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# Effect of Surface Modifying Biopolymers on Sand Cohesion

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# **EFFECT OF SURFACE MODIFYING BIOPOLYMERS ON SAND COHESION**

by

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Submitted in partial fulfillment of the requirements

for the honors program

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## **ABSTRACT**

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Coastal erosion is a substantial problem in the United States and throughout the world. A novel approach to mitigating this problem is through the application of surface-modifying biopolymers to sand on beaches. Field research conducted by Dr. Amine Dahmani has shown that these organic complexes can coat granular sediments and increase sediment cohesion, thereby decreasing the erodability of the sediment. The goal of this thesis is to quantify the impact of proprietary surface-modifying biopolymer formulations on sand cohesion in order to better engineer this innovative solution for sand retention and potentially contaminated sediment sand cap stabilization. The impact of the biopolymer treatment on sand cohesion was evaluated with the use of the direct shear test (ASTM D3080). Testing was performed on both untreated control sand samples and sand samples treated with various dosages of biopolymer. Several variations of the testing method were evaluated in order to develop an appropriate testing protocol. The results indicate that treating sand with biopolymers can significantly increase sand cohesion. In addition, it was determined that this increased cohesion is directly related to the concentration of biopolymer.

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## 1. INTRODUCTION

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### 1.1 Coastal Erosion

Coastal erosion is a substantial problem in the United States and around the world. In the United States alone, over 80,000 acres of coastal wetlands are lost each year (Dahl & Stedman, 2013). Coastal erosion is caused by the action of waves and currents removing sand from the shoreline and depositing that sand farther away from the coast. Large storms, flooding, and human activities all exacerbate this type of erosion (NOAA, 2016). In particular, the damming of rivers disrupts the natural process of deposition by preventing sediment from being transferred from inland waterways to the coast (McCully, 2001). Coastal erosion is an especially expensive problem in the United States. Each year, coastal erosion causes over \$500 million in coastal property loss. On top of this, the Federal Government spends approximately \$150 million annually on various coastal erosion control measures (NOAA, 2013). Mitigating erosion is therefore an important and relevant engineering problem.

Physically, sediment's resistance to this type of erosion can be quantified by the Shields' parameter,  $\theta$  (Shields, 1936). This parameter represents the ratio of fluid bottom shear stress to the immersed weight of the sediment grain and is expressed with the following equation:

$$\theta = \frac{\tau}{\rho(s - 1)gD}$$

where:

$\tau$  = fluid bottom shear stress

$\rho$  = fluid density

$s$  = relative density of sediment compared to water

$g$  = acceleration due to gravity

$D$  = diameter of sediment grains

Once the critical threshold value of  $\theta$  for a particular sediment is exceeded, that sediment can be mobilized by the acting fluid motion. For cohesive sediments, like clays, threshold  $\theta$  values are typically much larger than for non-cohesive sediments such as sand (National Research Council, 2007). Therefore, higher fluid shear stresses are required to initiate sediment erosion in cohesive sediments.

## **1.2 Typical Erosion Control Measures**

There are three commonly used approaches to mitigating the effects of coastal erosion: structural solutions, vegetative solutions, and beach nourishment methods (National Research Council, 2007). Structural approaches to erosion mitigation include the construction of seawalls, groins, revetments, bulkheads, and breakwaters. These structures attempt to serve as barriers to the ocean's erosive forces. Sea grasses and similar vegetation are often planted along shorelines with the goal of improving sand stability and lessening wave energy. Finally, beach nourishment is the practice of taking sand from inland sources and depositing that sand on beaches. This process simulates and speeds up the natural sediment deposition process.

## **1.3 Soil/Sediment Stabilization via Biopolymers**

In addition to the methods described above, recent research has shown that natural biopolymers can decrease soil erodability and increase soil stability. In nature, extracellular polymeric substances (EPS) secreted from microorganisms can coat sediment and increase the cohesive properties of the sediment. These mucilage-like secretions consist of proteins and carbohydrates that form biofilms on sediment grains. These biofilms can bind individual grains together and thereby improve sediment stability (Yallop et al., 1994; Le Hir et al., 2007). In

addition, Widdows et al. (2006) showed that there is a clear correlation between EPS secretions and increased critical erosion velocity. Similarly, Black et al. (2001) showed that treating sand with xanthan gum (an EPS produced by *Xanthomonas campestris*) increased the critical shear stress needed to suspend the sand grains.

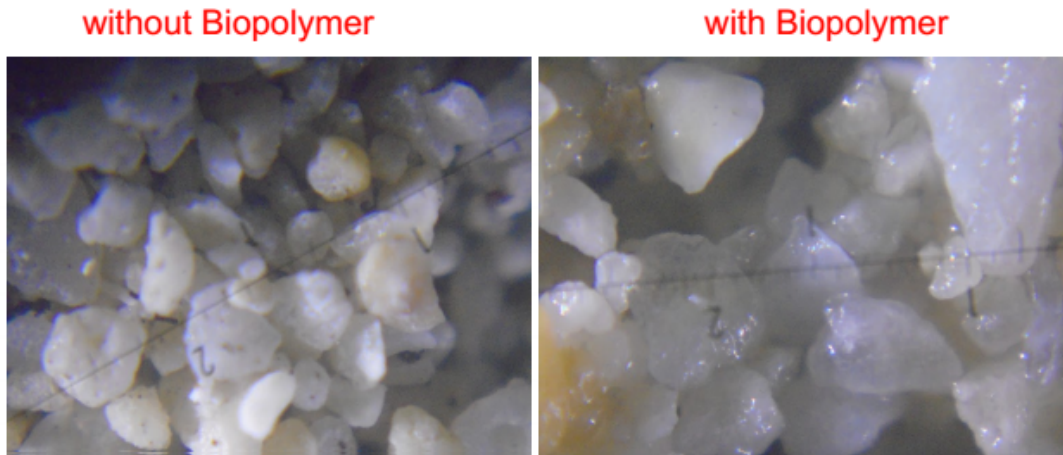
Studies have also been conducted to evaluate the effect of biopolymers on soil cohesive strength. Banagan et al. (2010) demonstrated that the biofilm produced by *Flavobacterium johnsoniae* significantly increased the measured shear strength of saturated sand thereby increasing sand stability. Ayeldeen and Negm (2014) used direct shear testing to show that xanthan gum treatments increase the cohesive strength of sand. In addition, they found that sand cohesion was directly related to the concentration of biopolymer treatment. Khatami and O’Kelly (2012) used triaxial compression testing to show that agar treatments can considerably improve the shear strength of sand. Finally, Guo (2014) used unconfined compression and direct shear tests to evaluate the effect of different biopolymers on both loess and sand strength.

#### **1.4 Proprietary Protein-Polysaccharide Biopolymers**

Dr. Amine Dahmani has developed proprietary protein-polysaccharide surface-modifying biopolymer formulations that can be used to improve sediment stability and minimize the erodability of beach sand. These eco-friendly and biodegradable formulations are composed of vegetable protein extracts and polysaccharides that are designed based on the characteristics of site sand and ocean water characteristics. The biopolymers simulate EPS secretions and coat sand grains during application. These coatings imitate the biofilms previously described and increase sand cohesion. Figure 1.1 shows the difference between untreated and biopolymer treated sand grains. Preliminary testing conducted in Mexico demonstrated that biopolymer



treated beaches retained greater volumes of sand over a three-month period compared with geotube-protected beaches (Dahmani, 2016). These results indicate that these proprietary surface-modifying biopolymers show promise at reducing beach erosion.



**Figure 1.1** (a) untreated sand; (b) biopolymer treated sand (from Dahmani)

### **1.5 Statement of Problem/Proposed Project**

There are currently no laboratory testing results documenting the effect of Dr. Dahmani's biopolymer treatments on sand cohesion. This thesis attempts to answer three main questions. First, can the effect of treating sand with these proprietary biopolymers be quantified through laboratory testing? If yes, how does biopolymer treatment dosage impact sand cohesion? Lastly, what is the effect of biopolymer treatment formulation on sand cohesion?

To answer these questions, various methods of test sample preparation were explored to develop an appropriate protocol to evaluate biopolymer-induced cohesion. Direct shear testing was used to determine the cohesion of both treated and untreated sand samples. Finally, the results obtained for two formulations and dosages were compared. The testing methods developed in this thesis may be used in the future to screen and optimize formulation/dosage combinations for site-specific sands before pilot-scale tests are developed in the field.

