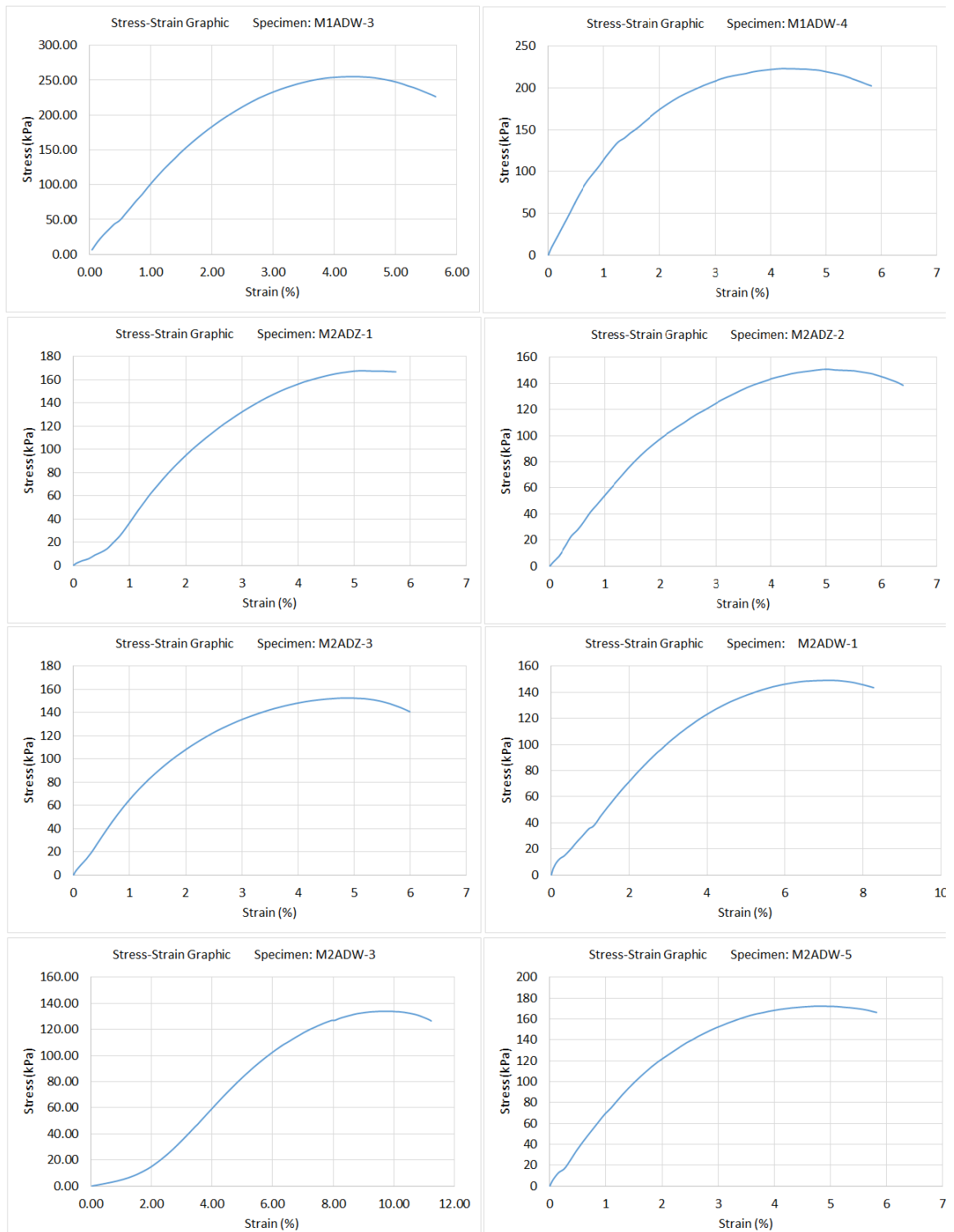
Conversion Factor: 6.89 kPa = 1 psi

Figure B.3. Stress-Strain Graphics of Acrylate Grouted Sand



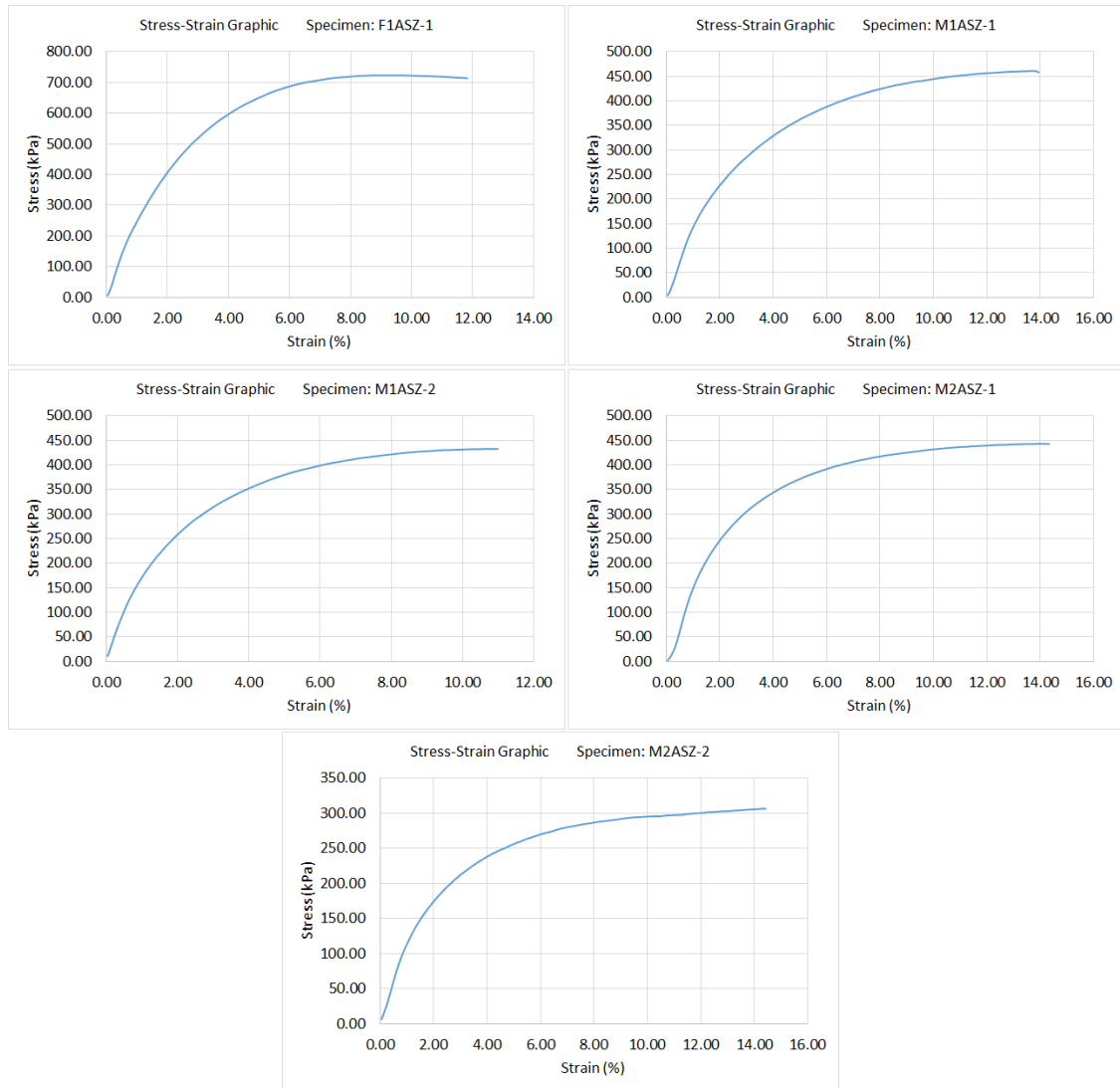
