Cement Stabilization of Embankment Materials

JULY 2015

Final Report

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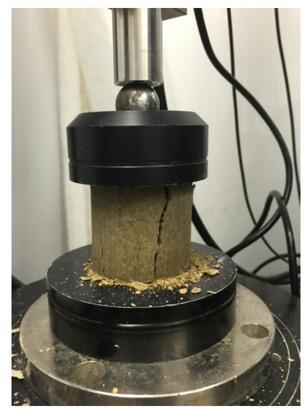

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16. Abstract

Embankment subgrade soils in Iowa are generally rated as fair to poor as construction materials. These soils can exhibit low bearing strength, high volumetric instability, and freeze/thaw or wet/dry durability problems. Cement stabilization offers opportunities to improve these soils conditions. The objective of this study was to develop relationships between soil index properties, unconfined compressive strength and cement content. To achieve this objective, a laboratory study was conducted on 28 granular and non-granular materials obtained from 9 active construction sites in Iowa. The materials consisted of glacial till, loess, and alluvium sand. Type I/II portland cement was used for stabilization. Stabilized and unstabilized specimens were prepared using Iowa State University 2 in. by 2 in. compaction apparatus. Specimens were prepared, cured, and tested for unconfined compressive strength (UCS) with and without vacuum saturation. Percent fines content (F_{200}), AASHTO group index (GI), and Atterberg limits were tested before and after stabilization. The results were analyzed using multi-variate statistical analysis to assess influence of the various soil index properties on post-stabilization material properties.

Results indicated that F_{200}, liquid limit, plasticity index, and GI of the materials generally decreased with increasing cement content. The UCS of the stabilized specimens increased with increasing cement content, as expected. The average saturated UCS of the unstabilized materials varied between 0 and 57 psi. The average saturated UCS of stabilized materials varied between 44 and 287 psi at 4% cement content, 108 and 528 psi at t 8% cement content, and 162 and 709 psi at 12% cement content. The UCS of the vacuum saturated specimens was on average 1.5 times lower than that of the unsaturated specimens. Multi-variate statistical regression models are provided in this report to predict F_{200}, plasticity index, GI, and UCS after treatment, as a function of cement content and soil index properties.

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CEMENT STABILIZATION OF EMBANKMENT MATERIALS

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EXECUTIVE SUMMARY

Embankment subgrade soils in Iowa are generally rated as fair to poor as construction materials. These soils can exhibit low bearing strength, high volumetric instability, and freeze/thaw or wet/dry durability problems. Cement stabilization offers opportunities to improve these soils conditions. The Iowa Department of Transportation (DOT) is considering the use of portland cement as an additive for stabilizing embankment materials in situ. The objective of this study was to develop relationships between soil index properties, unconfined compressive strength and cement content. To achieve this objective, a laboratory study was conducted on 28 granular and non-granular materials obtained from 9 active construction sites in Iowa. The materials consisted of glacial till, western Iowa loess, and alluvium sand. Type I/II portland cement was used in this study.

Stabilized and unstabilized specimens were prepared using Iowa State University 2 in. by 2 in. compaction apparatus. Specimens were prepared, cured, and tested for unconfined compressive strength (UCS) with and without vacuum saturation. Percent fines content (F_{200}), AASHTO group index (GI), and Atterberg limits were tested before and after stabilization. The results were analyzed using multi-variate statistical analysis to assess influence of the various soil index properties on post-stabilization material properties. Following the results of this study, a draft laboratory testing and evaluation procedure is provided in the Appendix of this report.

Key findings from the test results and analysis are as follows:

- F_{200} of the material decreased with increasing cement content for a majority of the soils. The percent cement content, F_{200} before treatment, and liquid limit were found to be statistically significant in predicting the F_{200} after treatment. The multi-variate model showed an R^2 of about 0.9 and RMSE of about 7% in predicting the F_{200} after treatment.

- With the exception of a few materials, the liquid limit and plasticity index of all materials decreased with increasing cement content. The one untreated soil classified as “unsuitable”, classified as “suitable” after stabilized with cement. Some of the untreated soils that were classified as “select”, classified as “suitable” after stabilized with cement. The classifications changed because of reduction in plasticity index. All soils classified as “suitable” at 12% cement content because of no plasticity. The percent cement content and clay content parameters were found to be statistically significant in predicting the plasticity index of materials after stabilization. The multi-variate model showed an R^2 of about 0.5 and RMSE of about 5%.

- The GI values decreased with increasing cement content for a majority of the soils. The percent cement content, F_{200}, liquid limit, and plasticity index parameters were found to be statistically significant in predicting the group index values after treatment. The multi-variate model showed an R^2 of about 0.7 and RMSE of about 3.

