Final Design Report
For the Use of Carbonated Cement Kiln Dust as a Soil Stabilization Amendment

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Disclaimer

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Acknowledgements

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The project team would like to specifically express the appreciation and indebtedness to professor Alarick Reiboldt and laboratory manager Gerjen Slim at the Engineering Department of Northern Arizona University for endless support on this Capstone project; and professor Pranshoo Solanki from Illinois State University for his previous study on Engineering Properties and Moisture Susceptibility of Silty Clay Stabilized with Lime, Class C Fly Ash, and Cement Kiln Dust.

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1.0 Project Understanding

1.1 Project Purpose

The project purpose is to determine the effectiveness of Carbonated Cement Kiln Dust for use as a soil stabilization amendment. Cement is one of the most Carbon intensive materials to produce. One of the by-products of the cement manufacturing process is Cement Kiln Dust (CKD). Adding gaseous Carbon Dioxide under the right conditions to CKD will form Carbonated Cement Kiln Dust (CCKD). One potential use of CCKD is as a stabilizing amendment for compacted soils. As of now, CCKD is not put in use. By conducting this study, the project team will determine the efficacy of CCKD as a stabilizer for soils.

1.2 Project Background

Carbonated Cement Kiln Dust (CCKD) has a potential use as stabilizer for soils due to its chemical components (mainly composed of Carbonated Calcium). The project team will conduct tests as requested by the client to determine if CCKD can be used as a stabilizer. Lime and Cement Kiln Dust have been proven to be usable to improve soil strength. Therefore, the project team will compare the results of tests on CCKD with the results of the same tests on CKD and lime to determine the efficacy of CCKD as a stabilizer for soils. Moreover, CCKD is made from CKD, which is currently treated as waste by Cement Manufacturer, and Carbon Dioxide CO_2. By proving the use of CCKD as soil stabilization amendment, the project team can help reduce the CKD waste and a part of CO_2 emission due to Cement manufacturing process, which is accounted to approximately 5% of Carbon Dioxide CO_2 emission that human produced [1].

1.3 Technical Considerations

Many previous studies indicated that lime and CKD could be used as soil stabilizers. For example, Little (2000) reported that the long-term effect of lime stabilization on fine grained soils, encountered in Texas, induces a 1,000% or more increase in resilient modulus (M_r) over that of the untreated soil. The AASHTO T274 method was used to determine the resilient modulus values. Values of M_r typically falls within a range of 210 and 3,500 MPa. The strength values determined for lime- stabilized soil was reported as high as 7,000 to 10,000 kPa. TST was also performed to evaluate the moisture susceptibility on 7-day cured specimens [2]. In another the study by Parsons and Kneebone (2004), eight different soils with classifications of CH, CL, ML, SM, and SP were tested for strength, swell and durability to evaluate the relative performance of CKD as a stabilizing stabilizer. Results were compared with previous findings for the same soils stabilized with lime, cement, and fly ash. Substantial increase in strength and decrease in swell was found with the addition of CKD. CKD treated soil samples were also reported to have a performance in wet-dry testing that is similar to that for lime, fly ash and cement treated soil [3]. Because CCKD contains mainly lime, therefore, CCKD also has potential to be used as a soil stabilizing amendment.

1.4 Project Constraints

When conducting the study, the project team determined that the following problems would be the potential limitations for the project: CKD/CCKD Variability; Soil Variability; and Laboratory Soils Testing.

1.4.1 CKD/CCKD Variability

The composition of CKD/CCKD is a challenge for the project. CKD/CCKD can have different compositions of chemical components, therefore, the addition of CKD/CCKD to soil samples can have different impacts if the composition of CKD/CCKD is not consistent, which can affect the obtained data for the project. This problem can be mitigated by using the same type of soil throughout the project.

1.4.2 Soil Variability

The composition of a soil sample is also a challenge for this project. Even when the same type of soil will be used throughout the project for testing, the results obtained may not be the same for each soil sample as soil samples can have different compositions of chemical components. This problem can be minimized by using the same type of soil throughout the project.

1.4.3 Laboratory Soils Testing

The consistency of data obtained from soils testing is a challenge for the project. The test on soils can produce different data even when using the same procedure on the same sample. To mitigate this problem, the team will conduct a minimum of three trials on each sample and average the results.

1.5 Stakeholders

The stakeholders of this project are the client, cement manufacturing companies, construction companies and the global community. Each of the stakeholders will have a stake in the outcome of this project.

1.5.1 The Client

Professor Alarick Reiboldt, Civil and Environmental Engineering Instructor at Northern Arizona University, is the client who requested for the project. This project will provide him more information for his research on CCKD.

1.5.2 Cement Manufacturing Companies

Cement manufacturing companies will be benefit from the obtaining of CKD as CKD is currently listed as a by-product of the cement manufacturing process.

1.5.3 Construction Companies

Construction companies will be the ones using the product (CCKD) if CCKD proves to be a good stabilizer for soils.

1.5.4 Global Community

The production of CCKD will reduce the amount of CO_2 created by the cement manufacturing process. Therefore, the global community can be benefit from the reduction of CO2 in the atmosphere.

1.6 Scope of Services

This section of the proposal describes the work that the project team will conduct to implement the project and meet the client's needs to complete the study on Carbonated Cement Kiln Dust (CCKD) as a soil stabilization amendment. The team will have 6 main tasks to be done as shown below.

Task 1.0: Literature Review

A literature review will provide the team with a deeper understanding of key points prior to working on the project. The literature review helps the team determine an experimental design for the project based on previous studies.

Task 2.0: Soil Selection

Task 2.1: Determining Soil Used

The data obtained from soil testing is usually not consistent. The composition of a soil sample is a challenge to the project. Even when same procedures of testing will be used throughout the project, the results obtained may not be the same for each soil sample as soil samples can have different compositions of chemical components. Therefore, the team will decide on what type of soil shall be used throughout this project to mitigate the errors obtained in soil testing. Because there are several previous studies on the use of lime, Class C Fly Ash and Cement Kiln Dust (CKD) as soil stabilizers, the team will contact the people who studied this case to determine what type of soil is most fitted for the project. By knowing the classification of soil that has been used in previous studies, the team can conduct testing on a similar type of soil and verify the obtained results with the results from previous studies.

Task 2.2: Obtaining Soil Samples

After determining what type of soil is most fitted for this project, the team will develop similar soil samples that belong to the same classification as the soil samples used in previous studies for this project. By using the same type of soils studied previously, the team may be able to mitigate the errors made when conducting technical works. The team will also have a basis to compare the tests' results to. Soil samples will be obtained from sites that are located within Flagstaff, Arizona.

Task 2.3: Soil Classification

The project team will conduct soil classification to determine if the soils obtained from sites belong to the same classification as mentioned above. To determine the classification of soil samples, the project team will conduct sieve analysis according to ASTM D421 to obtain the particle size distribution of soil samples, and Atterberg limit tests according to ASTM D4318-10e1 to obtain the Atterberg limits of soil (liquid limit and plastic limit). After knowing the particle size distribution and Atterberg limits of soil samples, the project team will analyze the results to determine if the obtained soil samples belong to the desired classification. Testing process will be done until the project team obtained the desired classification.

Task 3.0: Preparing Soil Samples

Task 3.1: Determining Amount of Mixtures

Based on previous studies, to determine the efficacy of CCKD as a stabilizer for soils, the team will prepare a minimum of 10 different soil mixtures. The type of soil used for this project shall be based on the previous study, which belongs to Port series and is classified as CL-ML with a liquid limit of approximately 27% and a plasticity index of approximately 5% [4]. One of the specimen will be prepared without the addition of lime, CKD and CCKD; and used for control. Other 9 mixtures will be prepared for the project by adding a specific amount of lime (3, 7, or 10%), CKD (5, 10 or 15%) and CCKD (9, 18 or 28%) to the raw soil. The mixture plan can be found in Table 1.1 below.

Table 1.1: Mixture Plan

Mixture	Control	Lime1	Lime2	Lime3	CKD1	CKD2	CKD3	CCKD1	CCKD2	CCKD3
Lime	-	3.42%	6.84%	10.27%	-	-	-	-	-	-
CKD	-	-	-	-	5%	10%	15%	-	-	-
CCKD	-	-	-	-	-	-	-	9.18%	18.36%	27.54%
Soil	100%	96.58%	93.16%	89.73%	95%	90%	85%	90.82%	81.64%	72.46%

Task 3.2: Obtaining Lime, CKD and CCKD

The amounts of Lime, CKD and CCKD obtained for the Capstone Project will be in accordance with the experimental plan explained above.

Task 3.3: Preparing Soil Mixtures

After obtaining Lime, CKD and CCKD, the project team will prepare the mixtures in accordance with the experimental plan explained above. Each amount of additive including the control will be prepared with 3 samples to ensure that the data is consistent between tests. The results of these tests before and after adding cement, CKD and CCKD will then be compared to determine the efficacy of CCKD as a soil stabilization amendment. Additional tests and statistical analysis will be considered in case that the obtained data is not consistent.

Task 4.0: Soil Strength Test

The following tests are necessary to determine the shear strength of soils: Direct Shear and Triaxial Shear Test (Unconsolidated Undrained Test). By obtaining the parameters that measure soil strength, the team will be able to determine if CCKD can help increase the strength of soil samples.

Task 4.1: Proctor Compaction Tests

The project team will conduct Proctor Compaction Test in accordance with ASTM D698 to determine optimum moisture content and maximum dry unit weight of soil samples.

Task 4.2: Direct Shear Test

The project team will conduct Direct Shear Test based on ASTM D3080 to obtain the data of shear stress to horizontal displacement and shear stress to normal stress to determine peak shear strengths, effective cohesions and effective friction angles of soil samples.

Task 4.3: Triaxial Shear Test

The project team will conduct Triaxial Test (Unconsolidated Undrained Test) based on ASTM D2850-03a to determine undrained shear strength of the soil sample.

Task 5.0: Analysis Results

The team will analyze obtained results from the testing process to obtain the desired properties of soil samples using statistical methods according to each test. The analyzing process will be conducted along with the testing process. The team will compare the results after each test to ensure that there is no mistake in results, and that the team will have enough time to redo the tests in case mistake occurs. After obtaining the desired properties of all soil samples, the team will compare the results of conducted tests with previous studies' results to determine if CKD/CCKD can be used as soil amendment.

Task 6.0: Project Management

To ensure quality deliverables of the results on time, the project team will conduct the following tasks for project management.

Task 6.1: Scheduling

The project team estimates the time each task will take. The estimated duration, start date and end date of each task are shown in Table 1.2 below.

Table 1.2: Project Schedule

Tasks	Start Date	End Date
1.0 Literature Review	Jan 16	Jan 29
2.0 Soil Selection	Jan 30	Feb 19
2.1 Determining Soil Used	Jan 30	Feb 5
2.2 Obtaining Soil Samples	Feb 6	Feb 12
2.3 Soil Classification	Feb 13	Feb 19
3.0 Preparing Soil Samples	Feb 20	Feb 26
3.1 Determining Amount of Mixtures	Feb 20	Feb 26
3.2 Obtaining lime, CKD and CCKD	Feb 20	Feb 26
3.3 Preparing Soil Mixtures	Feb 20	Feb 26
4.0 Soils Testing	Feb 27	Apr 9
4.1 Proctor Compaction Tests	Feb 20	Feb 26
4.2. Direct Shear Tests	Feb 27	Mar 19
4.3. Triaxial Shear Tests	Mar 20	Apr 9
5.0 Analysis Results	Apr 10	Apr 23
6.0 Project Management	Jan 16	May 5

Each task shall take certain duration as shown in Table 1.2. For Project Management, the project team will create a schedule at the start of the project. To ensure quality deliverables of the results on time, the team will conduct meeting once a week during the project duration. Therefore, project management tasks last throughout the project duration (approximately 4 months).