Conversion Factor: 6.89 kPa = 1 psi

Figure B.4. Stress-Strain Graphics of Acrylate Grouted Sand



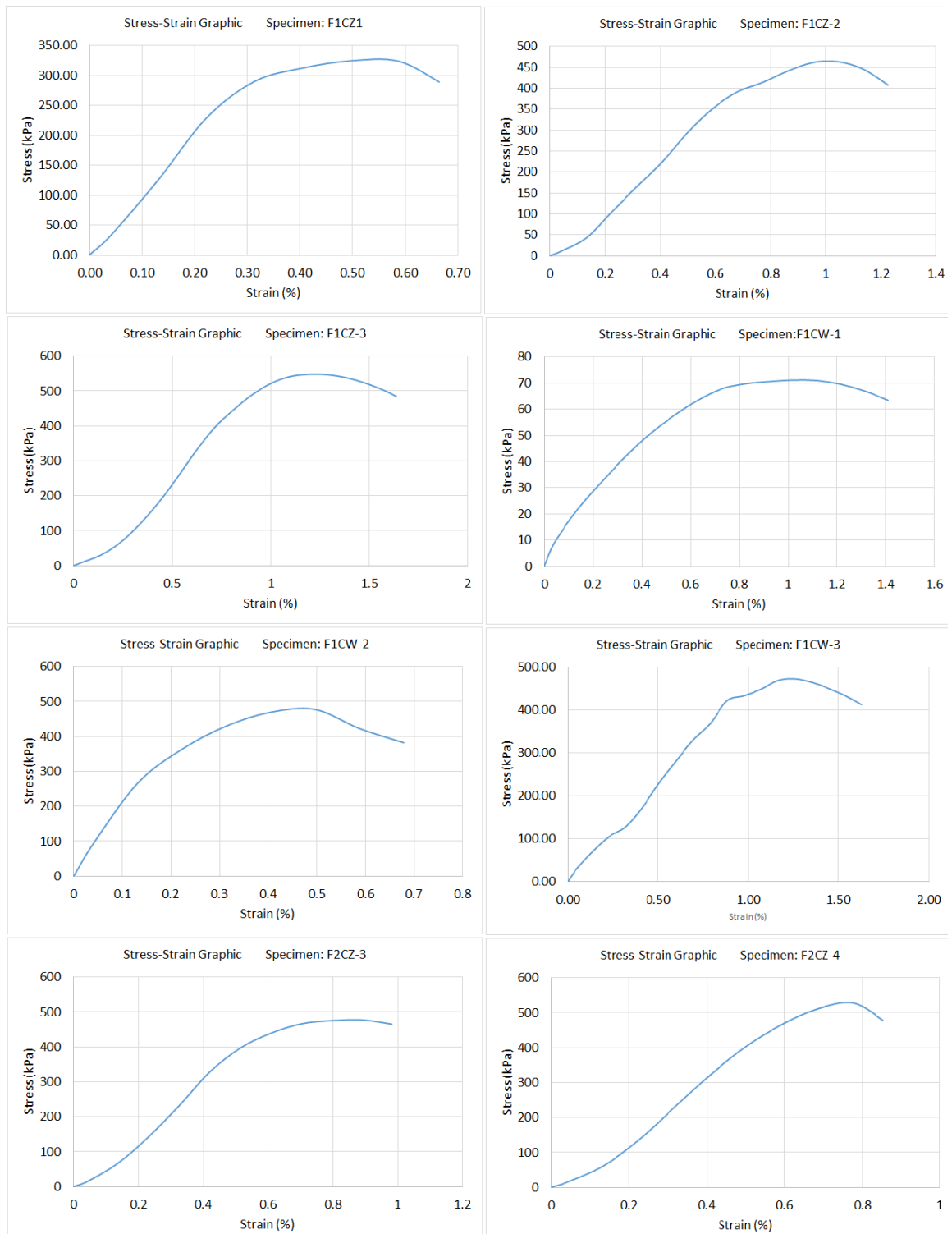
Conversion Factor: 6.89 kPa = 1 psi