- The UCS of specimens increased with increasing cement content, as expected. The average saturated UCS of the unstabilized materials varied between 0 and 57 psi. The average saturated UCS of stabilized materials varied between 44 and 287 psi at 4% cement content, 108 and 528 psi at t 8% cement content, and 162 and 709 psi at 12% cement content. The draft laboratory testing and evaluation procedure for cement stabilization mix design provided in Appendix B targets a 100 psi saturated unconfined compressive strength. The UCS of the saturated specimens was on average 1.5 times lower than of the unsaturated specimens.

- The percent cement content, sand content, fines content, and liquid limit were found to be statistically significant in predicting unsaturated and vacuum saturated UCS. The models showed an R^2 of about 0.85 and RMSE of about 75 psi for vacuum saturated specimens and 97 psi for unsaturated specimens.

CHAPTER 1: INTRODUCTION

Embankment subgrade soils in Iowa are generally rated as fair to poor as construction materials, with a majority of the soils classifying as A-4 to A-7-6 according to the AASHTO (2004). These soils can exhibit low bearing strength, high volumetric instability, and freeze/thaw or wet/dry durability problems. Cement stabilization offers opportunities to improve these soils conditions. The Iowa Department of Transportation (DOT) is considering the use of portland cement as an additive for stabilizing embankment materials in situ.

The objective of this study was to develop relationships between soil index properties, unconfined compressive strength and cement content. To achieve this objective, a laboratory study was conducted on 28 granular and non-granular materials obtained from 9 active construction sites in Iowa. The materials consisted of glacial till, western Iowa loess, and alluvium sand. Type I/II portland cement was used in this study.

Stabilized and unstabilized specimens were prepared using Iowa State University 2 in. by 2 in. compaction apparatus, and were tested for unconfined compressive strength (UCS) with and without vacuum saturation. Soil index properties such as the percent fines passing the No. 200, AASHTO group index, and Atterberg limits were assessed before and after stabilization. The results were analyzed using multi-variate statistical analysis to assess influence of the various soil index properties on post-stabilization material properties. Following the results of this study, a draft laboratory testing and evaluation procedure is provided in the Appendix of this report.

CHAPTER 2: TESTING METHODS

The ISU research team performed a series of laboratory tests on materials collected from various embankment construction sites in Iowa. Table 1 summarizes the test standards and procedures used in this study.

Table 1. Testing methods used in the study

Test standard or reference	Description of test
ASTM C593-06	Vacuum saturation
ASTM D422-63	Particle-size analysis
ASTM D698-12	Standard Proctor
ASTM D854-14	Specific gravity
ASTM D1140-14	Fines content passing the No. 200 sieve
ASTM D1557-12	Modified Proctor
ASTM D1633-00	Unconfined compressive strength (UCS)
ASTM D2487-11	Unified soil classification system (USCS)
ASTM D3282-09	American Association for State Highway and Transportation Officials (AASHTO) classification system
ASTM D4318-10	Atterberg limits
O'Flaherty et al. (1963)	ISU 2 in. x 2 in. compaction

Soil Index Properties

Particle-size analysis tests were conducted in accordance with ASTM D422-63 (ASTM 2014a). The distribution of particle sizes larger than 75 µm (opening size of the No. 200 sieve) is determined by sieving, and the distribution of particle sizes smaller than 75 µm is determined by the hydrometer method.

Percent passing the No. 200 sieve (F_{200}) was determined in accordance with ASTM D1140-14 (ASTM 2014e).

Atterberg limits tests to determine liquid limit (LL), plastic limit (PL), and plasticity index (PI) were conducted in accordance with ASTM D4318-10 (ASTM 2014b), using the "wet preparation" method. LL tests were performed using the multipoint method.

Utilizing the results of the above testing, each sample was classified using the Unified Soil Classification System (USCS) in accordance with ASTM D2487-11 (ASTM 2011b) and the

AASHTO classification system in accordance with ASTM D3282-09 (ASTM 2009). AASHTO group index (GI) values were determined in accordance with AASHTO (2004) using Eq. 1:

$$GI = (F_{200} – 35) \times [0.2 + 0.005 \times (LL-40)] + 0.01 \times (F_{200} -15) \times (PI – 10) \quad (1)$$

Specific gravity tests were conducted in accordance with ASTM 854-14 Method A – procedure for moist specimens (ASTM 2014).

Proctor Compaction

The relationship between moisture and dry unit weight of embankment materials was determined in accordance with ASTM D698-12 (ASTM 2012a) and ASTM D1557-12 (ASTM 2012b). The appropriate method was chosen based upon the grain-size distributions for each material. Method A was applicable for all soil materials. The tests were performed at five different moisture contents and the optimum moisture-density characteristics were obtained based upon the Li and Sego Fit model (Li and Sego 2000) fit to the data. Figure 1 shows the model, and Eq. 2 shows the relationship and the relevant parameters.