## 2. METHODOLOGY

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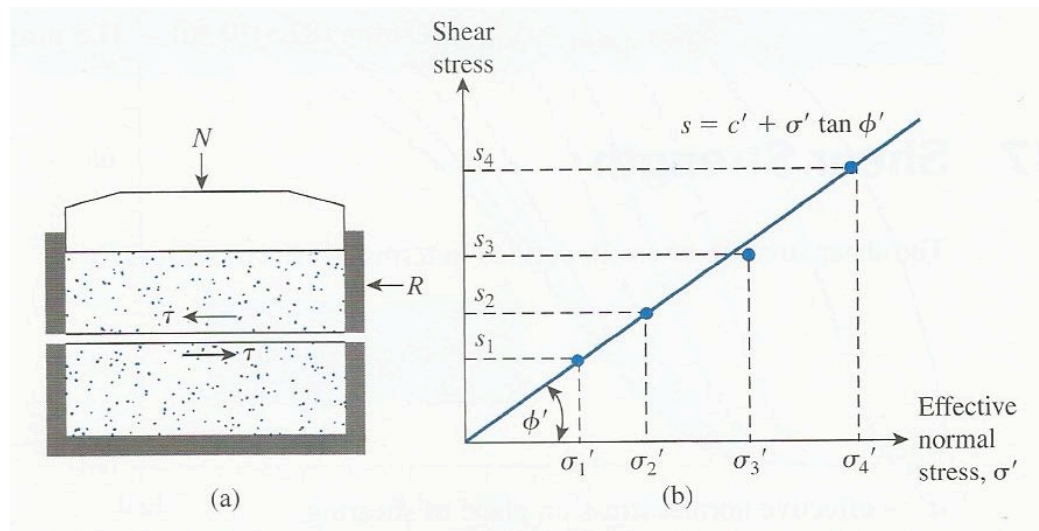
### 2.1 Direct Shear Test

The direct shear test is a standardized testing method (ASTM D3080) that is used to create the Mohr-Coulomb failure envelope for a given soil. From this failure envelope, soil friction angle and cohesion are derived. Friction angle and cohesion are strength parameters that can be used to determine a soil's shear strength at a given normal effective stress. To conduct a direct shear test, a soil sample is placed in the direct shear box. The shear box consists of two separate horizontal halves with an opening to hold the soil sample (Figure 2.2a). The shear box is then placed in the direct shear apparatus and a normal stress is applied to the top of the soil sample. Figure 2.1 shows the direct shear apparatus used to complete the testing described in this thesis.



**Figure 2.1** Direct shear testing apparatus

A horizontal displacement is then applied to the top half of the shear box while the bottom half is held stationary. This induces a horizontal shearing action in the soil sample. Test gauges record horizontal displacement, shear load, and vertical displacement. The soil sample is sheared until a maximum shear load is reached (i.e. the maximum point on a shear load vs. horizontal displacement curve). This maximum load is recorded and converted to shear stress. This testing procedure is repeated at different normal stresses. The resulting maximum shear stresses are then plotted versus their corresponding normal stresses. A linear regression is then performed to create the Mohr-Coulomb failure envelope (Figure 2.2b).



**Figure 2.2** (a) Diagram of typical direct shear box with applied forces; (b) plot of typical test results (Mohr-Coulomb failure envelope) (from Das, 2015)

Soil shear strength has two components: frictional strength and cohesive strength. Soil frictional strength is due to the friction forces generated between soil particles. Rather than using the typical coefficient of friction, engineers instead quantify soil frictional strength by using a parameter called angle of internal friction (or friction angle). Intuitively, a higher friction angle means higher frictional strength. In sands, friction angle is related to grain shape and level of compaction. Angular sands will have higher friction angles compared to round sands. Similarly,

a denser sand will have a higher friction angle than a loose sand. Soil cohesive strength results from bonding forces between soil particles. Clays typically have high values of cohesion, while engineers consider sand to have zero cohesive strength (Coduto et al., 2011).

The Mohr-Coulomb failure criterion is defined as follows:

$$s = c' + \sigma' * \tan (\phi')$$

where:

$\sigma'$  = effective normal stress

$c'$  = soil cohesion

$\phi'$  = soil friction angle

$s$  = soil shear strength

Graphically, the y-intercept of the plotted Mohr-Coulomb failure envelope is equivalent to soil cohesion. In addition, the inverse tangent of the slope of the failure envelope's line of best fit represents soil friction angle.

All direct shear testing conducted for this thesis was performed according to the ASTM D3080 standard. That standard should be referenced for detailed testing procedures. A horizontal displacement rate of 0.02 in/min was used for all tests. Each series of direct shear tests was conducted using the following normal stresses: 3.47 psi, 6.94 psi, 13.89 psi, 20.83 psi, and 27.78 psi. Finally, horizontal displacement, vertical displacement, and shear load data were collected at an interval of two seconds for each test.

## **2.2 Sieve Analysis**

A sieve analysis was performed on the selected test sand to determine the sand's grain size distribution. The resulting grain size distribution was then used to classify the sand

according to the Unified Soil Classification System. The following sieve sizes were used to conduct the analysis: No. 16, No. 20, No. 30, No. 50, No. 100, and No. 200 (see Figure 2.3 below).



**Figure 2.3** Sieve assembly

First, the mass of each empty sieve (and the pan) was determined. Next, the sieves were assembled together as shown in Figure 2.3. The sand sample was weighed and its mass was recorded. Approximately 500 g. of sand was used. The sand was then poured into the top sieve and the sieve assembly was placed into a sieve shaker machine. The sieves were shaken for 15 minutes. After this, each sieve was reweighed and the new masses were recorded. The mass of sand retained on each sieve was computed and then finally the percentage of sand passing each sieve was determined. The resulting grain size distribution curve is shown in section 3.1 of this thesis. Based on this curve, the sand's coefficient of uniformity  $C_u$  and coefficient of curvature  $C_c$  were determined using the following equations:

$$C_u = \frac{D_{60}}{D_{10}}$$

$$C_c = \frac{(D_{30})^2}{D_{60} * D_{10}}$$

where:

$D_{10}$  = grain diameter at 10% passing

$D_{30}$  = grain diameter at 30% passing

$D_{60}$  = grain diameter at 60% passing

These constants are used to determine whether a soil is well-graded or poorly-graded.

Typically well-graded soils have higher  $C_u$  values while poorly-graded soils have lower values.

In addition, a well-graded soil will have a  $C_c$  value between 1-3 (Coduto et al., 2011).

### 2.3 Sample Preparation Overview

A significant challenge with this project was developing and selecting an adequate test sample preparation method. After evaluating several preparation procedures, it was determined that the method of sample preparation can greatly impact the results and reliability of direct shear tests. Methods A through D described in sections 2.4-2.7 of this thesis represent initial efforts to create an effective and consistent testing method to evaluate the effect of biopolymers on sand cohesion. The results of these methods were not verified through repeated testing and, therefore, are not the main focus of this thesis. Rather, they are included to show the process that led to the development of test Method E. Method E was determined to be the optimal sample preparation procedure. Furthermore, direct shear tests were conducted in triplicate to verify the reproducibility of the Method E procedure.

## 2.4 Sample Preparation Method A

Method A was the initial sample preparation approach. The *SEDI* biopolymer formulation was evaluated using this method. First, biopolymer solutions were prepared. Two solution concentrations were assessed: 2g/L and 4g/L. The 2g/L solution was prepared by adding 0.3g of biopolymer powder to 150mL of tap water. Similarly, the 4g/L solution was prepared by adding 0.6g of biopolymer powder to 150mL of tap water. Next, the biopolymer/water mixture was stirred to ensure adequate mixing. The biopolymer solution was then added to 150g of air-dried test sand. The solution/sand mixture was then stirred to ensure that all sand grains were adequately coated. After this, the supernatant liquid was removed to leave the treated sand in a saturated condition. Next, approximately 30g of the sand was removed and placed in a small tin to determine the moisture content of the sand. Moisture content was determined by weighing this initial wet sample of sand, drying the sample overnight at 100°C, reweighing the dry sand, and then calculating the difference in wet and dry masses. This moisture content was used for verifying sample uniformity and determining sample dry unit weight.

The direct shear box was assembled together as per the testing device manufacturer's instructions. Two porous stones were saturated using tap water and one porous stone was then placed in the bottom of the direct shear box assembly. Next, approximately 130g of the treated sand were placed into the direct shear box assembly. The actual mass of the sample was measured to the nearest 0.01g. The treated sand was placed using three equal lifts and each lift was compacted using a hand tamper to ensure adequate compaction and uniform density. Figure 2.4 shows the difference between an uncompacted lift versus a compacted lift.





**Figure 2.4** Method A sample preparation: (a) uncompacted lift of sand; (b) compacted lift

The diameter and thickness of the sample was measured using a caliper to the nearest 0.01 in. The diameter of each sample was 2.50 in. and the approximate thickness of each sample was 0.84 in. Sample dry unit weights were determined using computed sample volumes and measured sample moisture contents. Next, the other porous stone was placed on top of the compacted sample and then the normal load cap was placed on top of the porous stone. The fully assembled direct shear box was inserted into the direct shear testing machine as per the manufacturer's instructions.