Figure B.5. Stress-Strain Graphics of Acrylate Grouted Sand



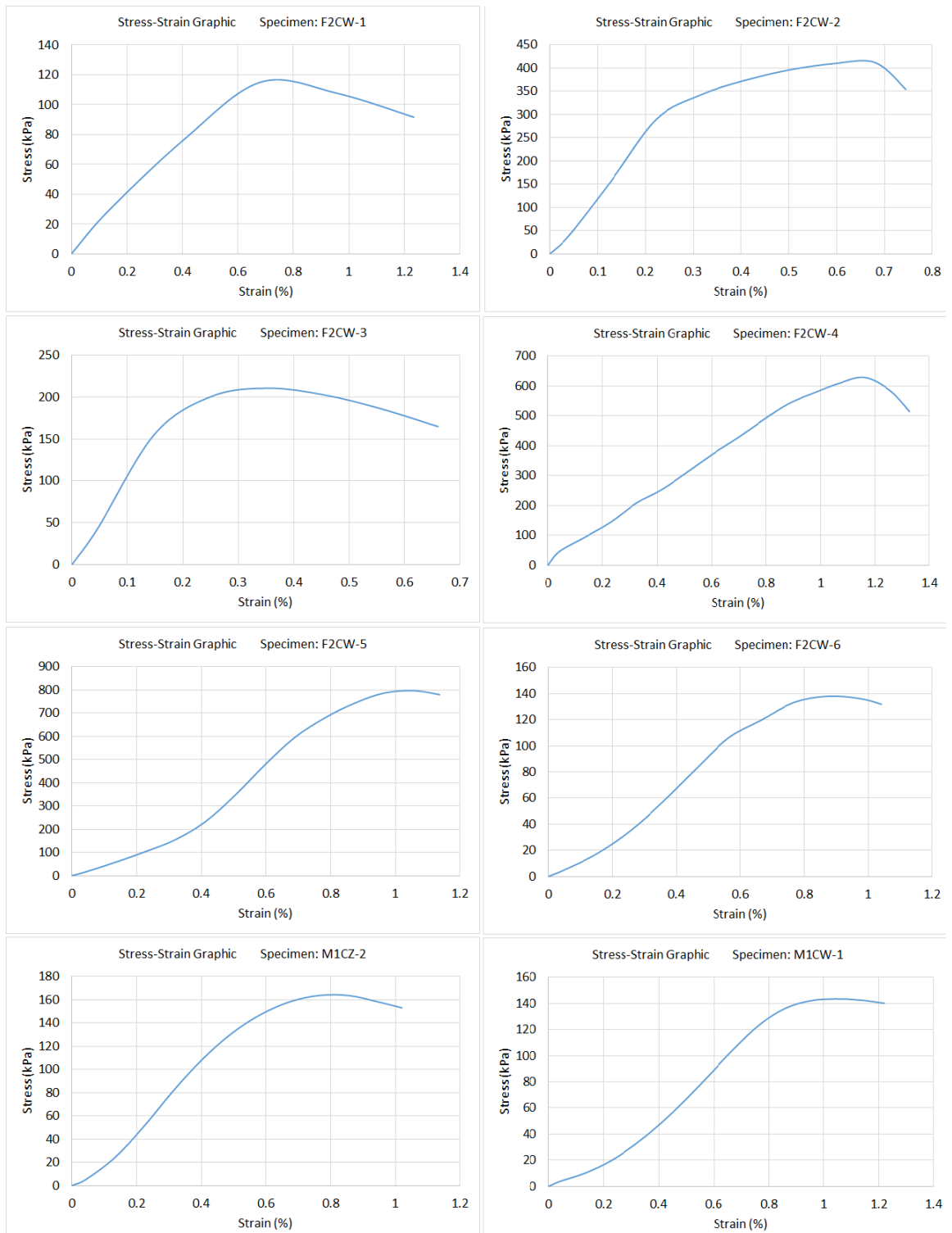
Conversion Factor: 6.89 kPa = 1 psi

Figure B.6. Stress-Strain Graphics of Acrylate Grouted Sand