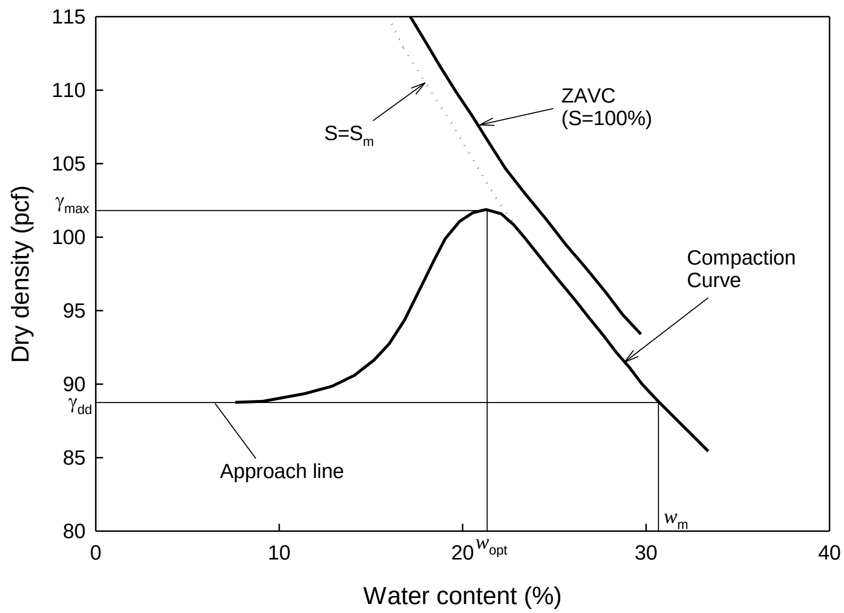

Figure 1. Theoretical relationship between water content and dry density (Reproduced from Li and Sego 2000)

$$\gamma_d\,(w) = \frac{G_s\,\gamma_w}{\left(1+\dfrac{w\,G_s}{S_m - S_m\left(\frac{w_m - w}{w_m}\right)^{n+1}\left(\frac{w_m^n + p^n}{(w_m - w) + p^n}\right)}\right)} \quad (2)$$

where,

γ_d = dry density of the soil;
G_s = specific gravity of the soil;
γ_w = density of water;
w = moisture content of the soil;
w_m = moisture content at S_m;
S_m = maximum of saturation; and
n and p = shape factors

S_m defines the maximum saturation boundary of the model on the wet side of optimum and the corresponding moisture content is defined as w_m. It can be determined from the wet side of the compaction curve running parallel to the zero air void curve. The parameter *n* is referred to as the shape factor, which affects the dome portion of the compaction curve. When *n* is increased, the dome portion of the compaction curve becomes sharper; and when n is decreased, the dome portion tends to become flatter. The parameter *p* influences the width of the upper portion of the curve. In determining the best fit parameters, S_m and w_m were first determined based on the data to establish the boundary of the curve, and shape factor *n* and *p* were adjusted until a maximum correlation coefficient (R^2) between the measured and the predicted values is achieved.

ISU 2 in. by 2 in. Compaction

ISU 2 in. by 2 in. compaction apparatus is described in O'Flaherty et al. (1963). The test procedure was used to prepare 2 in. diameter by 2 in. height (2 x 2) samples for UCS testing (Figure 2).

Figure 2. ISU 2 in. by 2 in. specimen compaction

Samples were compacted at their respective standard Proctor optimum moisture content. For cement treated materials, the optimum moisture content was determined using Eq. 3 with a water to cement (w/c) ratio of 0.25:

$$w_{\text{opt soil + cement}} = [(\text{\% cement added by weight}) \times (\text{w/c ratio})] + w_{\text{opt soil}} \tag{3}$$

The test procedure involved placing loose material in the compaction apparatus and dropping a 5 lb. hammer from a drop height of about 12 in. in a 2 in. diameter steel mold. O'Flaherty et al. (1965) provided guidance on the number of blows required to obtain standard Proctor densities for different soil types, as summarized in Table 2. The number of blows were selected based on the soil type and equal number of blows were applied on both sides of the sample, to compact the sample uniformly.

Table 2. Number of drop-hammer blows (O'Flaherty et al. 1963)

AASHTO Soil Type	Total number of drop-hammer blows
A-7 and A-6	6
A-4	7
A-3, A-2, and A-1	14

After compaction, the 2 x 2 specimens were sealed using a saran wrap and aluminum foil, and were placed in a Ziploc bag. Cement stabilized specimens were cured for 7 days at 110^{o}F, to simulate 28 day curing strength (Winterkkorn and Pamukcu 1990). Unstabilized specimens were tested shortly after compaction (no curing). Three samples were prepared at each cement content.