Task 6.2: Meetings

The team will have at least one team meeting every week to discuss tasks, and at least one meeting with the client every two weeks to report the results and plans for the tasks to follow. When conducting technical work, the team shall meet up with the technical advisor to ask for advices before conducting a new type of test.

Task 6.3: Deliverables

The team will document all the works done and compare with the schedule to ensure that the tasks are finished on time. The results of this project may also result in a published journal article. All deliverables will be delivered to the client by the end of CENE486 course.

1.7 Exclusions

The project team will only take responsibility to deliver work for the tasks listed in the Scope of Work for this project. The team will not take responsibility to finish work outside of this scope. Additional tasks will be considered if the tasks deem necessary for the project and approved by the client.

2.0 Technical Sections

This section of the final design report provides the details of work done by the team to obtain the desired results based on the project team's scope of work.

2.1 Literature Review

The soils used in the previous study on Engineering Properties and Moisture Susceptibility of Silty Clay Stabilized with Lime, Class C Fly Ash (CFA), and Cement Kiln Dust by professor Pranshoo Solanki from Illinois State University have a percent finer than sieve #200 of 94% (94% fines), a liquid limit of 27% and a plasticity index of 5%. According to Unified Soil Classification System (USCS), for soils with 50% or more fines, the soils used in previous study are classified as CL-ML Sandy Silty Clay. Table 2.1 below summarizes all necessary information regarding the soils used in previous study.

Table 2.1: Information on Soils used in Previous Study [4]

Method	Parameter/units	Value
ASTM D 2487	USCS Symbol	CL-ML
ASTM D 2487	% finer than 0.075 mm	83
ASTM D 422	% finer than 0.002 mm	11
ASTM D 4318	Liquid limit (%)	27
ASTM D 4318	Plasticity index (%)	5
ASTM D 854	Specific gravity	2.65
ASTM D 698	Optimum moisture content (%)	13.1
ASTM D 698	Max. dry unit weight (kN/m^3)	17.8
ASTM D 6276	pH	8.91

Note: USCS=Unified Soil Classification System.

A total of 40 specimens were prepared for previous study by adding a specific amount of additive, namely, lime (3, 6 or 9%), CFA (5, 10, 15%), and CKD (5, 10 or 15%) to the raw soil. These amounts of additives were determined based on the dry weight of soil (17.8 kN/m^3) as shown in Table 2.1. Prior to mixing, an amount of water based on the optimum moisture content of the raw soils was added to the specimens. Then, the mixtures were compacted according to Proctor Compaction Tests. After compaction, specimens were cured in a humidity room having a temperature of 23.0 ± 1.7°C and a relative humidity of approximately 96% for 28 days for specimens to obtain maximum strength [4].

However, for this project, because of the tight schedule, the project team will not be able to cure the specimens for a duration of 28-day to test the specimens at full strength. Therefore, after discussing with the technical advisor for this Capstone project, Professor Alarick Reiboldt, the project team determined to cure the specimens for a 7-day period, as curing the specimens for 7 days will allow the specimens to reach a certain minimum degree of strength prior to testing [7].

2.2 Soil Selection

CL-ML Sandy Silty Clay (USCS Classification) is the type of soils that the project team decided to use for this Capstone project.

2.2.1 Determining Soil Used

The data obtained from soils testing is usually not consistent. The composition of a soil sample is a challenge to the project. Even when the same procedure for a test is used, the result will vary from sample to sample. By conducting testing on a similar type of soil and verify the obtained results with results obtained from previous study, the project team can mitigate the errors obtained in soil testing. Therefore, the project team decided to use soils that belong to the same USCS classification as the soils used in previous study (CL-ML Sandy Silty Clay).

2.2.2 Obtaining Soil Samples

Because CL-ML Sandy Silty Clay is not available in Flagstaff, the project team decided to look for locations with silt-rich sediment. The team decided on the location after contacting NAU Geology faculty. Figure 2.1 below shows the location where the project team obtained the soils.

Figure 2.1: Silt-Rich Sediment Site

The location is located near NAU P63, close to E. Pine Knoll Dr. The team collected the soil three times. Each time, the team get over 50 kilograms of soils.

However, because the soils at this location do not belong to the same classification as soils used in previous study, the team had to engineer soils that belong to CL-ML Sandy Silty Clay classification by sieving. Through the sieving process, the project team was able to obtain approximately 35 kilograms of desired soils to use for this project.

2.2.3 Soil Classification

2.2.3.1 Sieve Analysis

Three (3) Sieve Analyses were conducted in accordance with ASTM D421 procedure to determine the percent finer of soils obtained from site. Data from Sieve Analysis can be found in Appendices A to C.

The original soil samples at site near NAU P63 have percent gravels of 22%, percent sands of 62% and percent fines of 16%. Table 2.2 below shows the average percent finer of each sieve.

Table 2.2: Average Percent Finer (PSD)

Sieve #	Sieve opening (mm)	Soil #1's % Finer	Soil #2's % Finer	Soil #3's % Finer	Average % Finer (AVG)
4	4.75	77.83	77.83	87.79	81.15
10	2	61.04	61.48	75.74	66.09
20	0.85	46.17	47.07	59.62	50.95
40	0.425	38.06	38.78	50.43	42.42
60	0.25	33.06	33.47	43.90	36.81
140	0.106	24.51	24.46	31.07	26.68
200	0.075	15.41	14.95	19.12	16.49
Pan	0.01	0.00	0.00	0.00	0.00

The average PSD graph is shown in Figure 2.2 below.

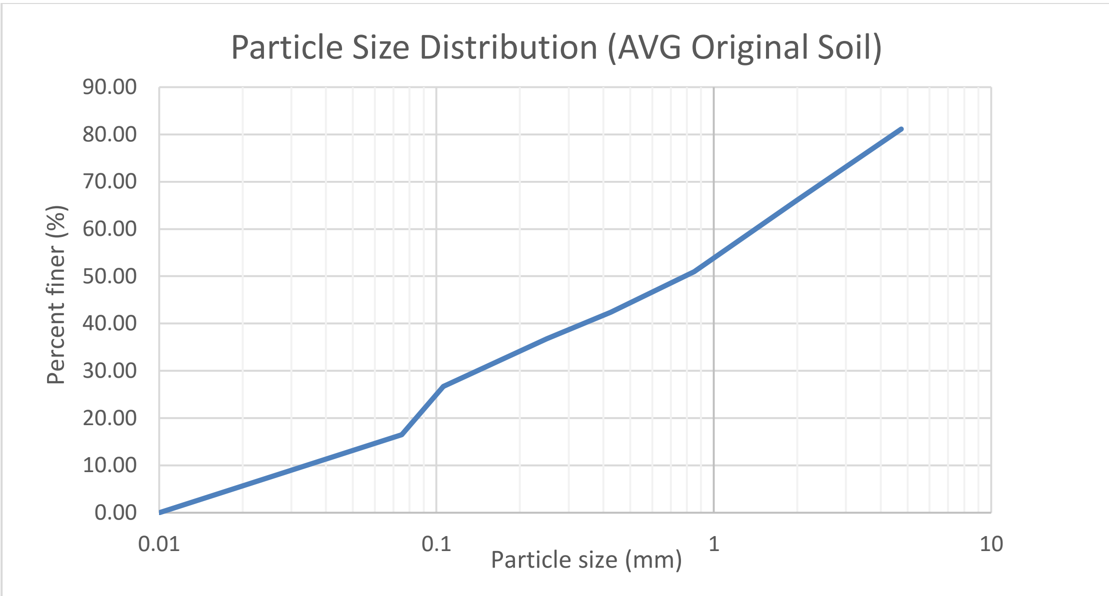

Figure 2.2: Average PSD Graph

2.2.3.2 Atterberg Limit Tests

Using soils retained on and passing through sieve #200, the project team conducted Atterberg Limit Tests in accordance with ASTM D4318-10e1. The soil samples have a liquid limit of 29.41% ± 1.488% and a plastic limit of 24.23% ± 0.8633%, resulting in a plasticity index of approximately 5.2%.

Tables 2.3 and 2.4 below show the results of Atterberg Limit Tests. Refer to Appendix D for data obtained from Atterberg Limit Tests.

Table 2.3: Average Liquid Limit

Sample #	**Liquid Limit (LL)**
LL1	28.71
LL2	29.13
LL3	31.88
LL4	27.93
Average Liquid Limit	**29.41**
Standard Deviation	**1.488**

Table 2.4: Average Plastic Limit

Sample #	**Plastic Limit (PL)**
PL1	24.59
PL2	23.90
PL3	26.32
PL4	23.31
PL5	23.93
PL6	24.19
PL7	23.64
PL8	23.95
Average Plastic Limit	**24.23**
Standard Deviation	**0.8633**

The average liquid limit and plasticity index obtained from Atterberg Limit Tests on soils obtained from the site in Flagstaff are close to the limit values of the soils used in previous study (27% and 5%, accordingly).

2.2.3.3 Soil Classification

Based on the Sieve Analysis and Atterberg Limit Tests' Results, the USCS classification for soils obtained from the site is **SM Silty Sand**.

Therefore, the team decided to keep only soils retained and passing through sieve #200. 'Sand' portion of these samples includes soils that pass through sieve #140, resulting in a soil sample that have roughly 40% sand and 60% fines. The USCS classification for the engineered soils is **CL-ML Sandy Silty Clay**.

Table 2.5 below shows the average PSD of the engineered soils. Refer to Appendices E to G for data on Engineered Soils.

Table 2.5: Engineered Soil's Average PSD

Sieve #	Sieve Opening (mm)	Soil 1's % finer	Soil 2's % finer	Soil 3's % finer	AVG % Finer
140	0.106	100.00	100.00	100.00	100.00
200	0.075	62.86	61.14	61.54	61.85
Pan	0.01	0	0	0	0

Figure 2.3 shows the average PSD graph of the engineered soils.