Conversion Factor: 6.89 kPa = 1 psi

Figure B.7. Stress-Strain Graphics of Colloidal Silica Grouted Sand



Conversion Factor: 6.89 kPa = 1 psi

Figure B.8. Stress-Strain Graphics of Colloidal Silica Grouted Sand

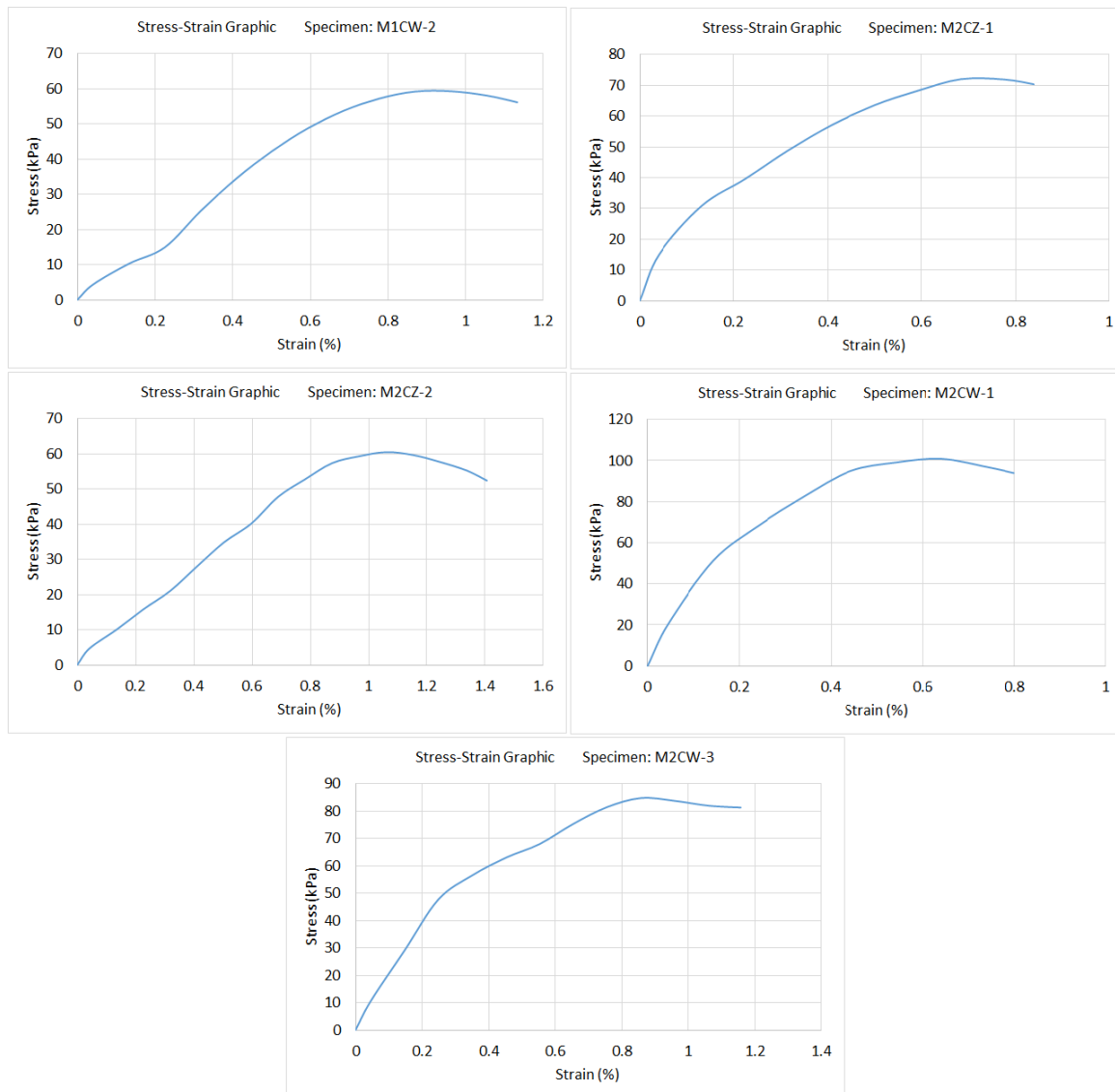
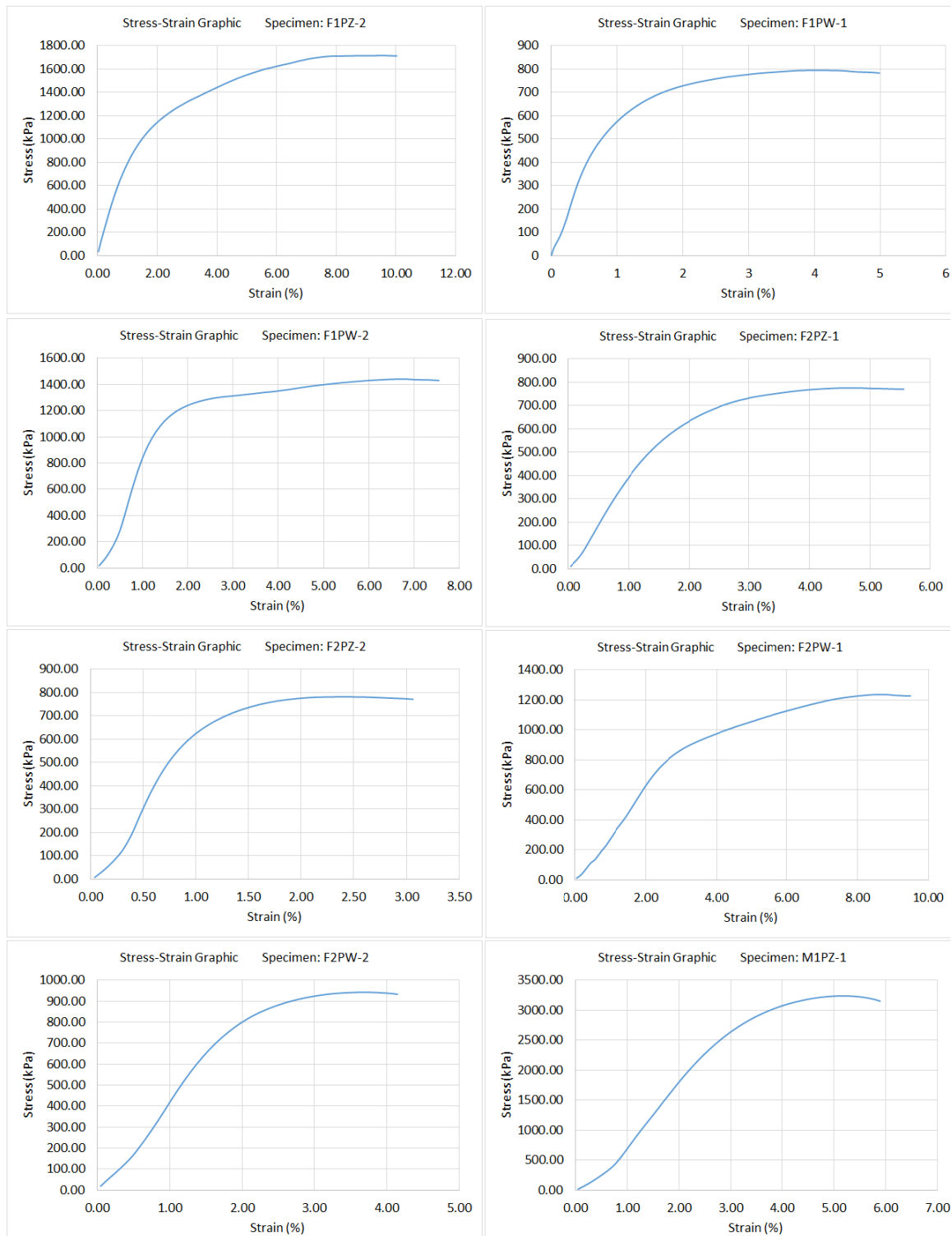
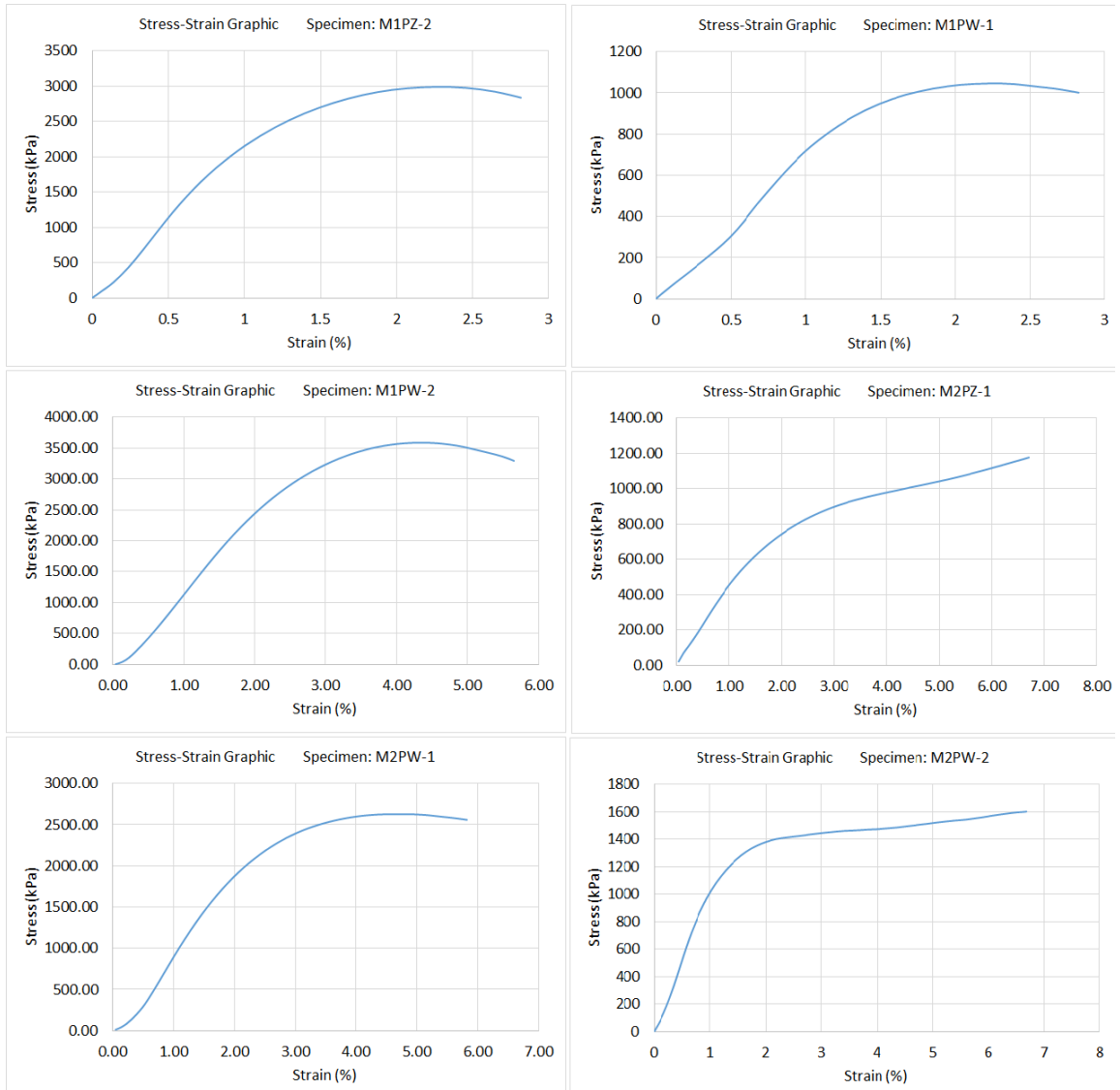