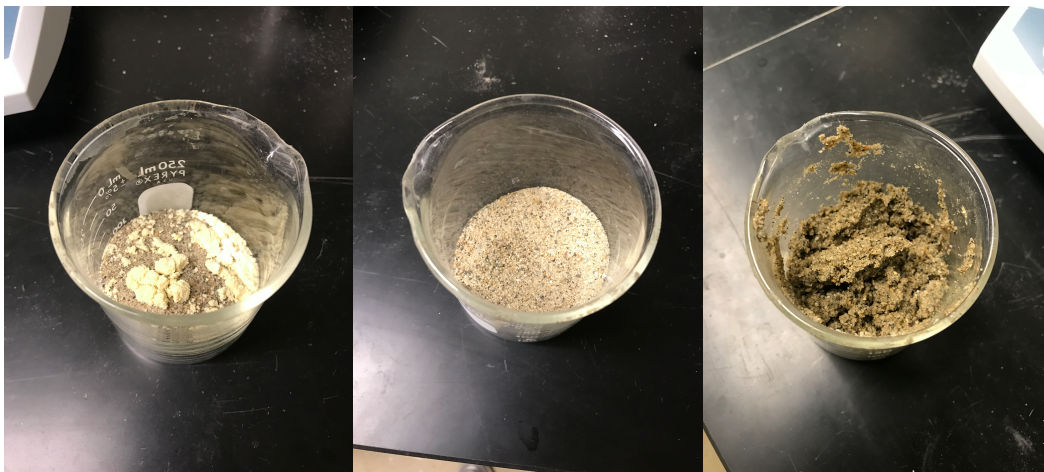
The direct shear test was then conducted on each sample according to ASTM D3080. Control samples were prepared using the same method described above; however, plain tap water was mixed with the dry sand instead of biopolymer solution. Section 3.2 of this thesis shows the results obtained using this method of sample preparation and also details the difficulties associated with this method.

## **2.5 Sample Preparation Method B**

A slightly different approach was then developed to address deficiencies discovered using the previous method. Instead of preparing a biopolymer solution, the biopolymer powder



was mixed directly with dry sand. A biopolymer/sand ratio of 10g/kg was assessed using two biopolymer formulations *SED1* and *SED6*. First, approximately 1.5g of biopolymer powder were added to 150g of air-dried sand. The biopolymer and sand were then mixed together using a spoon to ensure adequate distribution of biopolymer throughout the sand. To control the moisture content, approximately 30.5g of tap water was then added to the biopolymer/sand mixture. The sand and water were thoroughly mixed to ensure a uniform moisture content throughout the sample. This method of sample preparation yielded moisture contents of approximately 20%. Moisture contents were verified using the same method previously described in section 2.4 of this thesis. Figure 2.5 shows each step of this preparation procedure.



**Figure 2.5** Method B sample preparation: (a) unmixed biopolymer powder and sand; (b) biopolymer/sand mixture; (c) biopolymer/sand/water mixture

Each sample was compacted to an approximate thickness of 0.98 in. The direct shear box was assembled together, and inserted into the direct shear testing machine as per the testing device manufacturer's instructions.

The direct shear test was then conducted on the sample according to ASTM D3080. Control samples were prepared using the same method described above; however, water was added to plain sand instead of the biopolymer/sand mixture. Section 3.3 of this thesis shows the

results obtained using this method of sample preparation and also details the difficulties associated with this method.

## 2.6 Sample Preparation Method C

Based on previous research exploring the properties of biopolymer treated sand (Khatami & O’Kelly, 2012; Ayeldeen & Negm, 2014; Guo, 2014), it was determined that allowing the treated biopolymer/sand samples to cure for an extended period of time might yield more relevant results. Treated samples were prepared with biopolymer/sand ratios of both 5g/kg and 10g/kg using formulation *SEDI*. To do this, samples were made using the same procedure described in section 2.5 above with a few slight differences. First, instead of placing and compacting the sand directly in the direct shear box, samples were prepared in a cylindrical mold. Each sample was compacted to an approximate thickness of 0.98 in. Next, the samples were removed from the mold and placed into an oven. Figure 2.6 shows various steps of this sample preparation procedure.



**Figure 2.6** Method C sample preparation: (a) placing lift; (b) compacting lift with hand tamper; (c) fully compacted sample; (d) sample removed from mold

The samples were heated for a period of 24 hours at 100°C. The oven-dried samples were then removed from the oven and each sample was tested as per ASTM D3080. However, the porous stones were not wetted like they were for Methods A and B. Also, the edges of each cured sample had to be trimmed using a razor blade so they could properly fit inside the direct shear box assembly.

An effort was made to heat the control samples in the oven like the treated samples; however, the dried control samples basically fell apart and did not maintain their shape. Therefore, the control data from sample preparation Method B were used for this sample preparation method as well. Section 3.4 of this thesis describes results obtained using this method of sample preparation and also details the issues associated with this method.

## 2.7 Sample Preparation Method D

To better simulate the conditions actually experienced by sand on beaches, sample curing time and temperature were decreased. For this sample preparation method, treated samples were prepared with biopolymer/sand ratios of both 10g/kg and 20g/kg using formulation *SEDI*. Samples were made using the same procedure previously described in section 2.6; however, the samples were only heated for 6 hours at a temperature of 35°C. Figure 2.7 shows the top and bottom of a typical cured sample. Note that the bottom of the sample is still very moist.



**Figure 2.7** Method D sample preparation: (a) top of cured sample; (b) bottom of cured sample



The control data used for sample preparation Methods B and C were also used for this method. Section 3.5 of this thesis describes results obtained using this method of sample preparation and also details the issues associated with this method.

## 2.8 Sample Preparation Method E

Building off of the four previously described methods of sample preparation, this final method was developed. Method E follows the same procedures used in Methods C and D with a few significant differences. First, each sample was compacted to a thickness of approximately 0.91 in. instead of 0.98 in. In addition, each sample was heated for 24 hours at a temperature of 35°C before direct shear testing was conducted. Control samples were prepared identically to the treated samples (minus the addition of biopolymer powder). In fact, the control samples maintained their shape fairly well after being heated overnight. Some control samples broke apart slightly when being placed into the direct shear box, but these samples were easily remolded using a hand tamper. Figure 2.8 shows an example of both a cured treated sample and a cured control sample.



**Figure 2.8** Method E sample preparation: (a) top of cured treated sample; (b) bottom of cured treated sample; (c) cured control sample

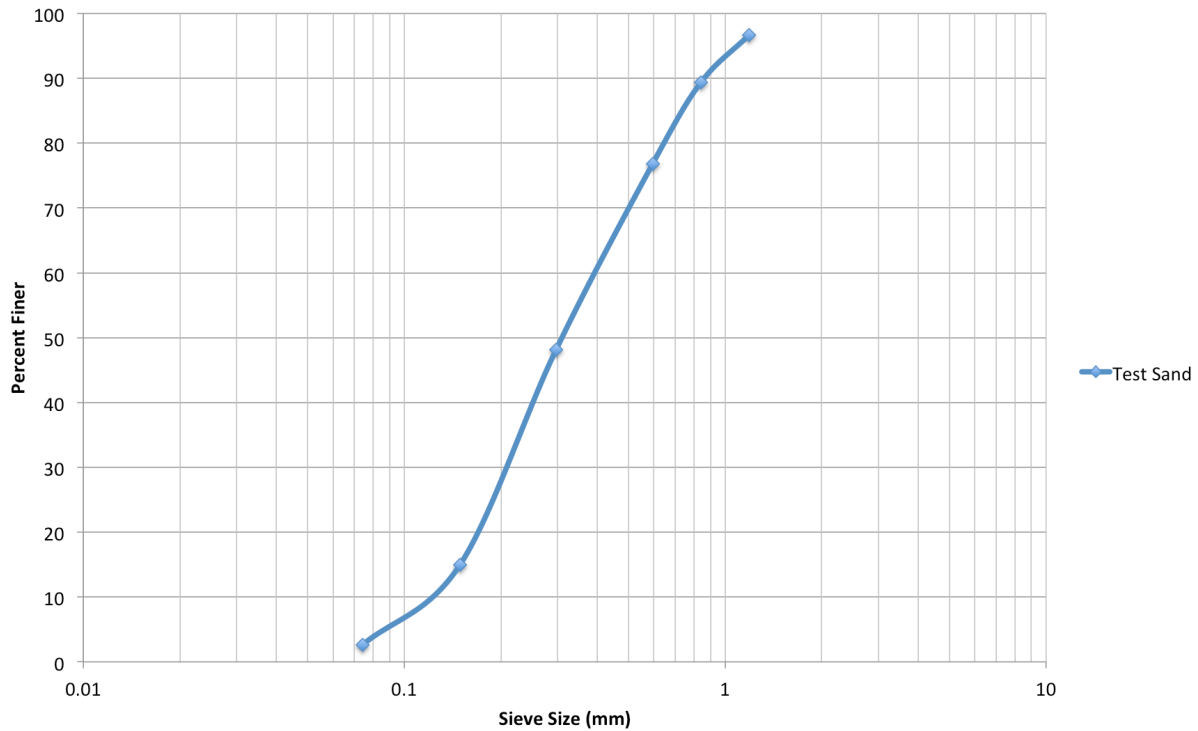
Using Method E, *SEDI* treated samples were prepared at biopolymer/sand ratios of both 5g/kg and 10g/kg. Direct shear tests were then conducted on these samples. Each test was

conducted in triplicate to verify the accuracy of the test and to determine the reproducibility of the testing method. Each control test was also conducted in triplicate. The results of this round of testing are described in section 3.6. Finally, Method E was used to evaluate the effect of biopolymer formulation *SED3*. The results obtained for *SED3* were then compared with results obtained for *SEDI*. These results are also assessed in section 3.6.

### 3. RESULTS AND DISCUSSION

#### 3.1 Sieve Analysis

*Sakrete Natural Play Sand* was used to conduct all testing described in this thesis. Figure 3.1 shows the grain size distribution curve for the test sand. In addition, the calculated  $C_u$  and  $C_c$  parameters for the sand are shown in Table 3.1.