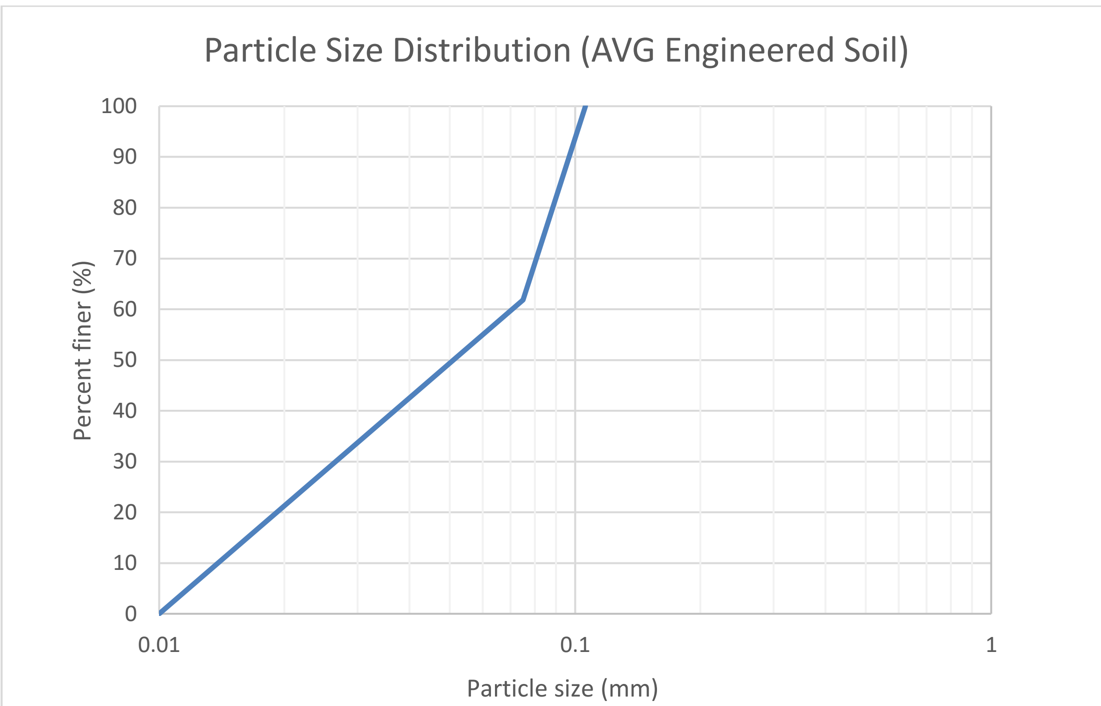

Figure 2.3: Engineered Soil's Average PSD Graph

2.3 Preparing Soil Mixtures

2.3.1 Determining Amount of Mixtures

To prepare soil mixtures, the team first determined the amount of additive that needs to be added to each sample before obtaining Lime, CKD and CCKD.

The engineered soils have a maximum dry unit weight of 16.91 kN/m^3, which is close to the maximum dry unit weight of the soils used in previous study. Therefore, the team decided to prepare CKD mixtures at 5, 10 and 15% like previous study.

For lime and CCKD mixtures, the amounts of lime and CCKD added to the mixtures were based on the percentage of Calcium Oxide (CaO) in the CKD provided. The chemical components of CKD are as shown in Table 2.6 below.

Table 2.6: CKD Chemical Components

CKD Chemical Components	SiO_2	13.83%
	Al_2O_3	3.00%
	Fe_2O_3	1.54%
	CaO	64.72%
	MgO	0.82%
	SO_3	5.31%
	Na_2O	0.05%
	K_2O	3.66%
	TiO_2	0.17%
	Cl	1.47%
	LOI	5.43%
	Total	**100.00%**
	Fineness (Passing 200 M)	91.41%

As shown in Table 2.6, Calcium Oxide (CaO) is 64.72% of CKD. Therefore, for lime samples to have the same amount of CaO as CKD, the project team decided to mix lime samples based on the proportion of CaO in CKD (64.72% to 94.57%), which was calculated to be 68.44%. The percent admixtures for lime samples were then calculated to be 3.42, 6.84 and 10.27% accordingly to 5, 10 and 15% CKD mixtures.

For CCKD samples, the percent admixtures were determined based on the amount of CKD reacting with CO_2 to be 9.18%, 18.36% and 27.54%. Refer to Appendix H for the stoichiometry analysis of CKD.

Table 2.7 below shows the amount of lime, CKD and CCKD as aggregates needed to add to each mixture.

Table 2.7: Amount of Lime. CKD and CCKD needed to add

Mixture	% Admixture	% Soil	Soil Amount (kg)	Mixture Amount (kg)	Aggregate Amount (kg)
Lime 1	3.42%	96.58%	3	3.10629	0.10629
Lime 2	6.84%	93.16%	3	3.22039	0.22039
Lime 3	10.27%	89.73%	3	3.34319	0.34319
CKD 1	5.00%	95.00%	3	3.15789	0.15789
CKD 2	10.00%	90.00%	3	3.33333	0.33333
CKD 3	15.00%	85.00%	3	3.52941	0.52941
CCKD 1	9.18%	90.82%	3	3.30319	0.30319
CCKD 2	18.36%	81.64%	3	3.67456	0.67456
CCKD 3	27.54%	72.46%	3	4.14001	1.14001

2.3.2 Obtaining Lime, CKD and CCKD

The total amounts of lime, CKD and CCKD needed are as shown in Table 2.8 below. These values were calculated based on the percent of lime (CaO) in CKD and CCKD.

Table 2.8: Total Amounts Needed

Total Lime	0.66987 kg
Total CKD	1.02064 kg
Total CCKD	2.11777 kg

The project team was able to obtain lime from lab manager Gerjen Slim; and CKD along with CCKD from Professor Alarick Reiboldt.

2.3.3 Preparing Soil Mixtures

Soil Mixtures were prepared in accordance with the values mentioned in Tables 2.7 and 2.8 above. Prior to mixing, a certain amount of water (approximately 0.52 kg) based on the soils' Optimum Moisture Content of 17.43% of raw soils) was added to the samples. All mixtures were packed and will be left for a period of 7-day to ensure the components mix well together.

2.4 Soils Testing

After conducting Proctor Compaction Tests in accordance with ASTM D698-91 and preparing soil mixtures, the team conducted at least three (3) Direct Shear Tests and three (3) Triaxial Shear Tests on each mixture. The project team started testing process for control samples on February 25, 2017. Summary of results is shown in the sections below.

2.4.1 Proctor Compaction

The project team conducted three (3) trials of Proctor compaction tests in accordance with ASTM D698-91. Refer to Appendices I to K for raw data from each trial. Table 2.9 below shows the average values of optimum moisture content and maximum dry unit weight.

Table 2.9: Proctor Tests' Results

Proctor Compaction Test #	1	2	3
Optimum Moisture Content (OMC) (%)	16.20	18.98	17.10
Maximum Dry Unit Weight (MDUW) (kN/m3)	17.45	16.54	16.74
AVG OMC	17.43 %		
AVG MDUW	16.91 kN/m^3		

2.4.2 Direct Shear

The Direct Shear machine was broken during Spring 2017 semester, and the replacements could not come in time for the deliverables. The project team was only able to obtain results for Control and Lime 1 mixtures. After the discussion with the client, Direct Shear results and analysis were excluded from deliverables.

2.4.3 Triaxial Shear: Unconsolidated Undrained

Thirty (30) tests of Triaxial Shear: Unconsolidated Undrained were conducted for this project in accordance with ASTM D2850-03a. All samples for Triaxial Shear tests were made using modified proctor hammer and a 4” compaction mold. Figure 2.4 shows a molded sample. These samples were then shaved down to the size that is fit for Triaxial Shear test. Refer to Section 2.5 for results of analysis.

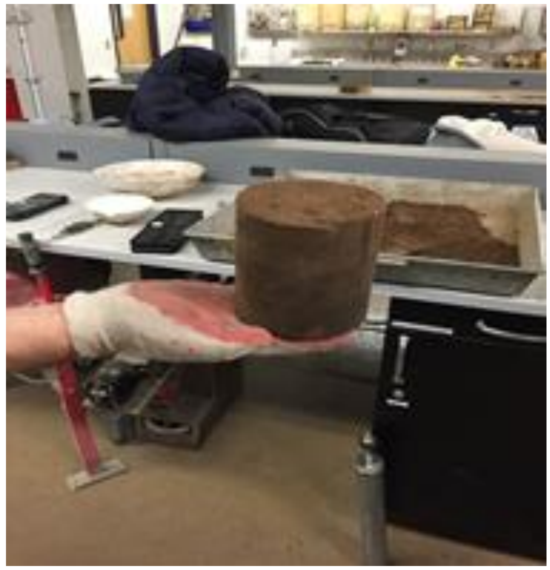

Figure 2.4: Molded Sample

2.5 Results of Analysis

Results from Triaxial Shear Tests are discussed in this section.

2.5.1 Triaxial Shear Results of Analysis

Table 2.10 below shows the average results obtained from thirty (30) Unconsolidated Undrained tests on ten (10) different proposed mixtures.

Table 2.10: Triaxial Shear Results with Percent Increase in Strength Compared to Control Samples

Mix	Amount of Calcium Oxide in Mix (%)	Average Shear Strength (psi)	Standard Deviation (psi)	Percent Increase (%)
Control	0	12.29	0.8428	-
CCKD1	3.273	22.98	3.309	87.06
CCKD2	6.546	21.44	2.960	74.47
CCKD3	9.819	28.06	4.121	128.4
CKD1	3.273	17.11	12.12	39.23
CKD2	6.546	17.94	1.895	46.06
CKD3	9.819	21.01	2.584	71.01
Lime1	3.273	9.983	7.249	-18.74
Lime2	6.546	26.81	9.578	118.3
Lime3	9.819	21.49	2.143	74.93

As shown in table 2.10 in green, CCKD 3 mixture has the highest average shear strength of 28.06 psi ± 4.121 psi with a percent increase of 128.4% compared to Control mixture. Meanwhile, Lime 1 mixture shows a slight decrease in strength compared to Control mixture with a very high standard deviation. The reasons for samples having high standard deviations in mixtures will be discussed further in Section 2.5.2.

Figure 2.5 below shows a comparison between average undrained shear strength and the percentage equivalent to the amount of Calcium Oxide in each mixture. Refer to Appendices L to N for more details on the results of different aggregates versus the results of Control mixture.

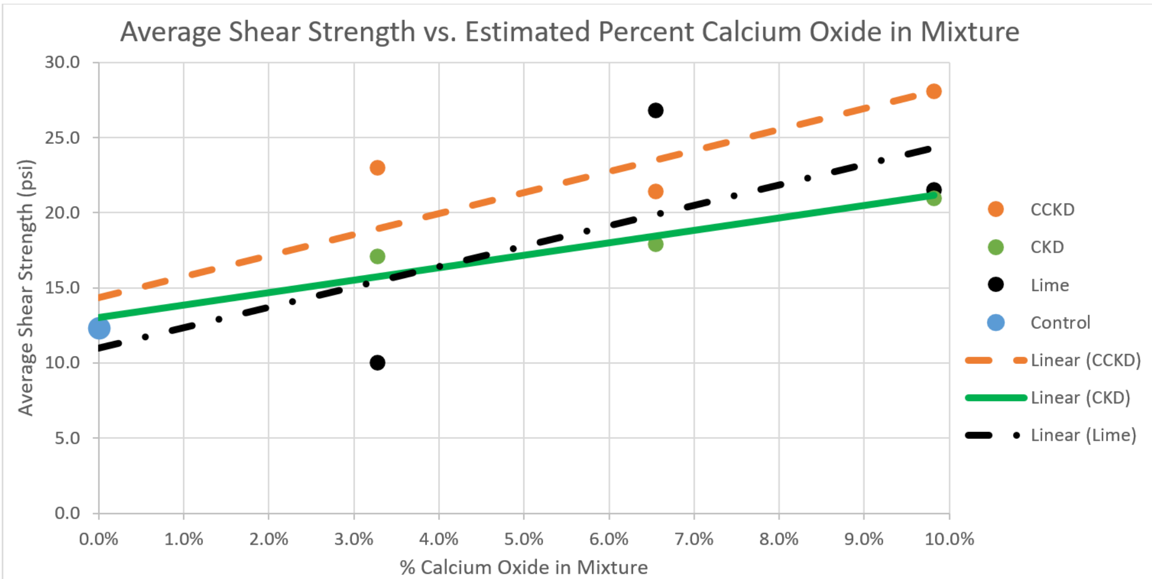

Figure 2.5: Average Shear Strength versus Estimated Percent Calcium Oxide in Mixture

As shown in Figure 2.5, the undrained shear strengths of all samples show a tendency of increase along with the percentage of Calcium Oxide in the mixtures, which is similar to the results obtained in previous study. The average results show that CCKD mixtures will produce the highest amount of shear strength compared to CKD and Lime mixtures.