Unconfined compressive strength (UCS)

The cured specimens were tested for UCS (Figure 3) in general accordance with ASTM D 1633-00 (ASTM 2007). The standard requires use of either 4 in. diameter by 4.584 in. height Proctor samples with a height to diameter (h/d) ratio of 1.15 or 2.8 in. diameter by 5.6 in. height samples with an h/d ratio of 2.0. Instead, 2 x 2 specimens were used in this study which have an h/d ratio of 1.0. This decision was made based on a previous study (White et al. 2005) with design of fly ash soil mixtures, where it was concluded that UCS can be determined using any of these three sample sizes: h/d = 1.0 (2x2 sample), 1.15 (Proctor), and 2.0 (2.8 in. x 5.6 in.).

Based on laboratory testing on fly ash soil mixtures, White et al. (2005) concluded that the UCS determined from 2 x 2 specimens can be multiplied by 0.86 to correlate with UCS of Proctor sized samples (h/d = 1.15) or 0.90 to correlate with samples that have h/d = 2. ASTM D1633-00 also provides a similar guidance in relating UCS on samples with h/d=1.15 to samples with h/d=2 as follows: "*If desired, make allowance for the ratio of height to diameter (h/d) by multiplying the compressive strength of Method B specimens* [with h/d = 2.0] *by factor 1.10. This converts the strength for an h/d ratio of 2.00 to that for the h/d ratio of 1.15 commonly used in routine testing of soil-cement.*" The ASTM D1633 correction factor provides a higher UCS value for samples with h/d = 1.15 than for samples with h/d = 2.0. This trend was true in White et al. (2005) study when 2 x 2 specimens were compared with 2.8 in. x 5.6 in. specimens, but not when compared with Proctor size specimens.

In this study, the uncorrected results are reported for the UCS values.

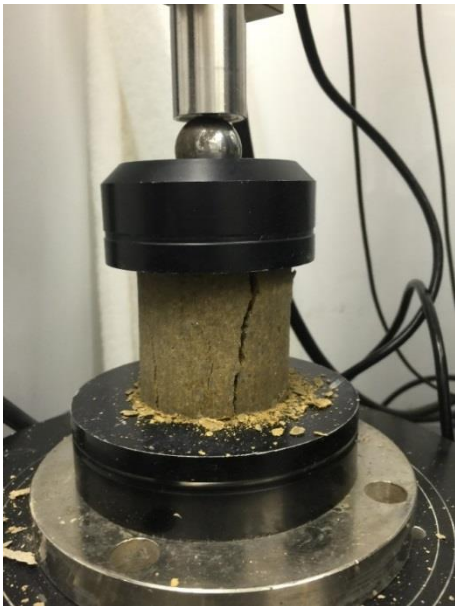

Figure 3. Specimen failure after measurement of UCS

The cured specimens were tested in unsaturated and saturated condition. The specimens were saturated using the vacuum saturated method as described in ASTM C593-06 (ASTM 2011a). The specimens were placed on a perforated Plexiglas plate in a vacuum vessel (Figure 4), and the chamber was evacuated using 24 in. of mercury for 30 minutes. Then the vacuum vessel was flooded to a depth sufficient to cover the soil specimens. After one hour of soaking, the specimens were removed from the vessel to conduct UCS testing. For samples that become fragile and cannot be removed from water for UCS testing, the UCS is reported as 0 psi.

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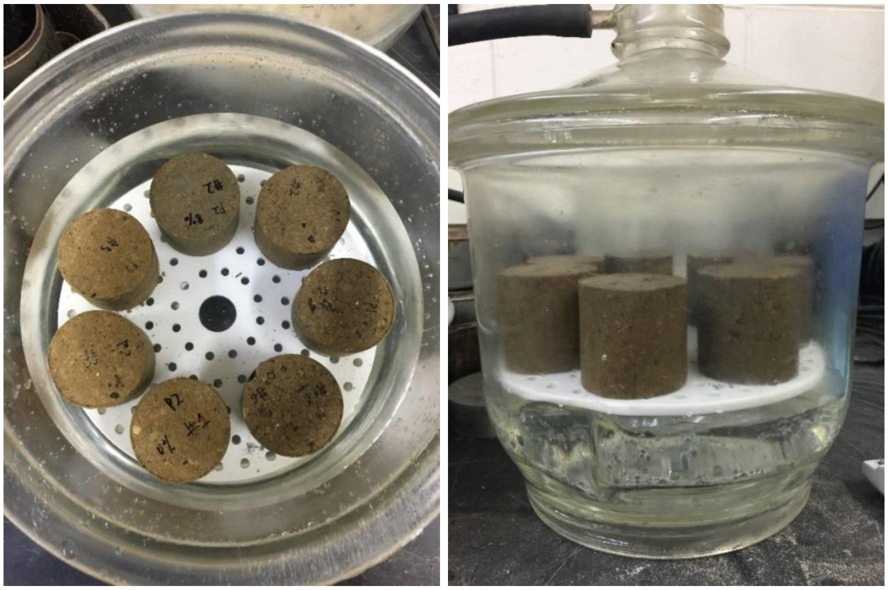

Figure 4. Vacuum saturation of cement stabilized specimens

Statistical Analysis

Multi-variate statistical analysis was conducted on the data generated from this study to assess the influence of various independent parameters (i.e., soil index properties, cement content) in predicting UCS, fines content passing the No. 200 sieve (F_{200}), PI, and AASHTO group index. Based on the analysis, prediction models were developed and presented in this report.