**Figure 3.1** Grain size distribution curve for test sand

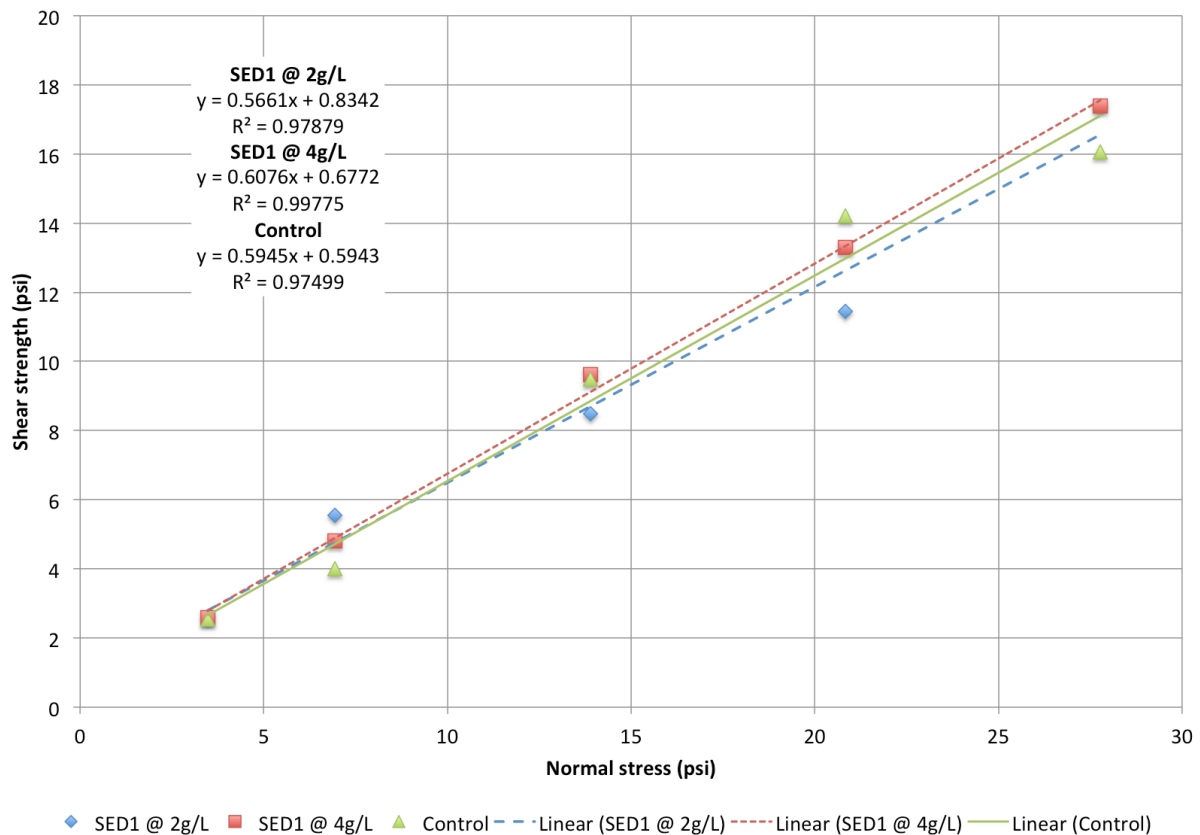
**Table 3.1** Test sand classification parameters

Parameter	$D_{10}$ (mm)	$D_{30}$ (mm)	$D_{60}$ (mm)	$C_u$	$C_c$
Value	0.12	0.20	0.40	3.33	0.83

Based on this information, the soil is classified as SP (poorly-graded sand) according to the Unified Soil Classification System. In addition, the soil used for testing mainly consists of medium to fine sand.

### 3.2 Method A

It was extremely difficult to control sample moisture content using this method. Therefore, sample dry unit weights varied from 93.3 pcf to 98.4 pcf. This variation in level of sample compaction most likely affected the validity of the results obtained using this method. Furthermore, the Mohr-Coulomb failure envelopes for the treated samples and the control samples were almost identical (shown in Figure 3.2).



**Figure 3.2** Mohr-Coulomb failure envelopes for Method A tests

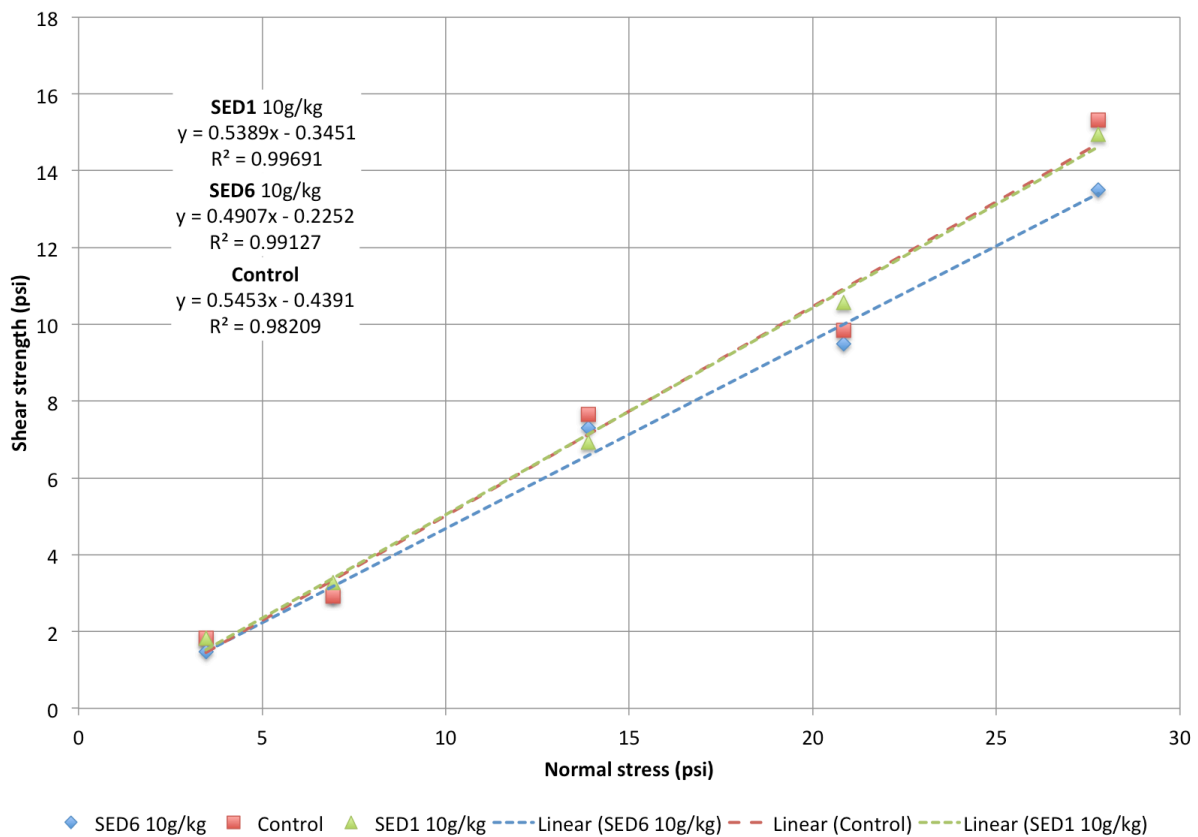
The derived values of sample friction angle and cohesion are shown in Table 3.2. There did not appear to be any significant increase in cohesion in the treated samples. However, due to the high level of variation in testing results and sample preparation, it was not possible to draw any conclusions regarding the effect of biopolymer treatment using this testing procedure.

**Table 3.2** Derived strength parameters for Method A tests

Sample	Friction angle (°)	Cohesion (psi)
Control	30.7	0.59
SED1 2g/L	29.5	0.83
SED1 4g/L	31.3	0.68

### 3.3 Method B

This testing procedure allowed for a better control of sample moisture content and, therefore, control sample level of compaction and dry unit weight. Sample dry unit weights ranged from 85.8 pcf to 87.1 pcf. However, the treated samples and the control samples once again had almost indistinguishable Mohr-Coulomb failure envelopes (shown in Figure 3.3).



**Figure 3.3** Mohr-Coulomb failure envelopes for Method B tests



The derived values of cohesion for both the treated samples and the control samples were negative. This was interpreted to mean that none of the samples exhibited any cohesive strength.

Table 3.3 shows the derived friction angles and cohesion values for this series of tests.

**Table 3.3** Derived strength parameters for Method B tests

Sample	Friction angle (°)	Cohesion (psi)
Control	28.6	~0
SED1 10g/kg	28.3	~0
SED6 10g/kg	26.1	~0

Figure 3.3 clearly shows that there is no distinguishable ordering of test sample shear strengths for each normal stress. For example, at 13.89 psi, the control sample has the greatest shear strength followed by the *SED6* sample and then the *SED1* sample. In contrast, at 20.83 psi, the *SED1* sample has the greatest shear strength followed by the control and then the *SED6* sample. Based on the results obtained using this preparation method, it was determined that the direct shear test may not be sensitive enough to quantify any difference in cohesion between biopolymer treated and untreated sand at high moisture contents.