Also, Figure 2.5 shows that the results from CKD and CCKD mixtures are more reliable compared to results from lime mixtures: the results from CKD and CCKD mixtures are closer to the linear fit lines while the results from lime mixtures are far apart. It is highly recommended to do similar tests to confirm the results obtained from lime mixtures.

The results obtained in this study agree that shear strength of a soil sample will increase as the percent of Calcium Oxide in the soil sample increases. However, the project team did not determine the maximum amount of CCKD that should be added to soil samples for the soils to reach maximum shear strength as this task was not part of the team's scope. It is highly recommended for the client to request another study on how much CCKD can be added to soil samples.

2.5.2 Factors Affecting Triaxial Shear Results

As shown in Section 2.5.1, the results obtained from this study highly vary with some samples having very high standard deviations. The project team indicated four (4) main factors that could have affected the preciseness of the results.

2.5.2.1 Shape of Samples

All samples for Triaxial Shear test were made using modified proctor hammer and a 4" compaction mold. Because samples made from 4" compaction mold are not fit for use in Triflex system, the project team had to shave the sample down to fit into the machine. The process of shaving the samples down could have damaged the externals of the compacted samples, reducing the strength of the samples.

2.5.2.2 Contents of CKD and CCKD Added when Preparing Mixtures

CKD and CCKD contain many different chemical components aside from Calcium Oxide as shown in Table 2.6 (CKD Chemical Components). Even though the project team tried to minimize the difference in contents added to create mixtures by mixing the aggregate up evenly prior to preparing the mixtures, the fact that the contents of CKD and CCKD added to the mixtures is unknown could have reduced the preciseness of obtained results.

2.5.2.3 Amount of Calcium Oxide Added to Each Sample

Each mixture made was used to create three (3) samples. By conducting three (3) tests on each mixture, the project team minimized the error presented in the percent of Calcium Oxide added in each mixture. However, the amount of Calcium Oxide added to each sample from the mixture could have varied between samples, resulting in different amounts of Calcium Oxide added and high standard deviations.

2.5.2.4 Moisture Loss during Curing Process

During the 7-day curing process, the project team left the samples inside the laboratory at room temperature. However, the project team did not test for moisture loss in samples with different aggregates. The moisture loss could have varied between samples with different aggregates, reducing the strengths of samples and the preciseness of obtained results.

2.6 Project Management

The project team prepared all deliverables to meet the schedules of CENE486C-1 Spring 2017. These deliverables include 50% Design Report, Project Status Presentations (1, 2 & 3), Project Status Meetings and Final Design Report.

Aside from Project Deliverables, the team also met up and discussed every week to ensure the project tasks are delivered on time with quality.

2.7 Project Impacts (Applications of Results)

The results of this study show that the shear strength of soils will increase by adding CCKD to soils. Shear strength increase will help resist failure and sliding along any plane inside soils, proving the use of CCKD as aggregate for soils used in foundations. A notable example of soils with weak shear strength as foundation is Leaning Tower of Pisa in Italy: this tower leans because its foundation is not supported by soils with high shear strength.

By proving the use of CCKD as a soil stabilizer to increase soils strength, this study has several direct impacts on different aspects of social, environmental and economic.

CCKD manufacturing process required CKD to react with Carbon Dioxide (CO_2) under the right conditions. This process will help reduce the amount of gaseous Carbon Dioxide in the atmosphere, greatly benefiting the global community. Also, because CKD has to react with Carbon Dioxide under the right conditions, potential new jobs will be available for the manufacturing process of CCKD.

Because CKD can be used to create CCKD mixtures, cement manufacturers will no longer have to treat CKD as waste, thus reducing the amount of CKD waste put to landfill. This will not only impact the environment, but also have huge impact on the economy. Moreover, producing CCKD from CKD waste will save natural resources by reducing the use of new materials as stabilizers.

2.8 Cost of Implementing the Design

This project is only a preliminary study on the use of CCKD as a soil stabilizer. The results obtained from this study proved that by adding CCKD to soils, the shear strength of soils will increase. However, the maximum amount of CCKD that can be added to soils was not determined as this is not part of this study's scope. For more efficiency in the use of CCKD as a soil stabilization amendment, it is highly recommended for the client to consider a more in-depth study into other properties and characteristics of CCKD before implementing the uses of CCKD.

3.0 Summary of Project Costs

3.1 Project Staffing

The project team consists of a senior engineer, an engineer and two (2) engineering interns. The senior engineer and the engineer are responsible for supervising and approving testing procedures, while the two (2) engineering interns helped conduct testing in the laboratory. Table 3.1 shows classifications, codes and qualifications for all the mentioned staff positions.

Table 3.1: Project Staff Descriptions and Qualifications

Staff Positions		
Classification	**Code**	**Qualifications**
Senior Engineer	SENG	Minimum of Bachelor's Degree in Civil Engineering, Licensed PE, at least 10 years of work experience
Engineer	ENG	Minimum of Bachelor's Degree in Civil Engineering, Licensed EIT, at least 2 years of work experience
Engineering Intern	INT	Minimum of Bachelor's Degree in Civil Engineering

Billing rate for each personnel classification is as shown in Table 3.2 below. Billing rates include base pay rates, benefits percentages of base pay rate and actual pays per hour. The profit percentage of actual pay has already been taken into consideration.

Table 3.2: Billing Rates

Classification	Base Pay Rate $/hr	Benefits % of Base Pay Rate	Actual Pay $/hr	Billing Rate $/hr
SENG	88	30	115	**115**
ENG	36	60	58	**58**
INT	25	80	45	**45**

The staffing hours are based on the time the engineers in the project team spent on tasks per scope of services. The total actual hours and predicted hours are as shown in Table 3.3.

Table 3.3: Project Hours

Task	SENG (hrs)	ENG (hrs)	INT (hrs)	Actual Hours	Predicted Hours
1.0 Literature Review	20	40	-	60	120
2.0 Soil Selection				170	128
2.1 Determining Soil Used	*25*	*10*	*-*	*35*	*48*
2.2 Obtaining Soil Samples	*-*	*10*	*100*	*110*	*40*
2.3 Soil Classification	*-*	*12.5*	*12.5*	*25*	*40*
3.0 Preparing Soil Samples	-	47	47	94	40
4.0 Soil Strength Tests				181.25	166
4.1 Proctor Compaction	*-*	*1.5*	*20*	*21.5*	*0*
4.2 Direct Shear Tests	*-*	*7*	*35*	*42*	*68*
4.3 Triaxial Shear Tests	*-*	*17.75*	*100*	*117.75*	*98*
5.0 Analysis Results	9.25	18.5	-	27.75	120
6.0 Project Management				111.75	228
6.1 Scheduling	*28.75*	*-*	*-*	*28.75*	*8*
6.2 Meetings	*17*	*17*	*17*	*51*	*60*
6.3 Deliverables	*16*	*16*	*-*	*32*	*160*
TOTAL (HRS)	**116**	**197.25**	**331.5**	**644.75**	**802.00**

From Table 3.3, the senior engineer committed 116 hours while the engineers spent 197.25 hours on supervising, approving testing procedures and analyzing results. The engineering interns worked for a total of 331.5 hours in the laboratory for mixtures' preparations and soils testing.

Also, as shown in Table 3.3, for actual hours, listed in green are the hours that the project team spent less than predicted, while listed in red are the hours that the project team spent more than predicted. The actual total hours committed to work on this study is 644.75 hours, less than the total predicted of 802 hours. This is mainly because some of the tasks such as analyzing results and management required less time than predicted.

Figure 3.1 shows the predicted Gantt chart that was proposed in Fall 2016 semester for this study. As shown in Figure 3.1's critical paths, all tasks are related to each other. The project team had to finish one task before starting the next one.

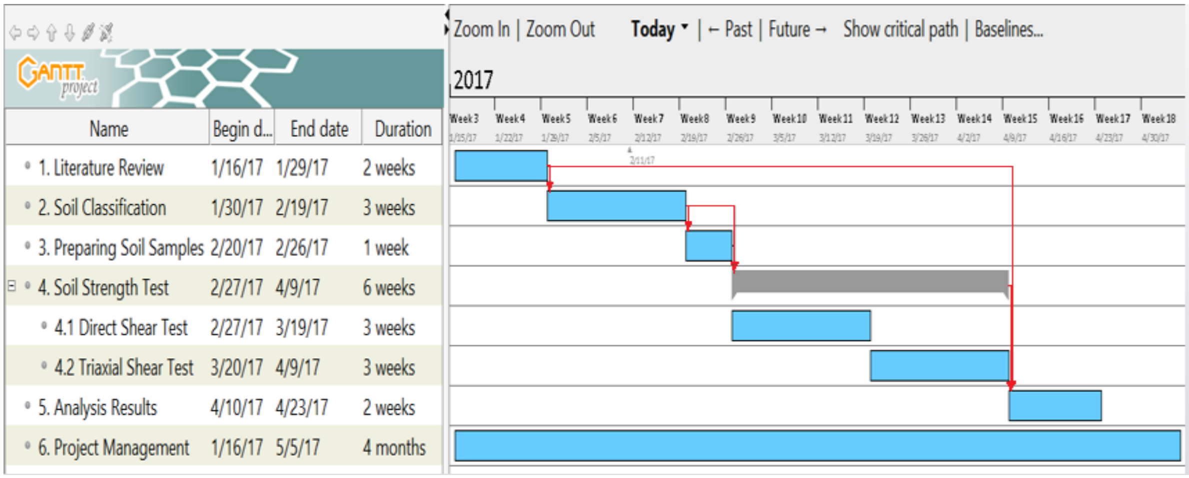

Figure 3.1: Gantt Chart (Predicted)

Figure 3.2 shows the actual Gantt chart for Spring 2017 semester based on the time the project team spent on this study. The actual Gantt chart is similar to the predicted Gantt chart in a way that all tasks are related to each other. The only differences between the two Gantt charts are that soil samples were prepared along with testing process, and that Direct Shear tests and Triaxial Shear tests were started at the same time.

The reason for the difference between the two Gantt charts is that project team was divided into two (2) teams: one was responsible for Direct Shear tests and the other was responsible for Triaxial Shear tests. Also, the project team determined that it was not possible to prepare all soil samples prior to testing process as the amount of samples made and used in this study was more than thirty (30) samples (including failed and retested samples), which require a lot of time for preparing and testing.