Analysis was performed using JMP statistical analysis software. The analysis was performed by incorporating the independent parameters in a linear multiple regression model. The statistical significance of the parameters were assessed using the *t*- and *p*-values associated with each parameter. The selected criteria for identifying the significance of a parameter included *p*-value ≤ 0.05 is significant, ≤ 0.10 is possibly significant, > 0.10 = not significant, and *t*-value <-2 or > +2 = significant. Higher the *t*- and *p*- values, greater is the statistical significance of the parameter.

CHAPTER 3: MATERIALS

This chapter presents the soil index properties of the 28 embankment materials collected from 9 field projects in this study. The field project materials were obtained from Polk, Warren, Linn, Pottawattamie, Mills, Woodbury and Scott Counties in Iowa. Embankment materials were obtained from multiple test beds at each project sites. Gradation, Atterberg limits, specific gravity, and compaction properties were tested for each material.

Table 3 to Table 8 provide a summary of the parent materials, particle size analysis, Atterberg limits, specific gravity, soil classification, and Proctor compaction test results. The grain size distribution curves of the embankment materials are separated by each project and shown in Figure 5 to Figure 13. The embankment materials consisted of cohesive soils with glacial till at three project sites and with western Iowa loess at four project sites. On one project site, granular material consisted of alluvial sand from the Missouri river flood plain. Of the 25 cohesive materials collected, 6 classified as select, 18 classified as suitable, and one classified as unsuitable per Iowa DOT material suitability specification (Iowa DOT 2014). The three granular soils collected were classified as suitable.

For cement stabilization, Type I/II portland cement was used in this study.

Table 3. Soil index properties of embankment materials obtained from Polk County

Parameter	Polk County TB1	Polk County TB2	Polk County TB3	Polk County TB4
	5/29/2014	**6/7/2014**	**8/5/2014**	**8/19/2014**
Parent Material	Glacial till	Glacial till	Glacial till	Glacial till
Gravel content (%) (> 4.75 mm)	0.4	3.9	2.6	1.8
Sand content (%) (4.75 mm – 75 μm)	11.6	25.8	28.7	24.6
Silt content (%) (75 μm – 2 μm)	66.4	34.7	45.8	50.9
Clay content (%) (< 2 μm)	21.6	35.6	22.9	22.7
LL (%)	49	45	36	34
PL (%)	28	34	20	17
PI (%)	21	11	16	17
AASHTO classification	A-7-6(21)	A-7-5(8)	A-6(9)	A-6(11)
USCS classification	CL	CL	CL	CL
USCS Description	Lean Clay	Lean clay with sand	Sandy lean clay	Lean clay with sand
Iowa DOT Material Classification	Suitable	Suitable	Suitable	Suitable
Soil Color	Olive Brown	Olive Brown	Very dark greyish brown	Olive Brown
Specific Gravity, Gs	2.673	2.679	2.670	2.672
Std. Proctor, w_{opt} (%)	19.6	20.0	16.0	16.0
Std. Proctor, γ_{dmax} (pcf)	103.9	104.0	110.0	110.6
Mod. Proctor, w_{opt} (%)	16.0	13.6	11.5	11.5
Mod. Proctor, γ_{dmax} (pcf)	112.3	120.0	122.0	123.0

Table 4. Soil index properties of embankment materials obtained from Warren County and Linn County 79

Parameter	Warren County TB1	Warren County TB2	Warren County TB3 (Grey)	Warren County TB3 (Brown)	Linn County 79
	6/3/2014	**7/22/2014**	**8/4/2014**	**8/4/2014**	**6/6/2014**
Parent Material	Glacial till	Glacial till	Glacial till	Glacial till	weathered loess
Gravel content (%) (> 4.75 mm)	2.0	5.0	0.7	0.6	0.7
Sand content (%) (4.75 mm – 75 μm)	27.5	31.6	18.7	29.2	46.0
Silt content (%) (75 μm – 2 μm)	37.3	31.9	39.1	33.7	26.4
Clay content (%) (< 2 μm)	33.2	31.5	41.5	36.5	26.9
LL (%)	44	40	54	40	31
PL (%)	31	19	20	20	25
PI (%)	13	21	34	20	6
AASHTO classification	A-7-5(9)	A-6(11)	A-7-6(28)	A-6(13)	A-4(1)
USCS classification	CL	CL	CH	CL	CL-ML
USCS Description	Lean clay with sand	Sandy lean clay	Fat clay with sand	Sandy lean clay	Sandy silty clay
Iowa DOT Material Classification	Suitable	Select	Unsuitable	Suitable	Suitable
Soil Color	Olive Brown	Light olive Brown	Very dark grey	Olive Brown	Olive Brown
Specific Gravity, Gs	2.676	2.673	2.715	2.674	2.684
Std. Proctor, w_{opt} (%)	16.5	15.0	21.0	17.0	13.5
Std. Proctor, γ_{dmax} (pcf)	111.1	113.8	102.0	109.5	117.4
Mod. Proctor, w_{opt} (%)	11.0	9.8	13.6	10.5	9.0
Mod. Proctor, γ_{dmax} (pcf)	123.9	128.5	115.5	125.0	130.8