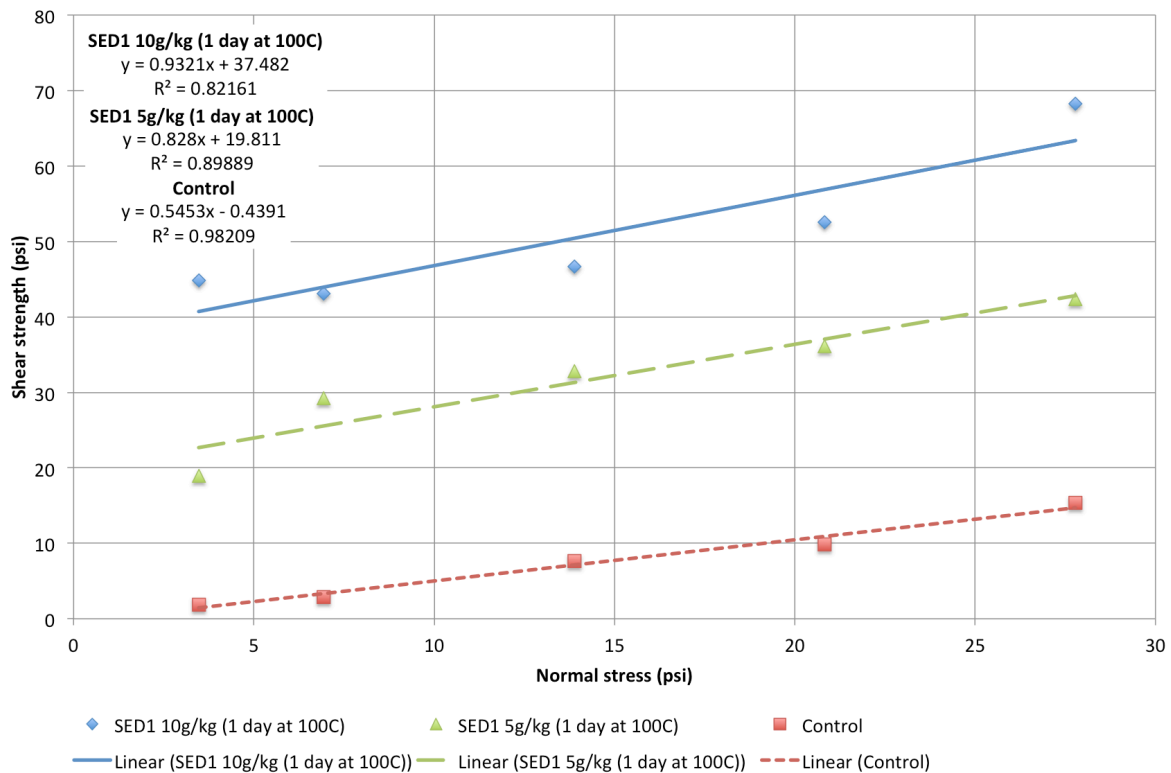
### 3.4 Method C

The curing process included in the Method C preparation procedure had a significant impact on direct shear testing results. Heating the treated samples for 24 hours at 100°C caused the samples to dry out and become very rigid. This increased rigidity greatly improved sand cohesion. Figure 3.4a shows a typical treated sample in the bottom half of the direct shear box after it has been tested to failure. Figure 3.4b shows the shear failure plane developed in a typical treated sample.



**Figure 3.4** Method C results: (a) treated sample in shear box after failure; (b) treated sample shear failure plane

The Mohr-Coulomb failure envelopes in Figure 3.4 show that there is a clear correlation between biopolymer treatment dosage and sand cohesion. Table 3.4 contains the derived strength parameters for each sample type. Cohesion almost doubled when the biopolymer/sand ratio was doubled. Friction angle also increased as biopolymer/sand ratio was increased.



**Figure 3.5** Mohr-Coulomb failure envelopes for Method C tests

**Table 3.4** Derived strength parameters for Method C tests

Sample	Friction angle (°)	Cohesion (psi)
Control	28.6	~0
SED1 5g/kg	39.6	19.8
SED1 10g/kg	43.0	37.5

While this method clearly demonstrated the effect of biopolymer treatments on sand cohesion and could be used to compare the effect of various treatments and treatment dosages on cohesion, it was determined that it would be more appropriate to conduct the tests at a temperature (35°C) that is more representative of actual field conditions.

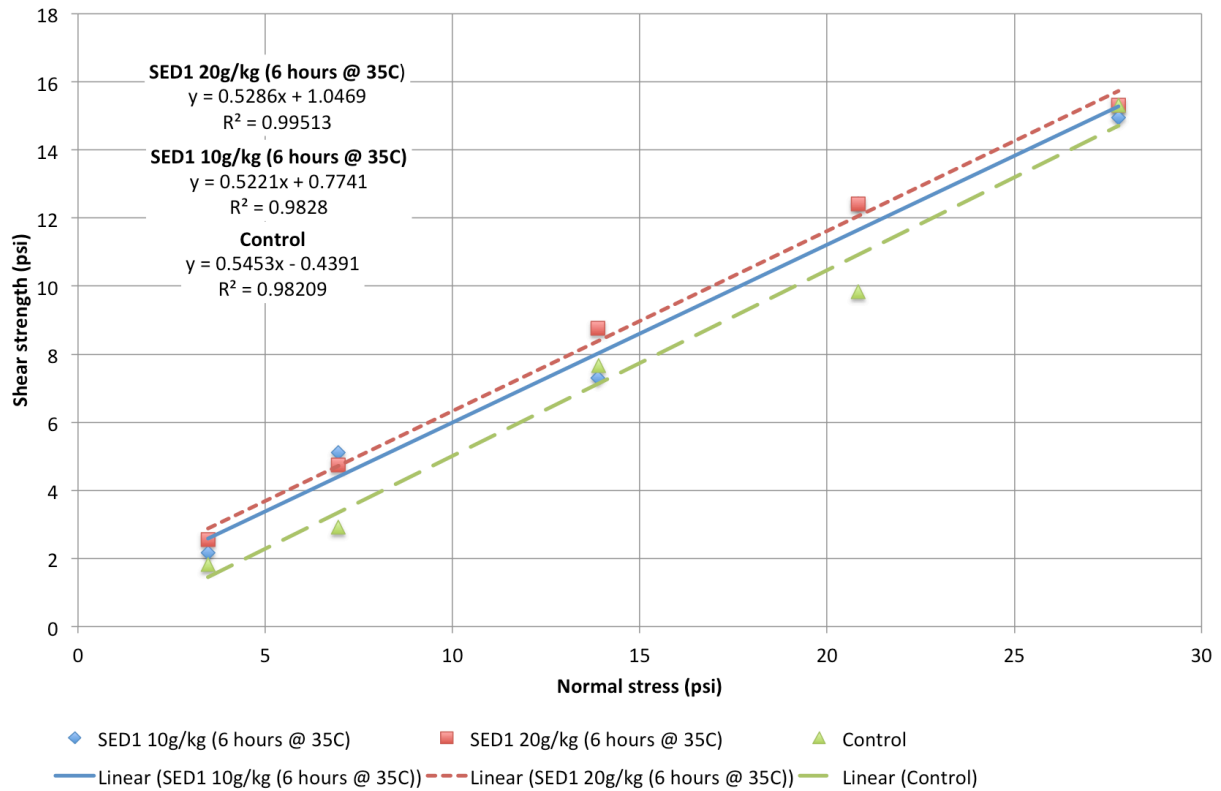
### 3.5 Method D

This sample preparation method provided curing conditions that are more realistic than Method C. After being heated in the oven for 6 hours at 35°C, each treated sample developed a rigid thin outer shell. Within this shell, the remainder of the sample remained moist and malleable. Figure 3.6 shows the interior of a typical treated sample prepared using this method.



**Figure 3.6** Method D results: (a) treated sample in shear box after failure; (b) interior of treated sample

The resulting Mohr-Coulomb failure envelopes for this series of tests show a slight increase in sample cohesion as biopolymer/sand ratio is increased. Table 3.5 contains the derived strength parameters for this series of tests. However, due to uncertainty in the precision of the direct shear test, the results obtained using this method may not be reproducible.



**Figure 3.7** Mohr-Coulomb failure envelopes for Method D tests

**Table 3.5** Derived strength parameters for Method D tests

Sample	Friction angle (°)	Cohesion (psi)
Control	28.6	~0
SED1 10g/kg	27.6	0.77
SED1 20g/kg	27.9	1.05

### 3.6 Method E

Curing samples at 35°C for 24 hours before testing proved to be both a practical and effective method at evaluating biopolymer treatment induced sand cohesion. Because of the

increased level of compaction, sample dry unit weights increased to approximately 93 pcf.

Appendix A presents data related to Method E sample preparation including sample moisture contents, wet unit weights, and dry unit weights. Figure 3.8 shows the interior of a typical treated sample. The outer rigid shell is noticeably larger than the shells developed on the treated samples using Method D.