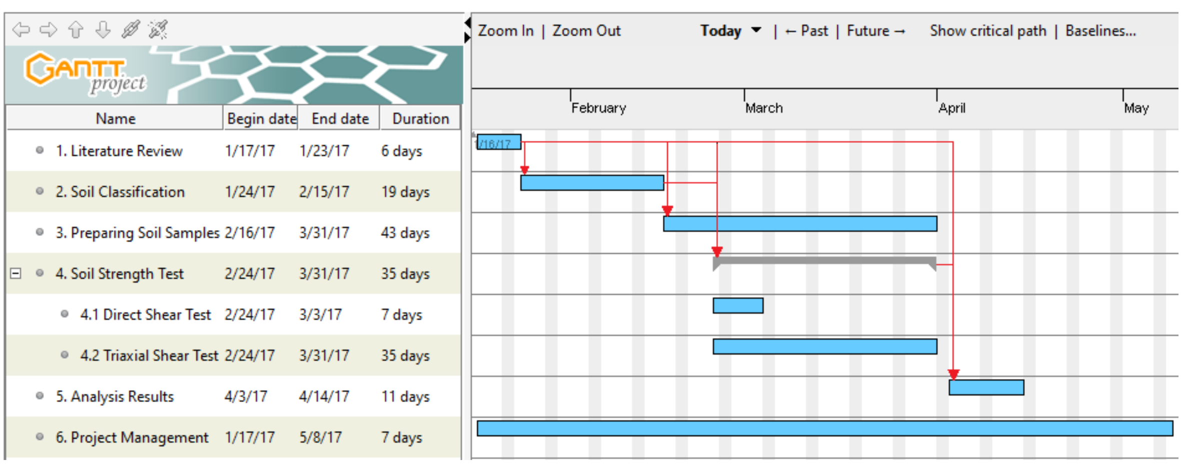

Figure 3.2: Gantt Chart (Actual)

3.2 Laboratory Cost

All testing procedures were conducted in the NAU Civil Engineering laboratory. The charge rate was based on the rate for use of NAU Civil Engineering laboratory ($100 per hour).

3.3 Summary of Project Costs

The total cost for this project is the sum of personnel and laboratory cost. Table 3.4 shows the summary of project costs.

Table 3.4: Summary of Project Costs

Engineering Services	Classification	Staffing Hours	Billing Rate	Actual Cost	Projected Cost
Personnel	SENG	116 hrs	$115/hr	$13,340	$22,540
	ENG	197.25 hrs	$58/hr	$11,441	$20,648
	INT	331.5 hrs	$45/hr	$14,918	$11,250
	Total Personnel			**$39,698**	**$54,438**
Laboratory Work	Soil Classification	6 hrs	$100/hr	$600	$4,000
	Sieving Soils	30 hrs	$100/hr	$3,000	-
	Proctor Compaction	9 hrs	$100/hr	$900	-
	Direct Shear	12 hrs	$100/hr	$1,200	$6,000
	Triaxial Shear (UU)	90 hrs	$100/hr	$9,000	$9,000
	Total Laboratory Cost			**$14,700**	**$19,000**
TOTAL COST				**$54,398**	**$73,438**

The actual total cost for this project is **$54,398**, which is less than the predicted cost of **$73,438**. The main reason for the difference is that personnel committed less hours for all tasks than predicted.

4.0 References

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5.0 Appendices

Appendix A: Sieve Analysis's Data on Raw Soil #1

Table 5.1: Data Soil #1

Sieve #	Sieve opening	Mass of sieve, A	Mass of sieve and	Mass of sample, W_n	Percent of mass	Cumulative percent $\sum R_n$	Percent finer, $(100 - \sum R_n)$
4	4.75	513.8	624.6	110.8	22.17	22.17	77.83
10	2	438.5	522.4	83.9	16.79	38.96	61.04
20	0.85	413.6	487.9	74.3	14.87	53.83	46.17
40	0.425	399.1	439.6	40.5	8.10	61.94	38.06
60	0.25	346.4	371.4	25	5.00	66.94	33.06
140	0.106	339	381.7	42.7	8.55	75.49	24.51
200	0.075	319.1	364.6	45.5	9.11	84.59	15.41
Pan	0.01	366.6	443.6	77	15.41	100.00	0.00
Σ	xx	xx	Xx	499.7	100		

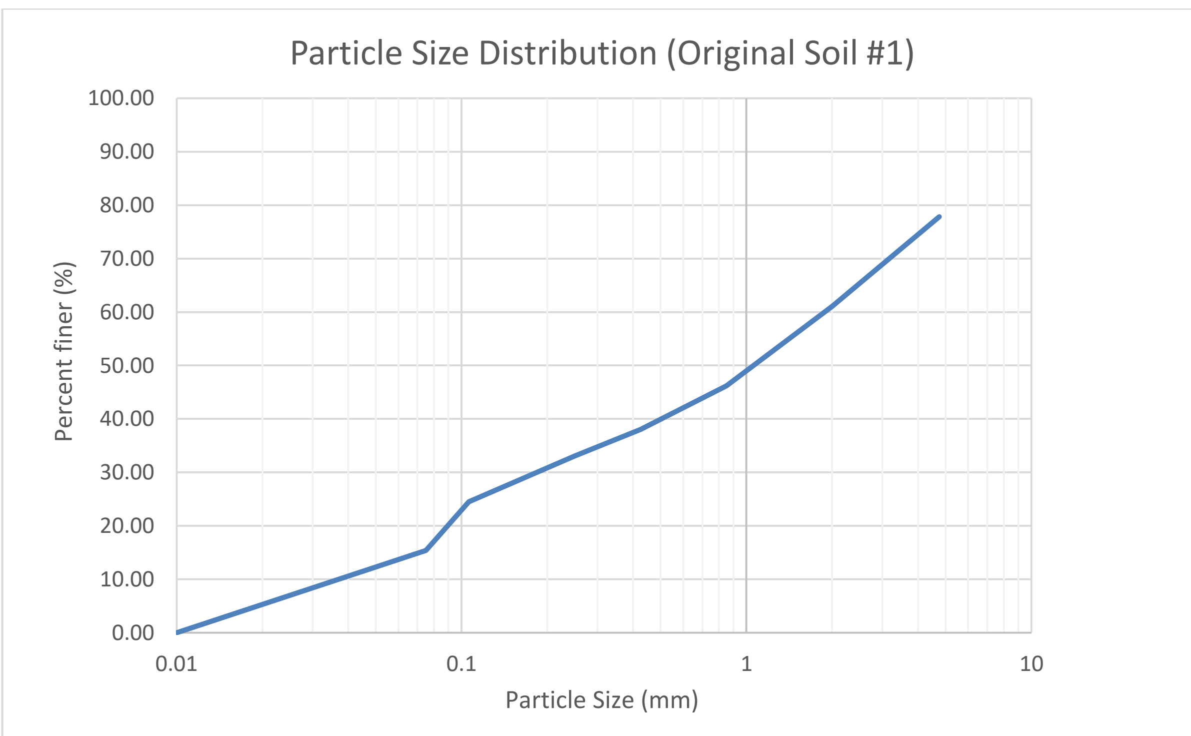

Figure 5.1: PSD Soil #1

Appendix B: Sieve Analysis's Data on Raw Soil #2

Table 5.2: Data Soil #2

Sieve #	Sieve opening	Mass of sieve, A	Mass of sieve and	Mass of sample,	Percent of mass	Cumulative percent $\sum R_n$	Percent finer, $(100 - \sum R_n)$
4	4.75	513.8	625.3	111.5	22.17	22.17	77.83
10	2	438.5	520.7	82.2	16.35	38.52	61.48
20	0.85	413.6	486.1	72.5	14.42	52.93	47.07
40	0.425	399.1	440.8	41.7	8.29	61.22	38.78
60	0.25	346.4	373.1	26.7	5.31	66.53	33.47
140	0.106	339	384.3	45.3	9.01	75.54	24.46
200	0.075	319.1	366.9	47.8	9.50	85.05	14.95
Pan	0.01	366.6	441.8	75.2	14.95	100.00	0.00
Σ	xx	xx	xx	502.9	100		

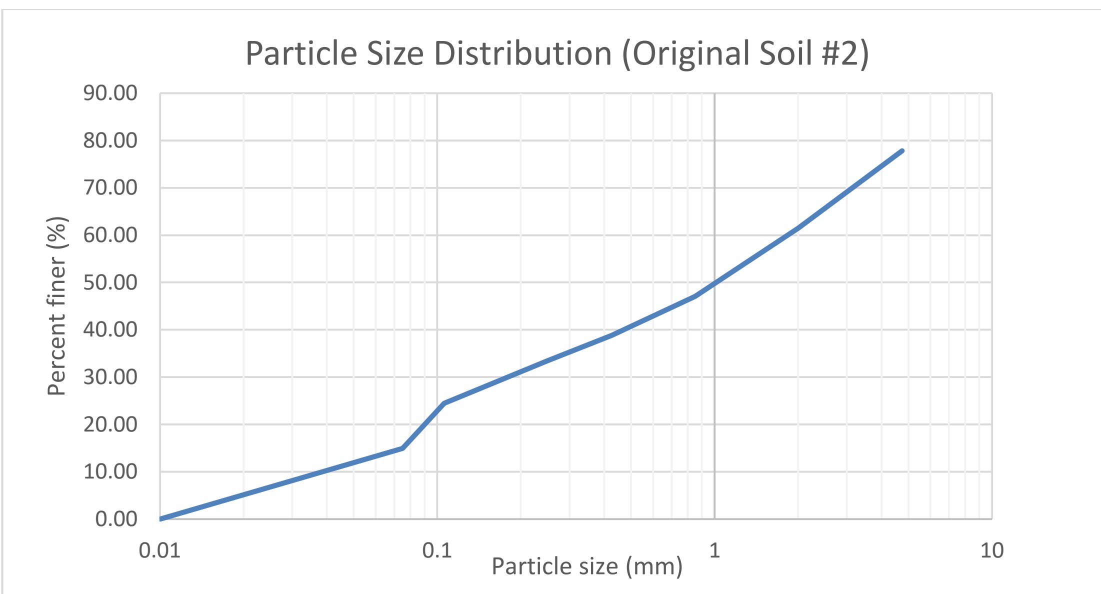

Figure 5.2: PSD Soil #2

Appendix C: Sieve Analysis's Data on Raw Soil #3

Table 5.3: Data Soil #3

Sieve #	Sieve opening	Mass of sieve, A	Mass of sieve and	Mass of sample,	Percent of mass	Cumulative percent $\sum R_n$	Percent finer, $(100 - \sum R_n)$
4	4.75	732.3	793.4	61.1	12.21	12.21	87.79
10	2	450.1	510.4	60.3	12.05	24.26	75.74
20	0.85	416.1	496.8	80.7	16.12	40.38	59.62
40	0.425	361.2	407.2	46	9.19	49.57	50.43
60	0.25	372.4	405.1	32.7	6.53	56.10	43.90
140	0.106	338.8	403	64.2	12.83	68.93	31.07
200	0.075	341.4	401.2	59.8	11.95	80.88	19.12
Pan	0.01	370.4	466.1	95.7	19.12	100.00	0.00
Σ	xx	xx	xx	500.5	100		