Figure B.9. Stress-Strain Graphics of Colloidal Silica Grouted Sand



Conversion Factor: 6.89 kPa = 1 psi

Figure B.10. Stress-Strain Graphics of Polyurethane Grouted Sand



Conversion Factor: 6.89 kPa = 1 psi

Figure B.11. Stress-Strain Graphics of Polyurethane Grouted Sand

APPENDIX C

SPECIFICATION DATA SHEETS OF CHEMICAL GROUTING MATERIALS

SIGMA-ALDRICH[®]sigma-aldrich.com

3050 Spruce Street, Saint Louis, MO 63103, USA

Website: www.sigmaaldrich.comEmail USA: techserv@sial.comOutside USA: eurtechserv@sial.com

Product Specification

Product Name:
LUDOX[®] SM colloidal silica - 30 wt. % suspension in H₂O

Product Number: 420794

MDL: MFCD00011232
Formula: O₂Si
Formula Weight: 60.08 g/mol



TEST	Specification
Appearance (Color)	Colorless or White
Appearance (Form)	Liquid
ICP Major Analysis	Confirmed
Confirms Silicon Component	
Specific Gravity	1.209 - 1.227
at 80 Degrees Fahrenheit	
pH	9.7 - 10.3
at 25 Degrees Celsius	
Viscosity	4.8 - 6.8 cps
at 25 Degrees Celsius	
Silica	29.0 - 31.0 %
Ratio of SiO ₂ /Na ₂ O	45 - 56
Size	320 - 400
Surface Area (m ² /g)	
Sulfate (as Na ₂ SO ₄)	≤ 0.06 %
Transmission	≥ 74.0 %
Registered Trademark	Confirmed
LUDOX is a registered trademark of W.R. Grace & Co.-Conn.	

Specification: PRD.1.ZQ5.10000035591

Sigma-Aldrich warrants, that at the time of the quality release or subsequent retest date this product conformed to the information contained in this publication. The current Specification sheet may be available at Sigma-Aldrich.com. For further inquiries, please contact Technical Service. Purchaser must determine the suitability of the product for its particular use. See reverse side of invoice or packing slip for additional terms and conditions of sale.

1 of 1

Figure C.1. Specification Data Sheet of Colloidal Silica

SealBoss®

2400 SealGel SLV Acrylate

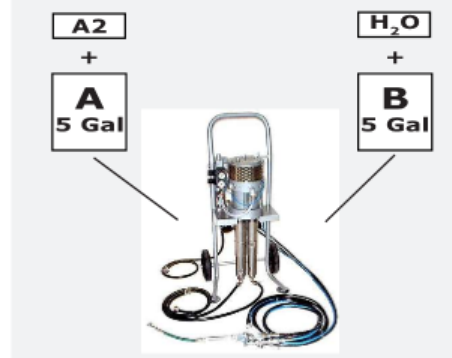


Product Data Sheet

SealBoss® 2400 SLV Acrylate Reaction times (approx.) as function of component B at various application temperatures (component/material) These gel times serve as a basis for the gel adjustment on site. They must be adapted to the actual local conditions according to gel quantity, water content, flow behavior and nature of the building structure.