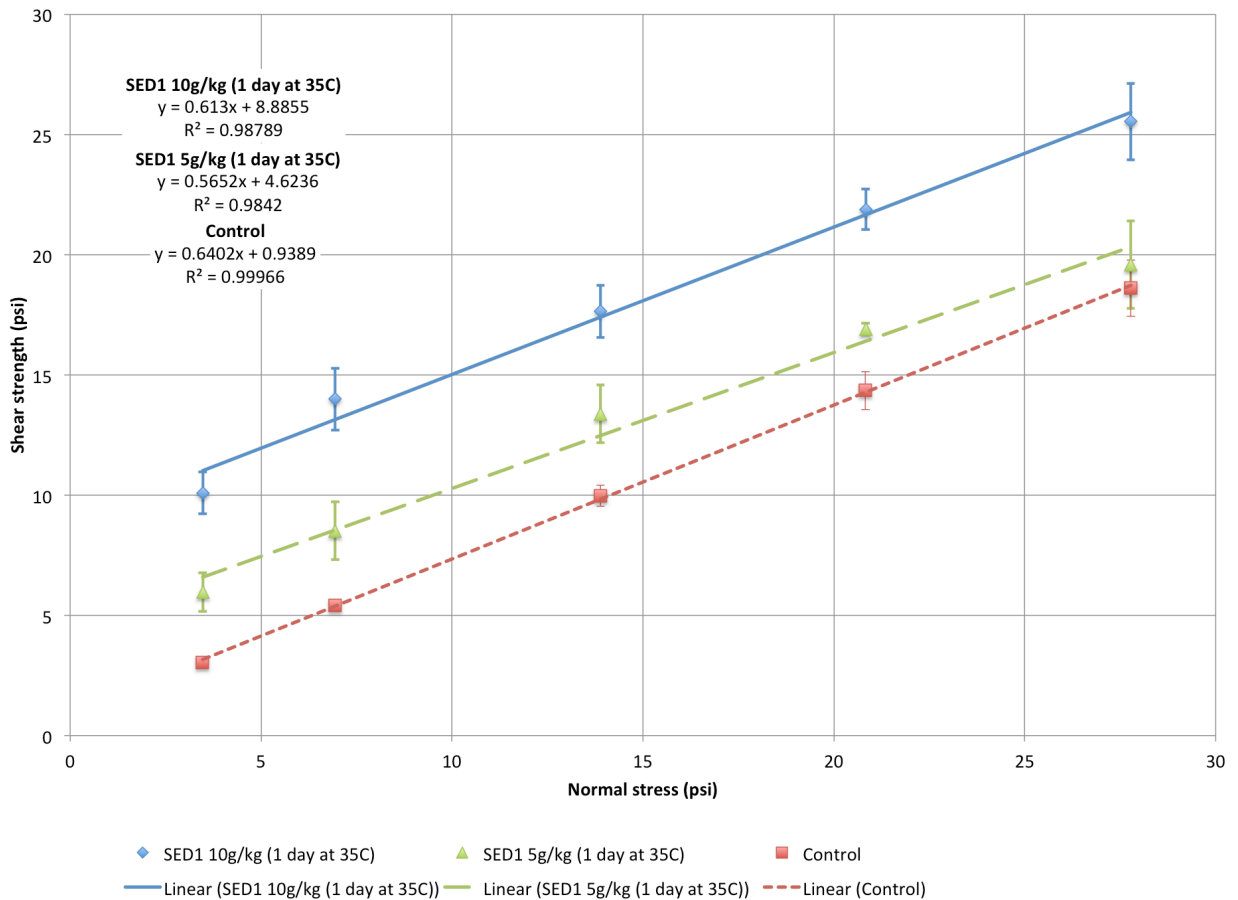


**Figure 3.8** Method E: interior of treated sample

The test results obtained using this method were also reproducible. Three test trials were performed for each of the treated samples and the control samples. Using the three resulting shear strengths found for each normal stress, an average shear strength was computed. These average shear strengths were then plotted versus normal stress for each sample type. Figure 3.9 shows the resulting Mohr-Coulomb failure envelopes. In addition, error bars were included for each point in the failure envelopes. These error bars represent the standard error associated with each group of three tests. Appendix B presents the test results of each set of trials, computed averages, computed standard deviations, and computed standard errors.

There was little to no variation in the results obtained for the control samples. Furthermore, the error bars for the treated samples show a clear separation between the 10g/kg biopolymer treated samples and the 5g/kg biopolymer treated samples. The derived strength

parameters for this set of tests are contained in Table 3.6. The control samples exhibited some cohesive strength. However, this is simply apparent cohesion caused by the negative pore water pressures experienced by the unsaturated sand (Coduto et al., 2011). When biopolymer/sand ratio was doubled from 0.5% to 1%, sample cohesion almost doubled. This result is consistent with the change in cohesion previously described in section 3.4 (Method C).

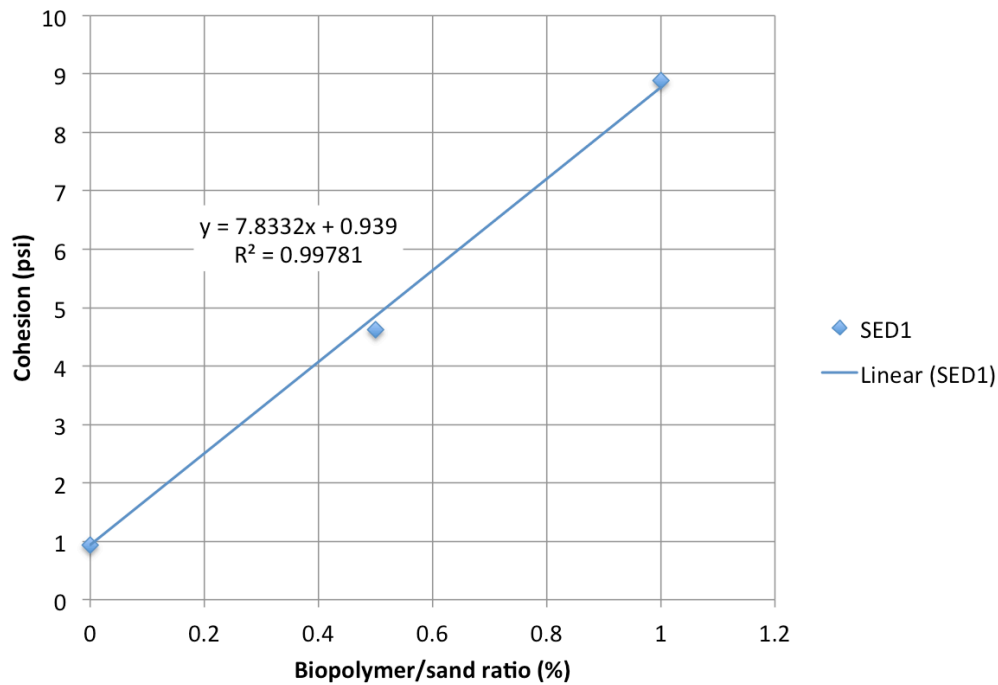


**Figure 3.9** Mohr-Coulomb failure envelopes for Method E tests

**Table 3.6** Derived strength parameters for Method E tests

Sample	Friction angle (°)	Cohesion (psi)
Control	32.6	0.94
SED1 5g/kg	29.5	4.6
SED1 10g/kg	31.5	8.9

Using the derived cohesion values, a dosage curve was plotted. Figure 3.10 illustrates the relationship between sand cohesion and biopolymer/sand ratio. The curve indicates that biopolymer concentration is directly related to sand cohesion. This curve may be used to extrapolate cohesion values for different biopolymer/sand ratios within the range of tests conducted.



**Figure 3.10** Method E: dosage curve for *SED1*

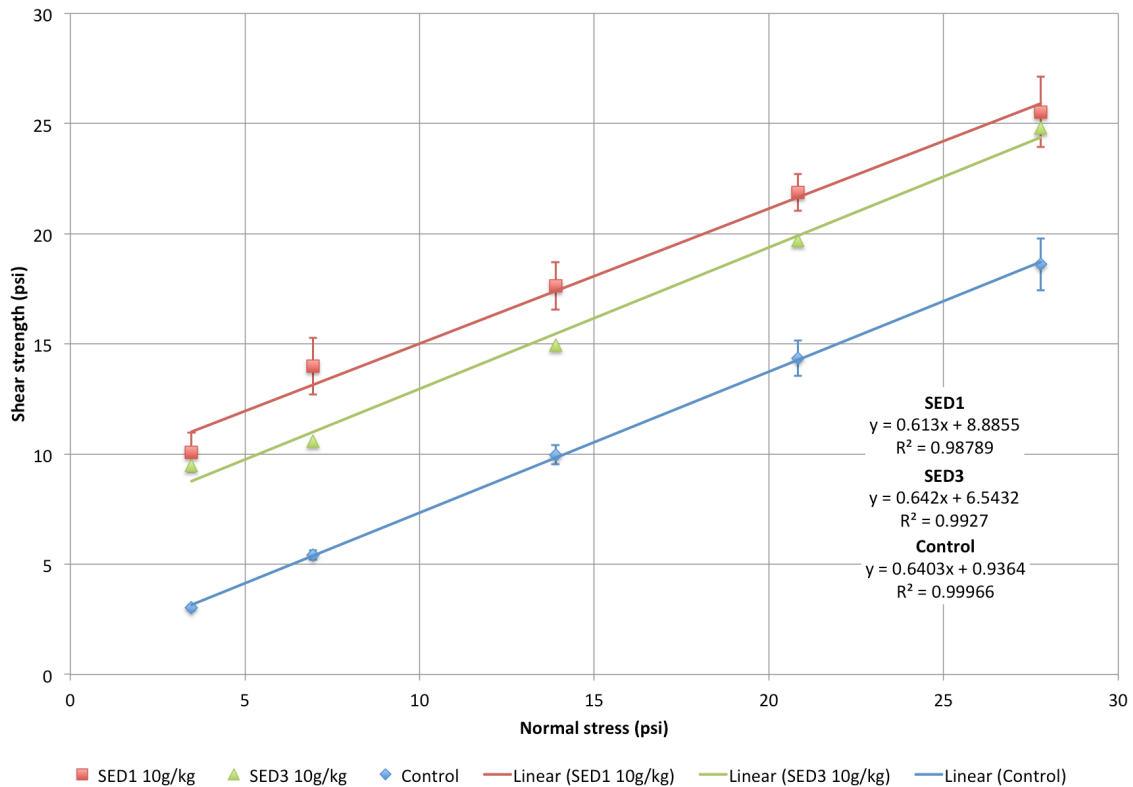
One additional set of tests was conducted using Method E to evaluate a different formulation of biopolymer. Treated samples were prepared using *SED3* at a biopolymer/sand ratio of 10g/kg. The results of these tests were then compared with the results obtained for *SED1* 10g/kg treated samples. The *SED3* formulation contains only polysaccharides while *SED1* is an engineered biopolymer containing proteins in addition to polysaccharides. Both formulations are shown in Figure 3.11. Note that *SED1* has a finer, more powdery texture compared with *SED3* which is more granular.