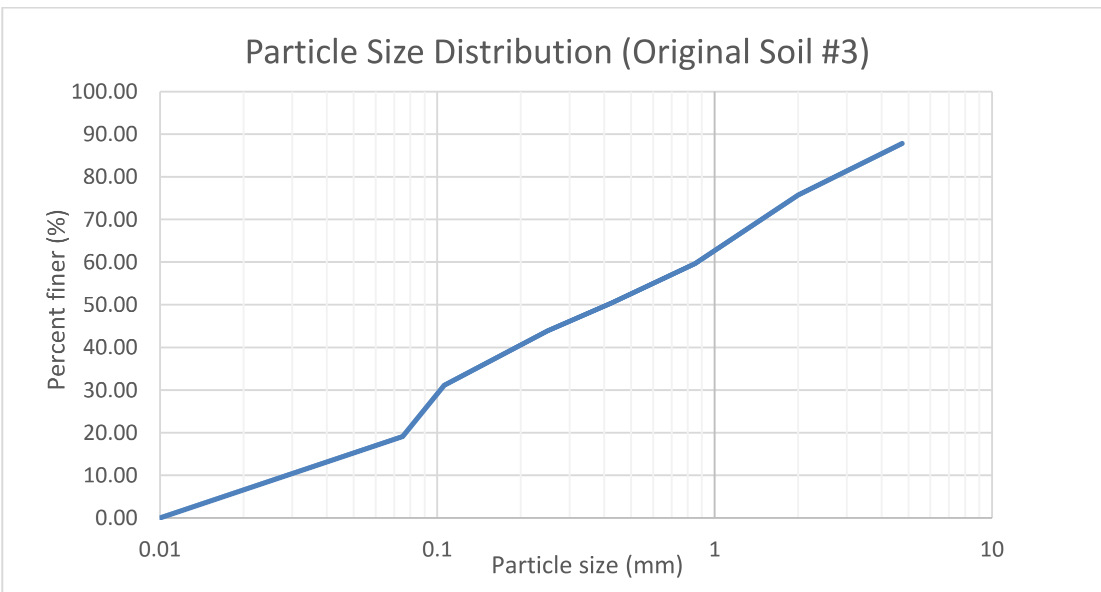

Figure 5.3: PSD Soil #3

Appendix D: Atterberg Limit Tests' Data

Table 5.4: Plastic Limit Data

Can	Wcan	Wmoist	Wdry	Wm-Wd	Wd-Wc	PL
1	11.99	16.55	15.65	0.9	3.66	24.59
2	11.73	14.27	13.78	0.49	2.05	23.90
3	11.66	13.1	12.8	0.3	1.14	26.32
4	11.57	14.85	14.23	0.62	2.66	23.31
5	15.66	17.68	17.29	0.39	1.63	23.93
6	12.58	14.12	13.82	0.3	1.24	24.19
7	11.46	12.82	12.56	0.26	1.1	23.64
8	11.87	14.82	14.25	0.57	2.38	23.95
				Average	PL =	**24.23**

Table 5.5: Liquid Limit Data

Can	Wcan	Wmoist	Wdry	Wm-Wd	Wd-Wc	w	N	LL
1	31.12	35.2	34.29	0.91	3.17	28.71	25	28.71
2	22.5	30.9	28.99	1.91	6.49	29.43	23	29.13
3	22.3	28.8	27.25	1.55	4.95	31.31	29	31.88
4	22.7	30.6	28.91	1.69	6.21	27.21	31	27.93
							Average LL =	**29.41**

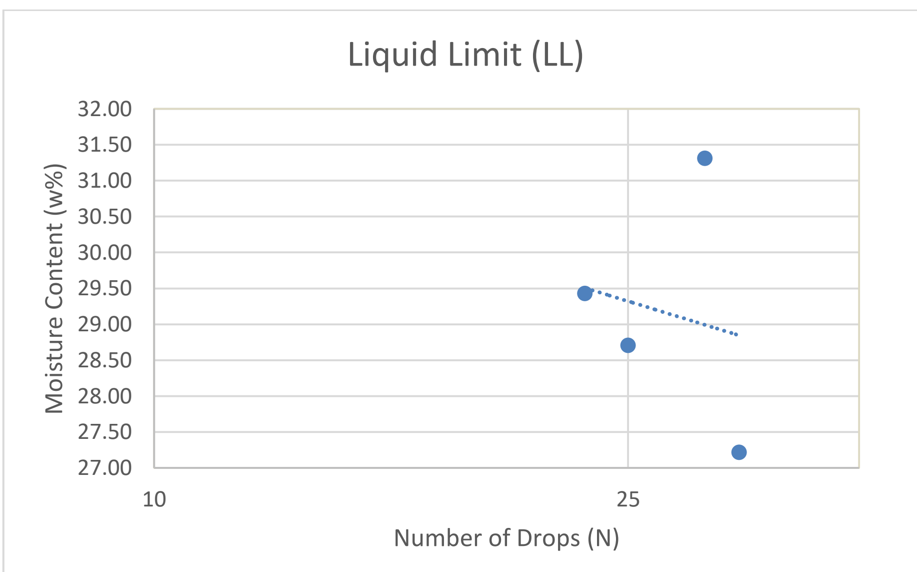

Figure 5.4: Liquid Limit Graph

Appendix E: Engineered Soil #1

Table 5.6: Engineered Soil #1

Sieve #	Sieve opening (mm)	Mass of sieve, A (g)	Mass of sieve and retained sample, B (g)	Mass of sample, W_n (g)	Percent of mass retained, R_n	Cumulative percent retained	Percent finer
140	0.106	n/a	n/a	0	0.0	0.0	100.0
200	0.075	319.1	364.6	45.5	37.1	37.1	62.9
Pan	0.01	366.6	443.6	77	62.9	100.0	0.0
Sum	xx	xx	xx	122.5	100		

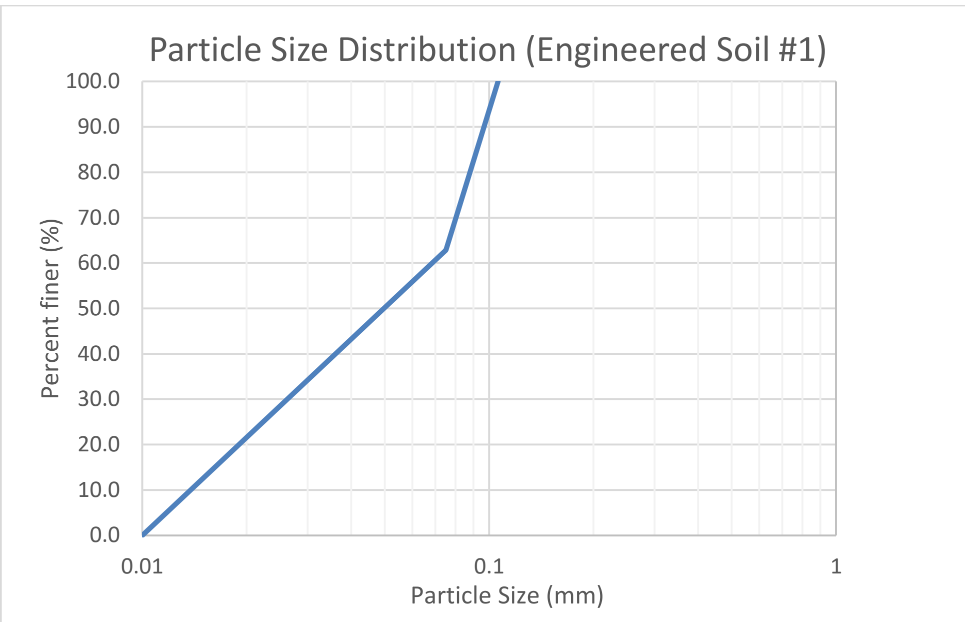

Figure 5.5: PSD Engineered Soil #1

Appendix F: Engineered Soil #2

Table 5.7: Engineered Soil #2

Sieve #	Sieve opening (mm)	Mass of sieve, A (g)	Mass of sieve and retained sample, B (g)	Mass of sample, W_n (g)	Percent of mass retained, R_n	Cumulative percent retained	Percent finer
140	0.106	339	384.3	45.3	0.0	0.0	100.0
200	0.075	319.1	366.9	47.8	38.9	38.9	61.1
Pan	0.01	366.6	441.8	75.2	61.1	100.0	0.0
SUM	xx	xx	xx	123	100		

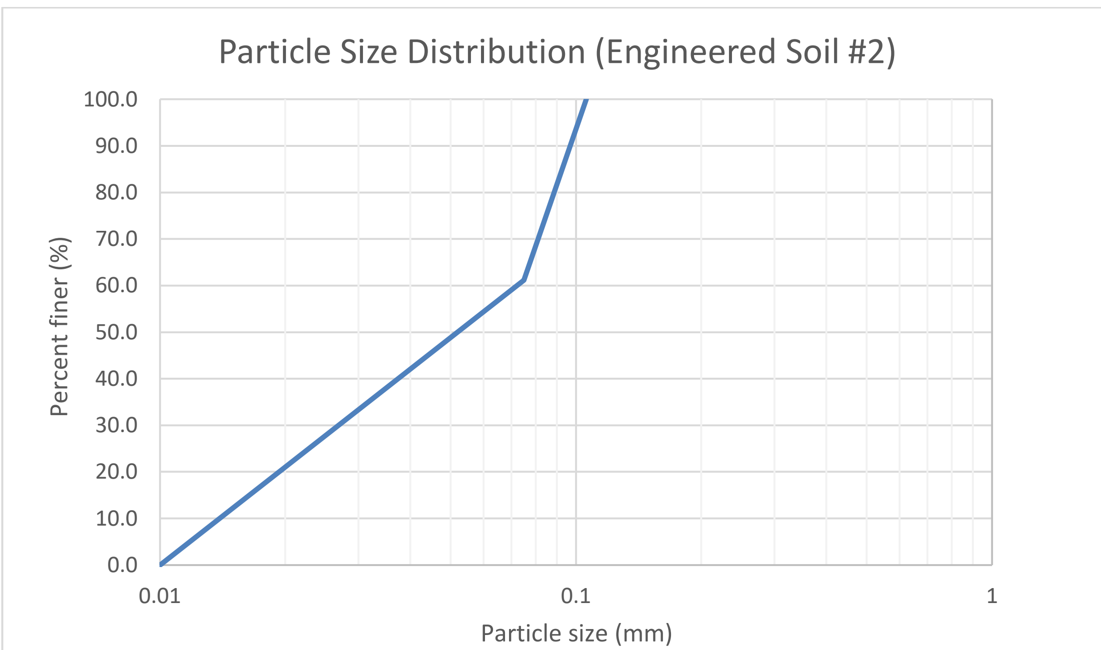

Figure 5.6: PSD Engineered Soil #2

Appendix G: Engineered Soil #3

Table 5.8: Engineered Soil #3

Sieve #	Sieve opening (mm)	Mass of sieve, A (g)	Mass of sieve and retained sample, B (g)	Mass of sample, W_n (g)	Percent of mass retained, R_n	Cumulative percent retained	Percent finer
140	0.106	338.8	403	0	0	0	100
200	0.075	341.4	401.2	59.8	38.46	38.46	61.54
Pan	0.01	370.4	466.1	95.7	61.54	100.00	0.00
SUM	xx	xx	xx	155.5	100		