Table 5. Soil index properties of embankment materials obtained from Linn County 77

Parameter	Linn County 77 TB1	Linn County 77 TB2	Linn County 77 TB3	Linn County 77 TB4	Linn County 77 TB5
	6/6/2014	**7/8/2014**	**7/15/2014**	**8/1/2014**	**9/8/2014**
Parent Material	Glacial till	Glacial till	Glacial till	Glacial till	Glacial till
Gravel content (%) (> 4.75 mm)	1.8	1.3	11.3	1.1	2.0
Sand content (%) (4.75 mm – 75 µm)	37.6	42.6	36.1	39.9	40.3
Silt content (%) (75 µm – 2 µm)	32.9	30.9	31.2	35.6	34.8
Clay content (%) (< 2 µm)	27.7	25.2	21.4	23.4	22.9
LL (%)	31	34	33	32	30
PL (%)	12	16	11	16	16
PI (%)	19	18	22	16	14
AASHTO classification	A-6(8)	A-6(7)	A-6(7)	A-6(6)	A-6(5)
USCS classification	CL	CL	CL	CL	CL
USCS Description	Sandy lean clay	Sandy lean clay	Sandy lean clay	Sandy lean clay	Sandy lean clay
Iowa DOT Material Classification	Select	Select	Select	Select	Select
Soil Color	Very dark grey	Olive Brown	Very dark grey	Very dark grey	Very dark grey
Specific Gravity, Gs	2.683	2.670	2.673	2.672	2.674
Std. Proctor, w_{opt} (%)	12.9	13.0	12.0	11.7	12.6
Std. Proctor, γ_{dmax} (pcf)	118.4	116.0	119.5	119.5	119.0
Mod. Proctor, w_{opt} (%)	8.8	9.0	8.0	8.1	8.6
Mod. Proctor, γ_{dmax} (pcf)	130.8	129.5	131.0	132.1	130.0

Table 6. Soil index properties of embankment materials obtained from Pottawattamie County and Woodbury County I-29

Parameter	Pottawattamie County TB1	Pottawattamie County TB2	Woodbury County I-29 TB1	Woodbury County I-29 TB2	Woodbury County I-29 TB3
	7/2/2014	**7/10/2014**	**7/9/2014**	**7/10/2014**	**8/7/2014**
Parent Material	Manufactured materials	Manufactured materials	Alluvium	Alluvium	Alluvium
Gravel content (%) (> 4.75 mm)	7.3	5.3	0.2	0.0	1.7
Sand content (%) (4.75 mm – 75 µm)	10.1	25.5	78.4	83.2	81.1
Silt content (%) (75 µm – 2 µm)	56.2	48.0	15.5	12.6	11.6
Clay content (%) (< 2 µm)	26.4	21.2	5.9	4.2	5.6
LL (%)	43	42	NP	NP	NP
PL (%)	18	19	NP	NP	NP
PI (%)	25	23	NP	NP	NP
AASHTO classification	A-7-6(20)	A-7-6(14)	A-2-4	A-2-4	A-2-4
USCS classification	CL	CL	SM	SM	SM
USCS Description	Lean clay with sand	Sandy lean clay	Silty sand	Silty sand	Silty sand
Iowa DOT Material Classification	Suitable	Suitable	Suitable	Suitable	Suitable
Soil Color	Dark brown	Very dark greyish brown	Olive Brown	Very dark greyish brown	Very dark greyish brown
Specific Gravity, Gs	2.697	2.709	2.657	2.654	2.654
Std. Proctor, w_{opt} (%)	17.5	17.5	17.5	15.5	15.0
Std. Proctor, γ_{dmax} (pcf)	106.0	106.3	102.5	102.8	104.5
Mod. Proctor, w_{opt} (%)	13.5	12.8	15.5	14.5	13.0
Mod. Proctor, γ_{dmax} (pcf)	117.5	117.5	109.2	105.0	110.0

Table 7. Soil index properties of embankment materials obtained from Scott County and Mills County