**Figure 3.11** (a) SED1 powder; (b) SED3 powder

Figure 3.12 shows the Mohr-Coulomb failure envelopes for *SED1*, *SED3*, and the control. There is a noticeable difference between the shear strengths obtained with *SED1* treatment versus *SED3* treatment. In addition, the cohesion achieved using *SED3* is more than 2 psi less than *SED1* sample cohesion. From this, it can be inferred that the presence of proteins in the engineered biopolymer may improve the biopolymer's ability to increase sand cohesion.



**Figure 3.12** Method E results: different formulations



### **3.7 Testing Methods and Constructability**

The testing procedure and sample preparation method described in section 2.8 of this thesis (Method E) may be used to simulate real-world biopolymer treatment construction practices. Each step in Method E simulates the biopolymer treatment application and curing process. In particular, mixing biopolymer powder with dry sand corresponds with digging small trenches in a beach, filling those trenches with biopolymer, and tilling the sand to ensure adequate mixing. Adding water to the biopolymer/sand test mixture simulates spraying the tilled beach sand with water. Finally, heating the treated test sand at 35°C in an oven for 24 hours simulates sustained exposure of the sand to hot conditions. During this time, the treated beach sand cures and there is a demonstrable increase in cohesion between sand grains. More site-specific tests could be conducted using this method by varying the curing period and temperature, and alternating wetting and drying periods that are more representative of the intertidal zone.

## 4. CONCLUSIONS

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### 4.1 Summary

The biopolymer treatments developed by Dr. Dahmani have a clear impact on sand cohesion. Based on the direct shear testing results, several conclusions can be drawn. First, sample preparation methods significantly affect the results of direct shear tests on biopolymer treated sand. At high moisture contents, it appears that the direct shear test itself may not be sensitive enough to measure changes in cohesion due to biopolymer treatment. However, when treated samples were allowed to cure for a period of 24 hours at both 100°C and 35°C, direct shear testing measured a significant increase in cohesion. This curing period reduced the moisture content of the samples and increased sample cohesion. The dosage of biopolymer treatment also affected measured cohesion values. Doubling biopolymer/sand ratio from 0.5% to 1.0% also doubled sand cohesion values. Finally, biopolymer composition in terms of polysaccharide and protein content may affect sand cohesion. There was a clear difference between the cohesion values derived for *SED1* treated samples (engineered polysaccharide-protein product) and *SED3* treated samples (polysaccharides only). However, further testing is necessary to verify this result.

### 4.2 Recommendations for Future Research

Additional studies may be conducted to investigate the effect of biopolymer formulation on sand cohesion. Additional biopolymer formulations that vary polysaccharide and protein content and type may be tested using the procedures described in section 2.8 of this thesis (Method E). Dosage curves should be developed for each formulation using the same approach described in this thesis. These dosage curves could then be used to optimize biopolymer dosage

selection. In addition, the effect of using saline water instead of fresh water when preparing samples should be investigated. The chemistry of saline water could positively or negatively impact the biopolymer's effect on sand cohesion.

The effect of biopolymer treatments on different types of sand should also be explored. Optimally, sand samples may be taken from beaches that necessitate erosion mitigation. Biopolymer dosage and formulation may then be optimized for that particular beach using the Method E procedures. The effect of curing time, temperature, and wetting conditions on treated sample cohesion could also be investigated. In the case of sediment sand cap stabilization, testing under saturated conditions should also be conducted. Finally, long-time testing should be conducted to determine the effective lifespan of biopolymer treatments.

## 5. REFERENCES

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## 6. APPENDICES

### 6.1 Appendix A: Method E Sample Preparation Data

Test Series		Control				
		Trial 1				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/13/17	4/13/17	4/13/17	4/13/17	4/13/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.91	0.91	0.91	0.91
	Volume (in <sup>3</sup> )	4.47	4.47	4.47	4.47	4.47
	Mass (g)	130.25	130.26	130.01	130.08	130.73
	Moisture content tin mass (g)	1.16	1.16	1.16	1.09	1.09
	Mass tin + wet sample (g)	30.45	30.45	30.45	31.50	31.50
	Mass tin + dry sample (g)	25.56	25.56	25.56	26.50	26.50
	Moisture content (%)	20.00	20.00	20.00	19.70	19.70
	Wet density (g/in <sup>3</sup> )	29.16	29.16	29.10	29.12	29.27
	Wet unit weight (lb/ft <sup>3</sup> )	111.1	111.1	110.9	110.9	111.5
	Dry unit weight (lb/ft <sup>3</sup> )	92.5	92.5	92.4	92.7	93.2
	Max shear load (lbs)	14.3	28.6	51.9	73.4	89.5
	Max shear stress (psi)	2.91	5.83	10.57	14.95	18.23

Test Series		Control				
		Trial 2				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/15/17	4/15/17	4/15/17	4/15/17	4/15/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.91	0.91	0.91	0.91
	Volume (in <sup>3</sup> )	4.47	4.47	4.47	4.47	4.47
	Mass (g)	130.11	130.37	130.34	130.15	130.43
	Moisture content tin mass (g)	1.16	1.16	1.16	1.09	1.09
	Mass tin + wet sample (g)	32.26	32.26	32.26	34.22	34.22
	Mass tin + dry sample (g)	27.14	27.14	27.14	28.75	28.75
	Moisture content (%)	19.70	19.70	19.70	19.80	19.80
	Wet density (g/in <sup>3</sup> )	29.13	29.19	29.18	29.14	29.20
	Wet unit weight (lb/ft <sup>3</sup> )	111.0	111.2	111.2	111.0	111.2
	Dry unit weight (lb/ft <sup>3</sup> )	92.7	92.9	92.9	92.7	92.9
	Max shear load (lbs)	16.1	25.1	50.1	75.2	102.1
	Max shear stress (psi)	3.28	5.11	10.21	15.32	20.80



Test Series		Control				
		Trial 3				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/18/17	4/18/17	4/18/17	4/18/17	4/18/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.91	0.91	0.91	0.91
	Volume (in <sup>3</sup> )	4.47	4.47	4.47	4.47	4.47
	Mass (g)	130.00	130.00	130.00	130.00	130.00
	Moisture content tin mass (g)	1.16	1.16	1.16	1.09	1.09
	Mass tin + wet sample (g)	30.00	30.00	30.00	30.00	30.00
	Mass tin + dry sample (g)	25.30	25.30	25.30	25.25	25.25
	Moisture content (%)	19.50	19.50	19.50	19.70	19.70
	Wet density (g/in <sup>3</sup> )	29.10	29.10	29.10	29.10	29.10
	Wet unit weight (lb/ft <sup>3</sup> )	110.9	110.9	110.9	110.9	110.9
	Dry unit weight (lb/ft <sup>3</sup> )	92.8	92.8	92.8	92.7	92.7
	Max shear load (lbs)	14.3	26.9	44.8	62.7	82.4
	Max shear stress (psi)	2.91	5.48	9.13	12.77	16.79

Test Series		SED1 5g/kg				
		Trial 1				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/4/17	4/4/17	4/4/17	4/4/17	4/4/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.92	0.91	0.92	0.92
	Volume (in <sup>3</sup> )	4.47	4.52	4.47	4.52	4.52
	Mass (g)	130.00	130.00	130.00	130.00	130.00
	Moisture content tin mass (g)	1.12	1.18	1.15	1.11	1.09
	Mass tin + wet sample (g)	30.00	30.00	30.00	30.00	30.00
	Mass tin + dry sample (g)	25.60	25.63	25.43	25.46	25.82
	Moisture content (%)	18.00	17.90	18.80	18.60	16.90
	Wet density (g/in <sup>3</sup> )	29.10	28.79	29.10	28.79	28.79
	Wet unit weight (lb/ft <sup>3</sup> )	110.9	109.7	110.9	109.7	109.7
	Dry unit weight (lb/ft <sup>3</sup> )	94.0	93.0	93.3	92.4	93.8
	Max shear load (lbs)	21.5	30.4	57.3	80.6	82.4
	Max shear stress (psi)	4.38	6.19	11.67	16.42	16.79