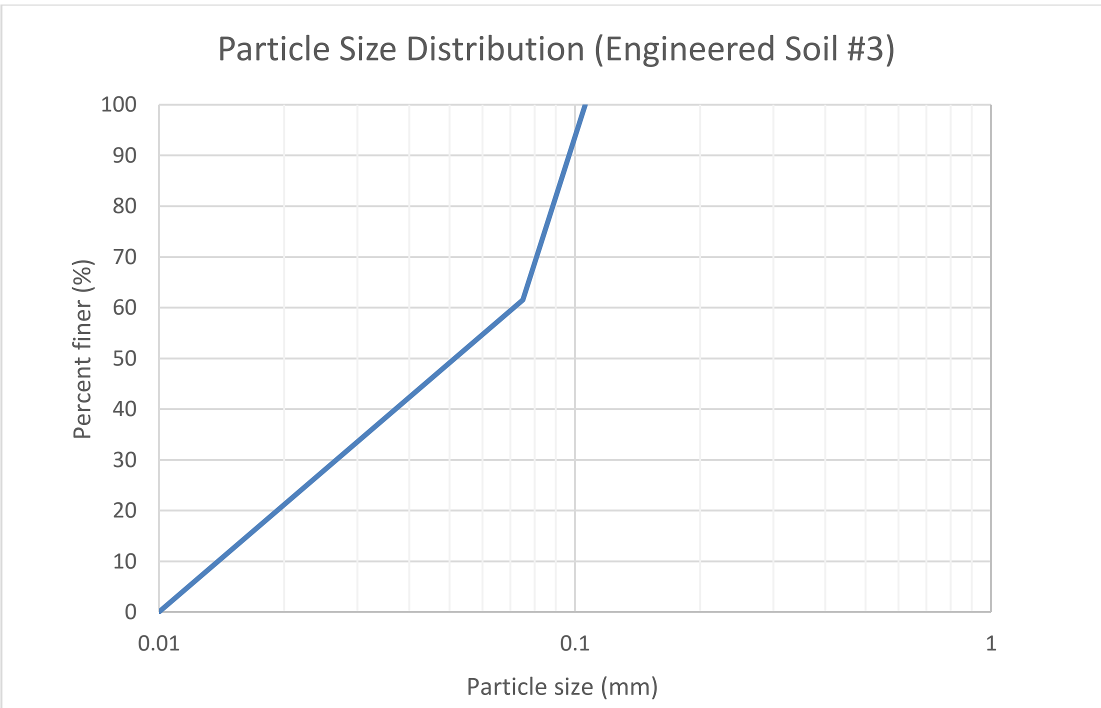

Figure 5.7: PSD Engineered Soil #3

Appendix H: Stoichiometry Analysis

Table 5.9: Stoichiometry Analysis

CKD		94.57 g CKD	Molar Mass (g/mol)	mol/ 94.57g CKD	Reactions with CO_2	Results	Molar Mass (g/mol)	mol from 94.57 g CKD	Mass (g)
SiO_2	13.83%	13.83g	60.08	0.2302	SiO_2+2CO_2 ->	$Si(CO_3)_2$	148.10	0.23018	34.09
Al_2O_3	3.00%	3g	101.96	0.0294	$Al_2O_3+3CO_2$ ->	$Al_2(CO_3)_3$	233.99	0.02942	6.88
Fe_2O_3	1.54%	1.54g	159.69	0.0096	$Fe_2O_3+3CO_2$ ->	$Fe_2(CO_3)_3$	291.71	0.00964	2.81
CaO	64.72%	64.72g	56.08	1.1541	$CaO+CO_2$ ->	$CaCO_3$	100.09	1.15413	115.51
MgO	0.82%	0.82g	40.30	0.0203	$MgO+CO_2$ ->	$MgCO_3$	84.31	0.02035	1.72
SO_3	5.31%	5.31g	80.06	0.0663	SO_3+CO_2 ->	N/A (SO_3)	80.06	0.06632	5.31
Na_2O	0.05%	0.05g	61.98	0.0008	Na_2O+CO_2 ->	Na_2CO_3	105.99	0.00081	0.09
K_2O	3.66%	3.66g	94.20	0.0389	K_2O+CO_2 ->	K_2CO_3	138.20	0.03886	5.37
TiO_2	0.17%	0.17g	79.87	0.0021	TiO_2+2CO_2 ->	$Ti(CO_3)_2$	167.88	0.00213	0.36
Cl	1.47%	1.47g	35.45	0.0415	$Cl+CO_2$ ->	N/A (Cl)	35.45	0.04146	1.47
LOI	5.43%								
Total	**100.00 %**	94.57g						Total Mass (CCKD) from 94.57 g CKD =	173.61
Fineness (Passing 200 M)	91.41%						94.57 g CKD ->	173.61	g CCKD

Appendix I: Proctor Test #1

Table 5.10: Proctor Test #1

Sample	m2 (g)	m1 (g)	MC (%)	V (m^3)	W2 (kN)	W1 (kN)	UW Y (kN/m3)	Dry UW (kN/m3)
1	N/A	4255	0.62	n/A	N/A	0.04173	n/a	n/a
2	5895	4255	12.08	0.0009359	0.05782	0.04173	17.19	15.33
3	6092	4255	13.88	0.0009542	0.05974	0.04173	18.87	16.57
4	6194	4255	16.17	0.0009377	0.06074	0.04173	20.27	17.45
5	6161	4255	18.49	0.0009374	0.06042	0.04173	19.94	16.83
6	6131	4255	20.98	0.0009343	0.06013	0.04173	19.69	16.28

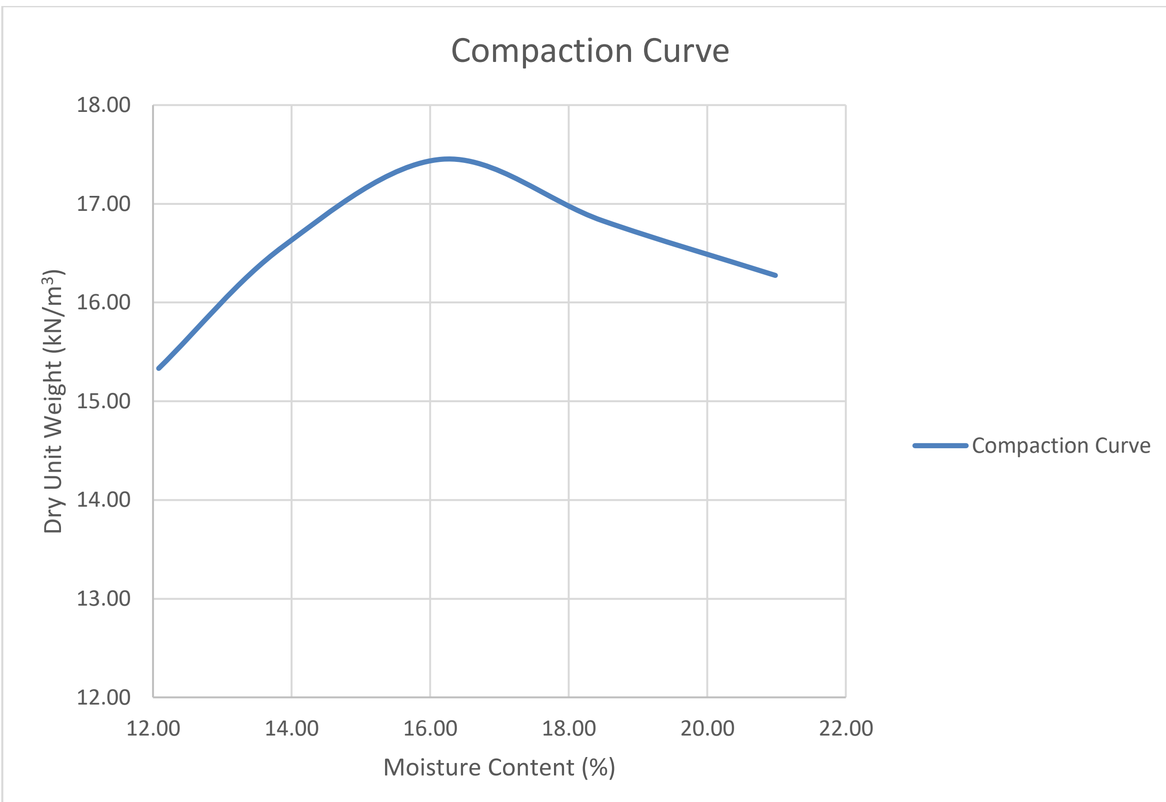

Figure 5.8: Compaction Curve #1

Appendix J: Proctor Test #2

Table 5.11: Proctor Test #2

Sample	m2 (g)	m1 (g)	MC (%)	V (m^3)	W2 (kN)	W1 (kN)	UW Y (kN/m3)	Dry UW (kN/m3)
1	6044	4255	16.12	0.0009367	0.05928	0.04173	18.73	16.13
2	6147	4255	17.01	0.0009719	0.06029	0.04173	19.09	16.32
3	6145	4255	19.36	0.0009390	0.06026	0.04173	19.74	16.54
4	6081	4255	23.20	0.0009232	0.05964	0.04173	19.40	15.75

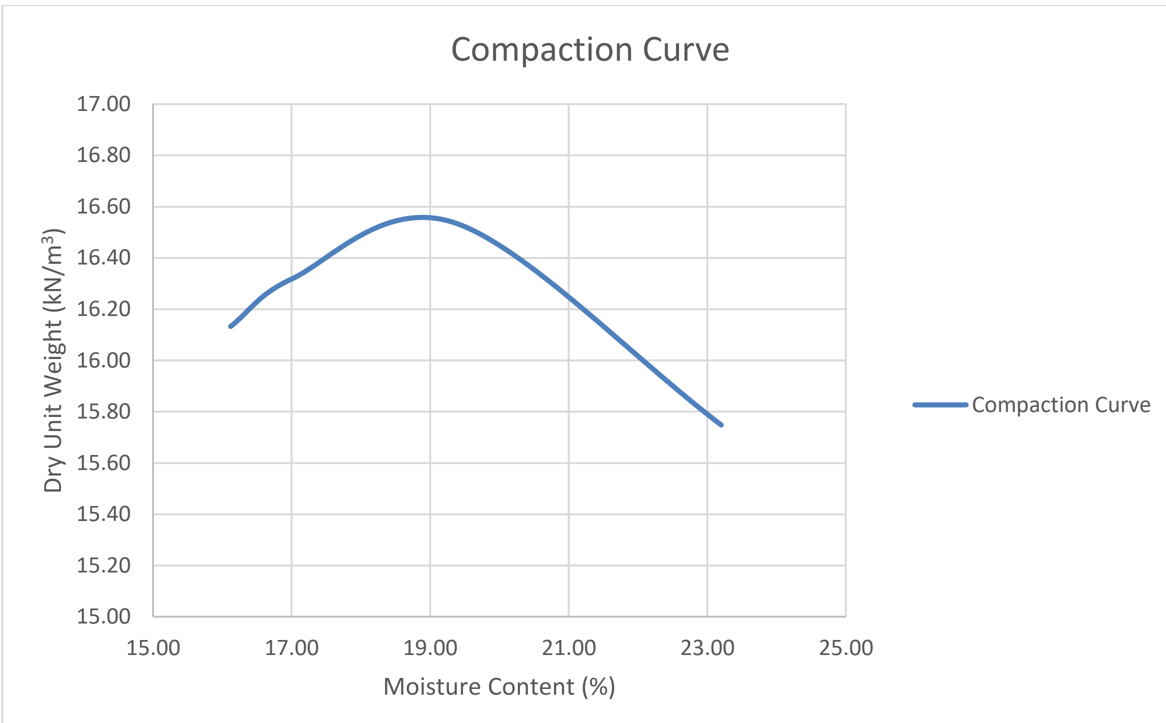

Figure 5.9: Compaction Curve #2

Appendix K: Proctor Test #3

Table 5.12: Proctor Test #3

Sample	m2 (g)	m1 (g)	MC (%)	V (m^3)	W2 (kN)	W1 (kN)	UW Y (kN/m3)	Dry UW (kN/m3)
1	6153	4291	14.85	0.0009656	0.06034	0.04208	18.90	16.46
2	6214	4291	17.22	0.0009610	0.06094	0.04208	19.62	16.74
3	6163	4291	19.20	0.0009644	0.06044	0.04208	19.04	15.97