Parameter	Scott County TB1	Scott County TB2	Scott County TB3	Mills County TB1	Mills County TB2
	7/16/2014	**7/31/2014**	**9/19/2014**	**6/26/2014**	**6/26/2014**
Parent Material	Loess	Loess	Loess	Loess	Loess
Gravel content (%) (> 4.75 mm)	0.1	1.0	2.0	0.1	3.9
Sand content (%) (4.75 mm – 75 μm)	1.0	24.3	29.2	3.1	6.4
Silt content (%) (75 μm – 2 μm)	72.9	45.5	45.9	70.6	34.9
Clay content (%) (< 2 μm)	26.0	29.2	22.9	26.2	54.8
LL (%)	39	35	28	38	36
PL (%)	32	24	17	34	31
PI (%)	7	11	11	4	5
AASHTO classification	A-4(10)	A-6(8)	A-6(5)	A-4(7)	A-4(6)
USCS classification	CL-ML	CL	CL	CL-ML	CL-ML
USCS Description	Silty Clay	Lean clay with sand	Sandy lean clay	Silty clay	Silty clay
Iowa DOT Material Classification	Suitable	Suitable	Suitable	Suitable	Suitable
Soil Color	Dark olive brown	Dark yellowish brown	Olive Brown	Dark yellow brown	Brown
Specific Gravity, Gs	2.680	2.672	2.673	2.725	2.726
Std. Proctor, w_{opt} (%)	16.5	15.5	13.0	17.0	16.0
Std. Proctor, γ_{dmax} (pcf)	108.0	111.1	119.5	108.5	110.8
Mod. Proctor, w_{opt} (%)	13.0	11.2	9.2	13.0	12.0
Mod. Proctor, γ_{dmax} (pcf)	118.0	122.5	131.0	117.2	119.5

Table 8. Soil index properties of embankment materials obtained from Woodbury County US 20

Parameter	Woodbury County (US20) TB1	Woodbury County (US20) TB2	Woodbury County (US20) TB3	Woodbury County (US20) TB4
	9/26/2014	**9/26/2014**	**10/18/2014**	**10/18/2014**
Parent Material	very deep loess	very deep loess	very deep loess	very deep loess
Gravel content (%) (> 4.75 mm)	0.0	0.0	0.1	0.0
Sand content (%) (4.75 mm – 75 µm)	8.8	1.3	4.2	6.4
Silt content (%) (75 µm – 2 µm)	68.8	73.3	69.6	72.0
Clay content (%) (< 2 µm)	22.4	25.4	26.1	21.6
LL (%)	32	35	35	31
PL (%)	25	27	23	24
PI (%)	7	8	12	7
AASHTO classification	A-4(7)	A-4(9)	A-6(12)	A-4(7)
USCS classification	CL-ML	CL	CL	CL-ML
USCS Description	Silty clay	Lean clay	Lean clay	Silty clay
Iowa DOT Material Classification	Suitable	Suitable	Suitable	Suitable
Soil Color	Olive Brown	Olive Brown	Olive Brown	Olive Brown
Specific Gravity, Gs	2.717	2.679	2.673	2.720
Std. Proctor, w_{opt} (%)	16.0	18.4	18.0	16.0
Std. Proctor, γ_{dmax} (pcf)	110.0	106.0	106.7	110.5
Mod. Proctor, w_{opt} (%)	12.4	14.0	14.0	13.0
Mod. Proctor, γ_{dmax} (pcf)	120.0	117.0	117.5	119.6

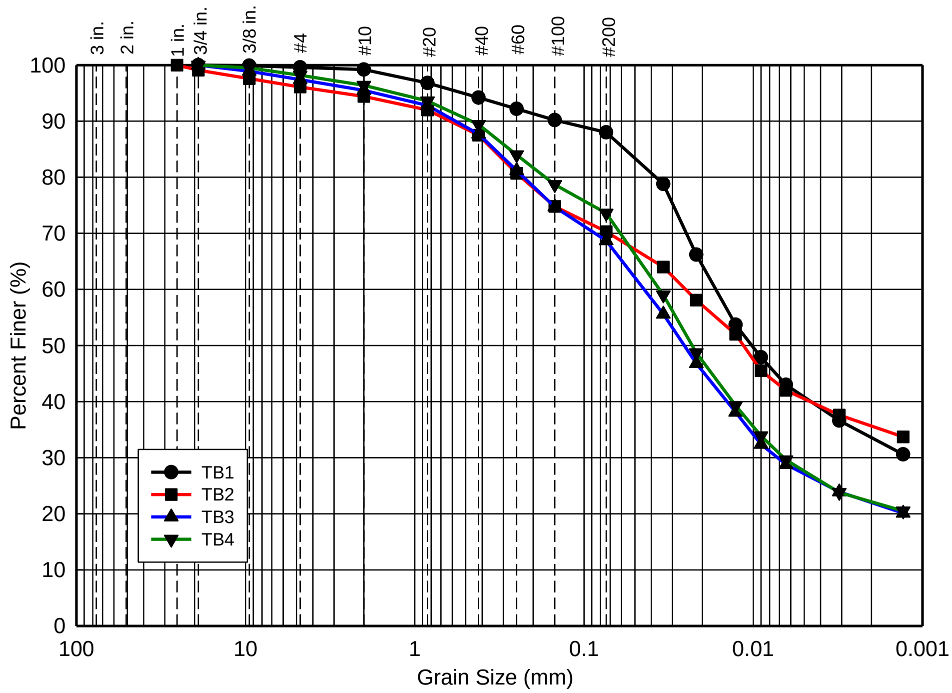

Figure 5. Grain size distribution of embankment materials obtained from Polk County