Test Series		SED1 5g/kg				
		Trial 2				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/6/17	4/6/17	4/6/17	4/6/17	4/6/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.91	0.91	0.91	0.91
	Volume (in <sup>3</sup> )	4.47	4.47	4.47	4.47	4.47
	Mass (g)	130.00	130.05	130.04	130.11	130.04
	Moisture content tin mass (g)	1.16	1.16	1.16	1.09	1.09
	Mass tin + wet sample (g)	34.50	34.50	34.50	32.06	32.06
	Mass tin + dry sample (g)	28.89	28.89	28.89	26.86	26.86
	Moisture content (%)	20.20	20.20	20.20	20.20	20.20
	Wet density (g/in <sup>3</sup> )	29.10	29.11	29.11	29.13	29.11
	Wet unit weight (lb/ft <sup>3</sup> )	110.9	110.9	110.9	111.0	110.9
	Dry unit weight (lb/ft <sup>3</sup> )	92.2	92.2	92.2	92.3	92.3
	Max shear load (lbs)	34.0	50.1	62.7	84.2	112.8
	Max shear stress (psi)	6.93	10.21	12.77	17.15	22.98

Test Series		SED1 5g/kg				
		Trial 3				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/8/17	4/8/17	4/8/17	4/8/17	4/8/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.91	0.91	0.91	0.91
	Volume (in <sup>3</sup> )	4.47	4.47	4.47	4.47	4.47
	Mass (g)	130.00	130.00	130.00	130.00	130.00
	Moisture content tin mass (g)	1.16	1.16	1.09	1.09	1.09
	Mass tin + wet sample (g)	30.00	30.00	30.00	30.00	30.00
	Mass tin + dry sample (g)	25.28	25.28	25.21	25.21	25.21
	Moisture content (%)	19.60	19.60	19.90	19.90	19.90
	Wet density (g/in <sup>3</sup> )	29.10	29.10	29.10	29.10	29.10
	Wet unit weight (lb/ft <sup>3</sup> )	110.9	110.9	110.9	110.9	110.9
	Dry unit weight (lb/ft <sup>3</sup> )	92.7	92.7	92.5	92.5	92.5
	Max shear load (lbs)	32.2	44.8	77.0	84.2	93.1
	Max shear stress (psi)	6.56	9.13	15.69	17.15	18.97

Test Series		SED1 10g/kg				
		Trial 1				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/3/17	4/3/17	4/3/17	4/3/17	4/3/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.92	0.92	0.91	0.91	0.92
	Volume (in <sup>3</sup> )	4.52	4.52	4.47	4.47	4.52
	Mass (g)	130.24	130.47	130.36	130.47	130.58
	Moisture content tin mass (g)	1.16	1.09	1.12	1.18	1.11
	Mass tin + wet sample (g)	24.83	24.71	25.67	27.01	25.39
	Mass tin + dry sample (g)	21.01	20.77	21.72	22.98	21.36
	Moisture content (%)	19.20	20.00	19.20	18.50	19.90
	Wet density (g/in <sup>3</sup> )	28.84	28.89	29.18	29.21	28.91
	Wet unit weight (lb/ft <sup>3</sup> )	109.9	110.1	111.2	111.3	110.2
	Dry unit weight (lb/ft <sup>3</sup> )	92.1	91.7	93.3	93.9	91.9
	Max shear load (lbs)	41.2	59.1	84.2	100.3	111.0
	Max shear stress (psi)	8.39	12.04	17.15	20.43	22.61

Test Series		SED1 10g/kg				
		Trial 2				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/5/17	4/5/17	4/5/17	4/5/17	4/5/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.91	0.91	0.91	0.91
	Volume (in <sup>3</sup> )	4.47	4.47	4.47	4.47	4.47
	Mass (g)	130.00	130.00	130.00	130.00	130.00
	Moisture content tin mass (g)	1.16	1.16	1.16	1.09	1.09
	Mass tin + wet sample (g)	30.00	30.00	30.00	30.00	30.00
	Mass tin + dry sample (g)	25.25	25.25	25.25	25.25	25.25
	Moisture content (%)	19.7	19.7	19.7	19.7	19.7
	Wet density (g/in <sup>3</sup> )	29.1	29.1	29.1	29.1	29.1
	Wet unit weight (lb/ft <sup>3</sup> )	110.9	110.9	110.9	110.9	110.9
	Dry unit weight (lb/ft <sup>3</sup> )	92.6	92.6	92.6	92.7	92.7
	Max shear load (lbs)	55.5	66.3	78.8	107.4	127.1
	Max shear stress (psi)	11.31	13.51	16.05	21.88	25.89

Test Series		SED1 10g/kg				
		Trial 3				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/5/17	4/11/17	4/11/17	4/11/17	4/11/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.91	0.91	0.91	0.91
	Volume (in <sup>3</sup> )	4.47	4.47	4.47	4.47	4.47
	Mass (g)	130.00	130.33	130.27	130.33	130.49
	Moisture content tin mass (g)	1.09	1.16	1.16	1.16	1.09
	Mass tin + wet sample (g)	30.00	30.11	30.11	30.11	30.39
	Mass tin + dry sample (g)	25.25	25.25	25.25	25.25	25.47
	Moisture content (%)	19.70	20.20	20.20	20.20	20.20
	Wet density (g/in <sup>3</sup> )	29.10	29.18	29.16	29.18	29.21
	Wet unit weight (lb/ft <sup>3</sup> )	110.9	111.2	111.1	111.2	111.3
	Dry unit weight (lb/ft <sup>3</sup> )	92.7	92.5	92.4	92.5	92.6
	Max shear load (lbs)	51.9	80.6	96.7	114.6	137.9
	Max shear stress (psi)	10.57	16.42	19.70	23.35	28.09

Test Series		SED3 10g/kg				
		Trial 1				
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi
Sample Data	Date Tested	4/19/17	4/19/17	4/19/17	4/19/17	4/19/17
	Diameter (in)	2.50	2.50	2.50	2.50	2.50
	Area (in <sup>2</sup> )	4.91	4.91	4.91	4.91	4.91
	Thickness (in)	0.91	0.91	0.91	0.91	0.91
	Volume (in <sup>3</sup> )	4.47	4.47	4.47	4.47	4.47
	Mass (g)	130.76	130.53	130.34	130.58	130.00
	Moisture content tin mass (g)	1.12	1.08	1.12	1.08	1.08
	Mass tin + wet sample (g)	30.92	30.74	30.92	30.74	30.74
	Mass tin + dry sample (g)	25.87	25.58	25.87	25.58	25.58
	Moisture content (%)	20.40	21.10	20.40	21.10	21.10
	Wet density (g/in <sup>3</sup> )	29.27	29.22	29.18	29.23	29.10
	Wet unit weight (lb/ft <sup>3</sup> )	111.5	111.3	111.2	111.4	110.9
	Dry unit weight (lb/ft <sup>3</sup> )	92.6	92.0	92.3	92.0	91.6
	Max shear load (lbs)	46.6	51.9	73.4	96.7	121.8
	Max shear stress (psi)	9.49	10.57	14.95	19.70	24.81



## 6.2 Appendix B: Method E Testing Data

Test Series		Shear Strength (psi)					Friction Angle (°)	Cohesion (psi)	R <sup>2</sup>
		Normal Stress = 3.47 psi	Normal Stress = 6.94 psi	Normal Stress = 13.89 psi	Normal Stress = 20.83 psi	Normal Stress = 27.78 psi			
Control	Trial 1	2.91	5.83	10.57	14.95	18.23	32.6	0.94	0.9997
	Trial 2	3.28	5.11	10.21	15.32	20.80			
	Trial 3	2.91	5.30	9.13	12.77	16.79			
	Average	3.04	5.41	9.97	14.35	18.61			
	Standard Deviation	0.21	0.37	0.75	1.38	2.03			
	Standard Error	0.12	0.21	0.43	0.79	1.17			
SED1 5g/kg	Trial 1	4.38	6.19	11.67	16.42	16.79	29.5	4.62	0.9842
	Trial 2	6.93	10.21	12.77	17.15	22.98			
	Trial 3	6.56	9.13	15.69	17.15	18.97			
	Average	5.96	8.51	13.38	16.91	19.58			
	Standard Deviation	1.38	2.08	2.08	0.42	3.14			
	Standard Error	0.80	1.20	1.20	0.24	1.81			
SED1 10g/kg	Trial 1	8.39	12.04	17.15	20.43	22.61	31.5	8.89	0.9879
	Trial 2	11.31	13.51	16.05	21.88	25.89			
	Trial 3	10.57	16.42	19.70	23.35	28.09			
	Average	10.09	13.99	17.63	21.88	25.53			
	Standard Deviation	1.52	2.23	1.87	1.45	2.76			
	Standard Error	0.87	1.29	1.08	0.84	1.59			
SED3 10g/kg	Trial 1	9.49	10.57	14.95	19.70	24.81	32.7	6.54	0.9927