B in ~ 20l / 5 gal water	Viscosity		Reaction time		
	Increase				
	22°C 70°F	10°C 50°F	22°C 70°F	10°C 50°F	
120g ~ 0.5%	120	330	90	480	sec
245g ~ 1.0%	60	180	105	300	sec
490g ~ 2.0%	40	90	60	180	sec
740g ~ 3.0%	30	60	50	120	sec
1000g ~ 5.0%	25	55	35	105	sec
1950g ~ 7.5%	17	40	25	75	sec

Combined Batch Size Per Kit 10 Gal



Technical Data

Type of material	2-comp. polyacrylate gel with (A2) Accelerator	
Density (20°C)	Comp. A / A2 A1: approx. 1.2 g/cm ³ A2: approx. 0.95 g/cm ³	Comp. B approx. 1.0 g/cm ³ (dissolved in water)
Color	A1: Amber A2: Colorless	Colorless
Viscosity	A1: approx. 25 cps A2: approx. 25 cps	Approx. 1 cps
Viscosity of mixture	Approx. 5-7 cps	
Mixing ratio	A1:A2 20:1 parts by weight A:B solution 1:1 parts by volume	B:water Approx. 5% solution
Reaction time (70°F/22°C)	Typical 20-40 sec, approx. depending on mixing ratio	
Application temperature	> 40°F or 5°C	
Application	2-comp. pump SealBoss® IP2C Gel Injection Pump	
Storage	At 40-85°F, 5-25°C in original, sealed containers, moisture & light protected, 1 yr shelf life	
Packaging	Comp. A1: 4.7 gal, Comp A2: 0.3 gal, Comp. B: 1 kg	
Typical Batch Size	Comp A1+ A2 = 5 gal, Comp. B + Water = 5 gal, total batch size per kit 10 gal	



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Revised 201705

SealBoss Corp. USA info@sealboss.com

ph. 877-932-2293 intl. 1+ 714-662-4445

SealBoss® 2400 SealGel SLV Acrylate

Figure C.2. Specification Data Sheet of Seal Gel 2400

De Neef® AC-400®

Acrylate Chemical Grout Resin

Product Description

AC-400 Chemical Grout is an acrylamide free acrylate monomer system sealant designed, for water control during tunneling operations, for curtain grouting, and for excavatable soil consolidation in situations where low tensile and compressive strengths can be tolerated. AC-400 can also be used for controlling infiltration in mainline and lateral sewer joints.

Packaging & Handling

AC-400 is used with SP-200 (sodium persulfate) and TE-300 (triethanolamine). Available in 5 gallon drums (50 lbs) Sold as a kit of 3 x 5 gallon drums (150 lbs total) with 1 gallon (10 lbs) TE-300 and 10 lbs SP-200.

WARNINGS:

- Do not let SP-200 and TE-300 come into contact with each other prior to field mixing. The reaction is exothermic (heat producing) and may cause fire.
- Store SP-200 and TE-300 separated from each other, at 40°F-80°F.
- TE-300 and SP-200 are incompatible with aluminum. Do not use aluminum equipment in the presence of TE-300 and SP-200.
- Prolonged exposure to U.V., sunlight and elevated temperatures above 85°F, will cause solidification of the product.

Applications

- Water control in tunneling
- Curtain grouting
- Soil support for excavation
- Mainline and lateral sewer grouting

Product Advantages

- Acrylamide free
- Pumps without modification to existing grouting equipment
- Extremely low viscosity grout (1-3 cPs)
- Very low permeability (5×10^{-9} cm/sec)
- Provided in liquid form (40% solids)
- No dust toxicity hazard
- Not flammable or explosive

Properties

AC-400 RESIN	
Appearance	Straw yellow liquid
Density	9.8 lbs/gal
Percent solids	39-41%
Specific Gravity	1.2
Boiling Point	200°F (93°C)
Solubility in water	100%
Toxicity	Very low toxicity (no certification program required)
Acute Oral Toxicity	LD ₅₀ 5000 mg/kg
AC-400 SOLUTION	
Viscosity	1-3 cps
Density	8.6 lbs/gal (1.04 mg/ml)
pH	6.5-7.5
Stability	3 days catalyzed
AC-400 CURED	
Appearance: White, flexible gel	
Solubility: Insoluble in water, kerosene, gasoline. Gel swells slightly in presence of water	
Permeability: Substantially impermeable to water (5×10^{-9} cm/sec) Stable in 100% humidity. Can dehydrate in dry conditions	
Chemical Resistance: Resistant against bacteria, fungi, and chemicals found in sewer systems	

Note: The data shown above reflects typical results based on laboratory testing under controlled conditions. Reasonable variations from the data shown above may result.