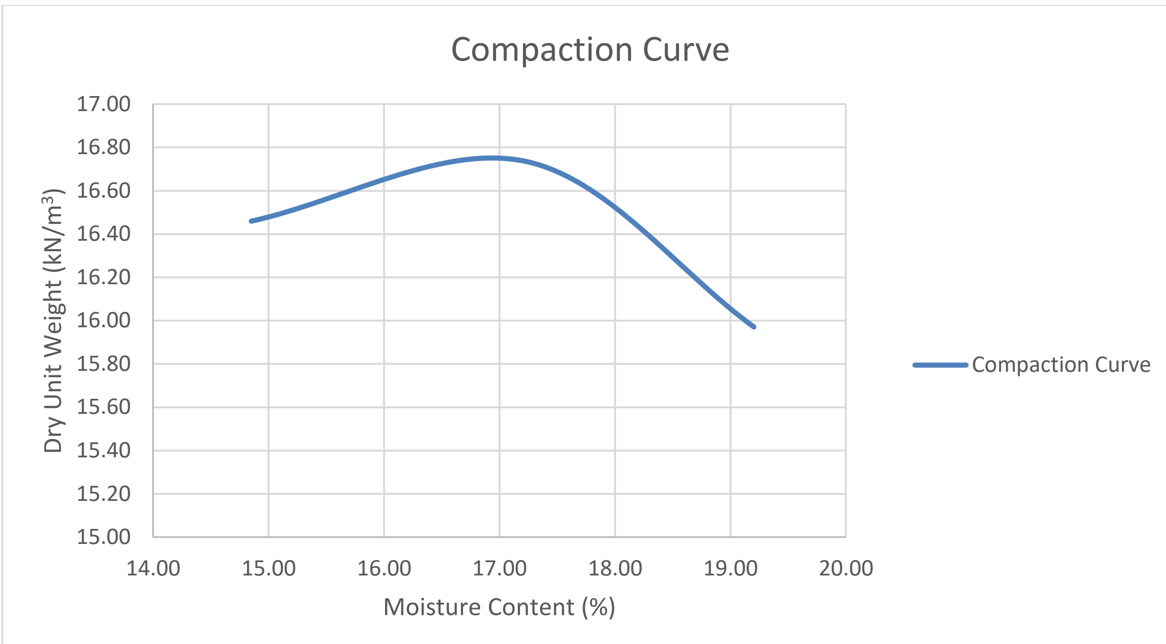

Figure 5.10: Compaction Curve #3

Appendix L: CCKD versus Control Results

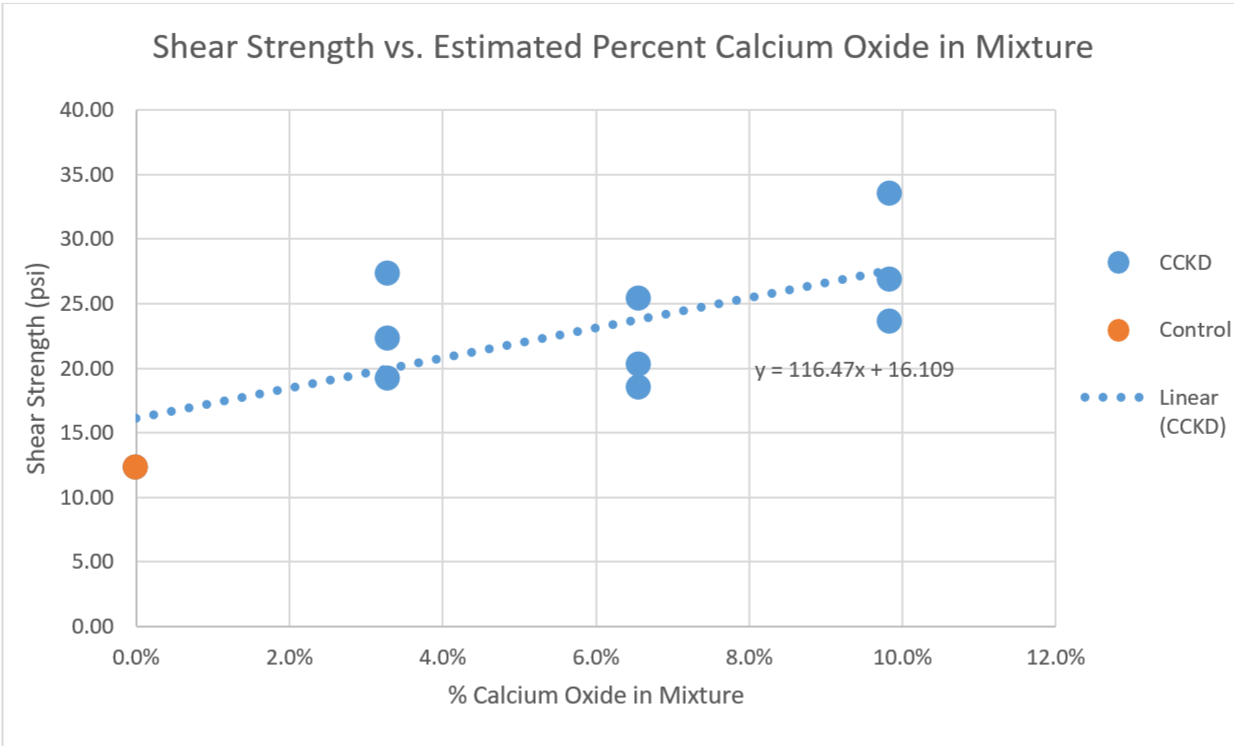

Figure 5.11: CCKD versus Control Results

Appendix M: CKD versus Control Results

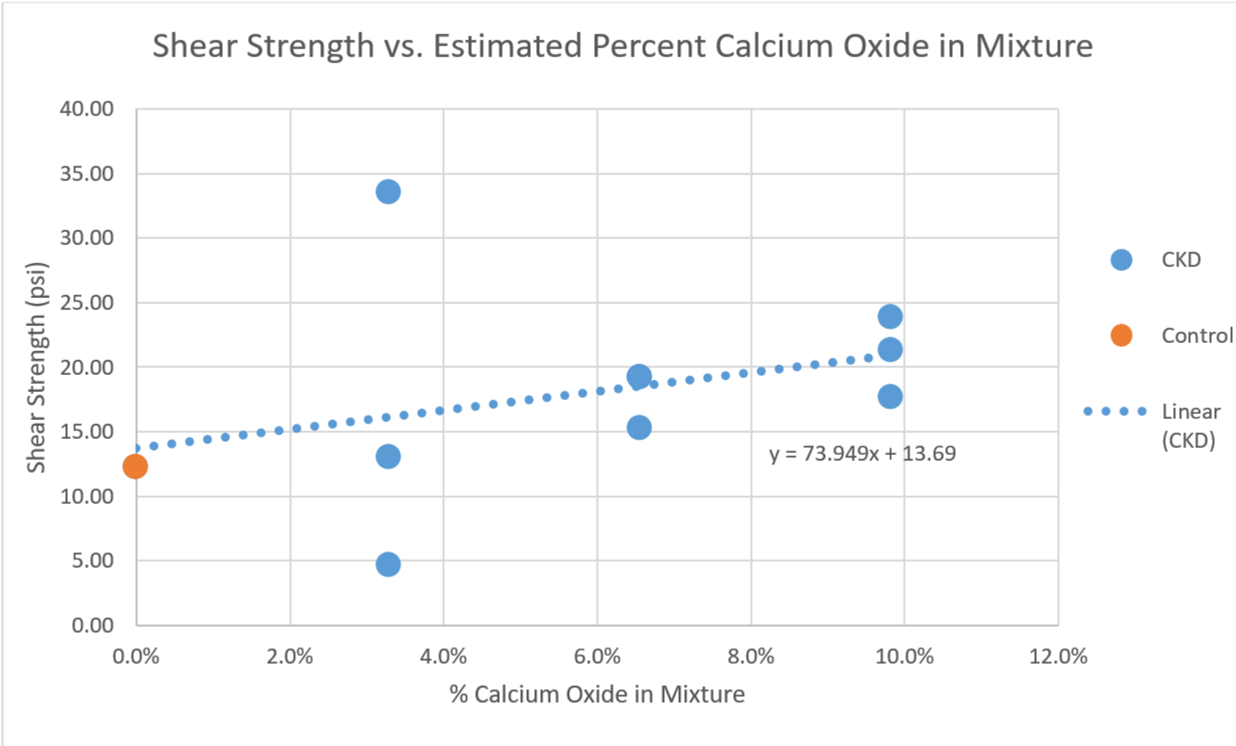

Figure 5.12: CKD versus Control Results

Appendix N: Lime versus Control Results

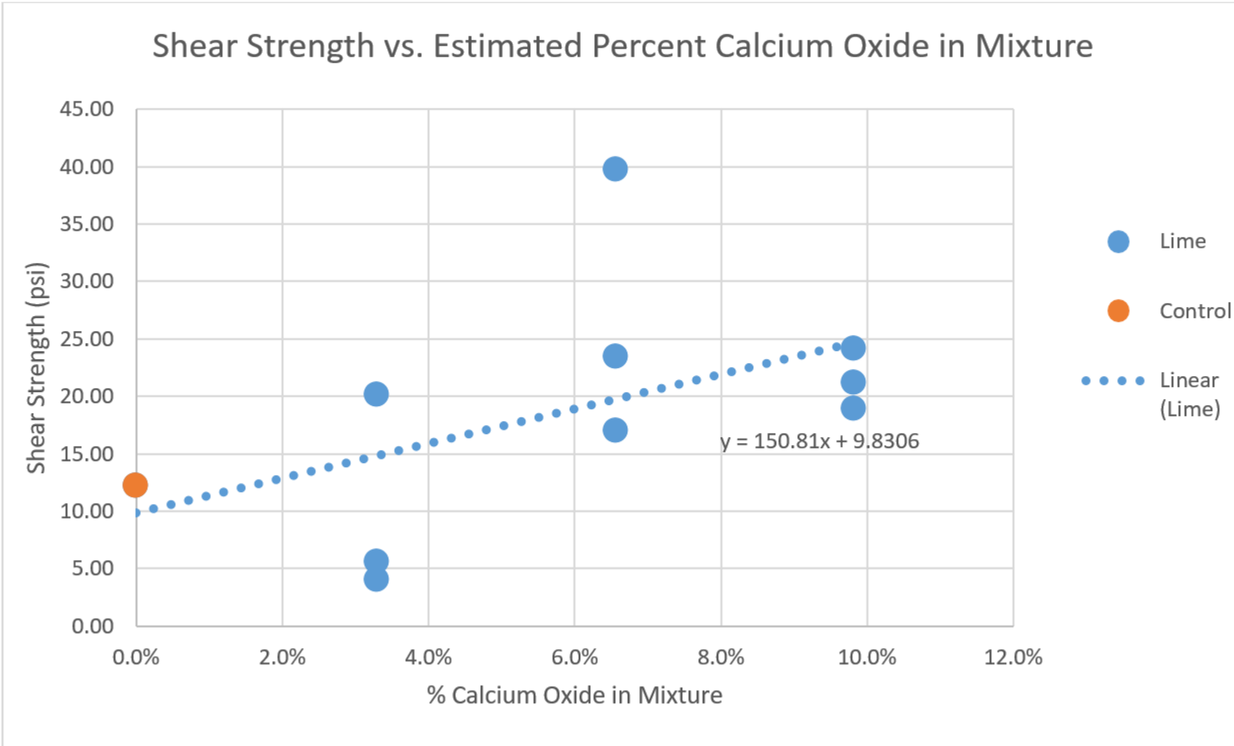

Figure 5.13: Lime versus Control Results