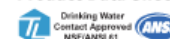
Figure C.3. Specification Data Sheet of De Neef AC-400

SealBoss®

1510 WaterStopFoil & 15X Accelerator



Product Data Sheet



Technical Properties	1510 WaterStopFoil	15X Accelerator
Appearance	Amber	Clear
Solids	100%	100%
Density, lb/gal - g/ml	1.12	0.93
Boiling Point, °C / °F	205°C / 400°F	170°C / 338°F
Flash Point, °C / °F	180°C / 356°F	125°C / 225°F
Viscosity, cps	160-250	20
Mixing Ratio	50-10 parts	1part
by Volume		
(2%-10% accelerator)		
Solubility in Water	not	
Packaging	1 gal 5 gal 55 gal	0.1 gal 0.5 gal
Storage / Shelf Life	Unopened Containers Only at 15-30°C / 58-85°F in dry, sun free indoors 2 years - 5 gal / 55 gal 1 year - 1 gal units	Unopened Containers Only at 15-30°C / 58-85°F in dry, sun free indoors 2 years
Reaction		
Induction Time, 20°C / 68°F	30 sec (10% 15X added)	
Gel time, 20°C / 68°F	70 sec (10% 15xs added)	
Induction Time, 20°C / 68°F	15 sec (15% 15X added)	
Gel time, 20°C / 68°F	50 sec (15% 15xs added)	
Properties Cured		
Physical properties may vary based on water & accelerator ratios & conditions during reaction		
Expansion, %	600-4000 (6-40 Times) depending on Accelerator ratio & counter pressure	
Elongation, %	10-20 ASTM D 638	
Shrinkage, %	<4% ASTM D1042	
Tensile Strength	65 psi ASTM D 638 >100 psi (>2% Accelerator, product reacted under pressure) 1550 psi	
Strength (Sand Filled)		
Corrosiveness	Non-Corrosive	
Appearance	Yellow-White Polyurethane Foam	
Toxicity	MDI Based, Good Resistance to Chemicals Resistant to Most Organic Solvents, Mild Acids, Alkali and Micro Organisms	



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SealBoss® 1510 WaterStopFoil & 15X Accelerator

Figure C.4. Specification Data Sheet of Polyurethane

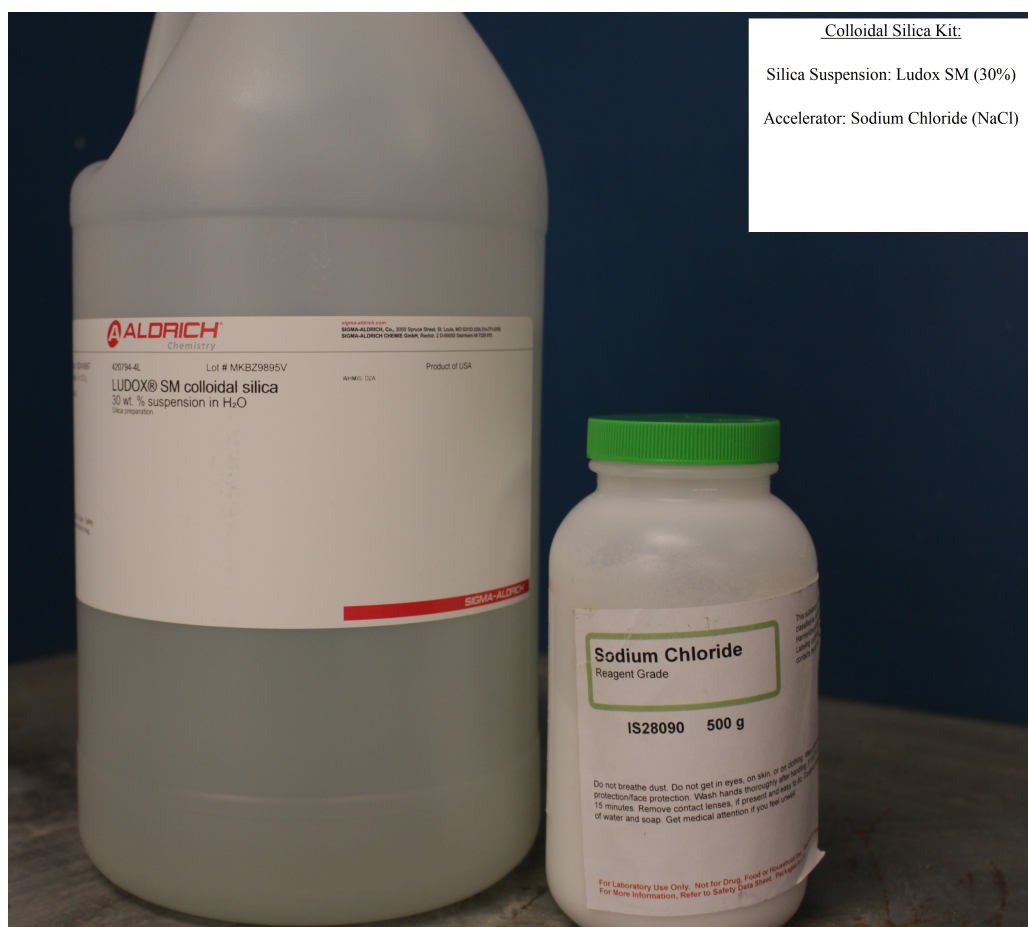


Figure C.5. Colloidal Silica Kit



Figure C.6. Acrylate Kit of Seal Boss



Figure C.7. Acrylate Kit of De Neef



Figure C.8. Polyurethane Kit

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