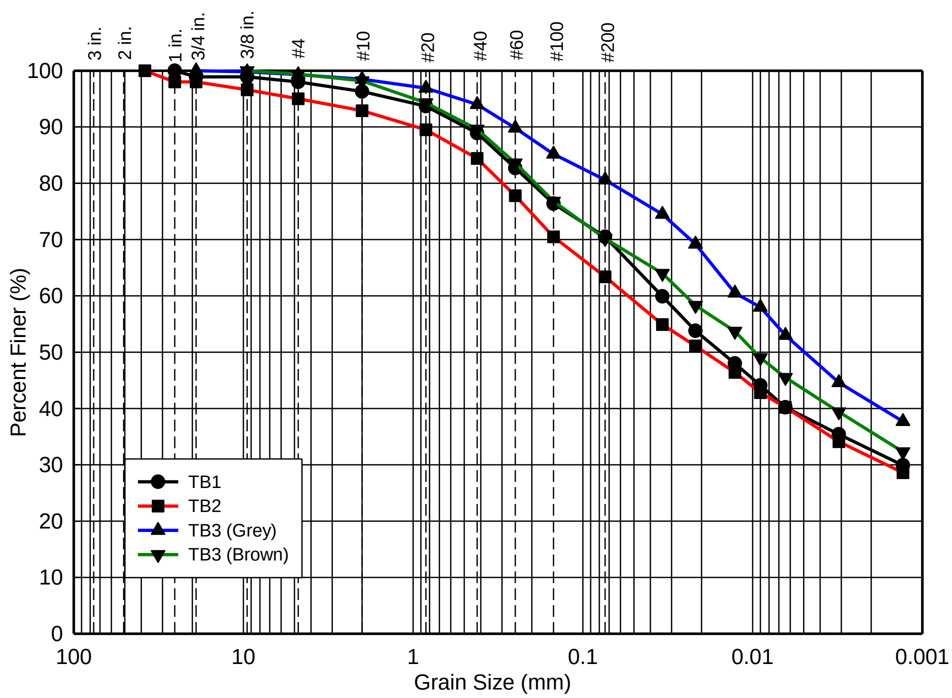

Figure 6. Grain size distribution of embankment materials obtained from Warren County

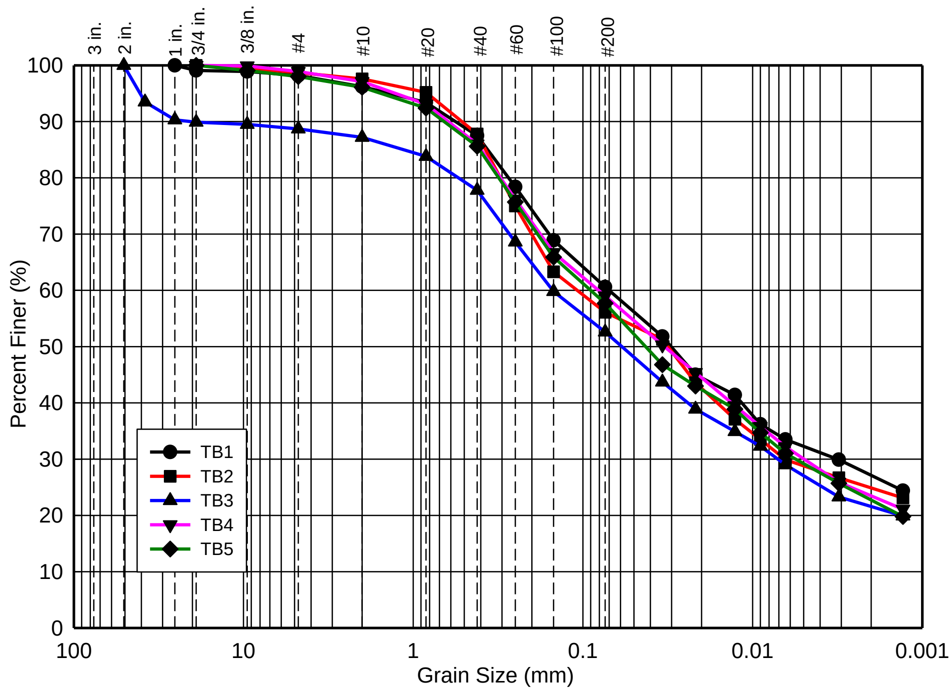

Figure 7. Grain size distribution of embankment materials obtained from Linn County 77

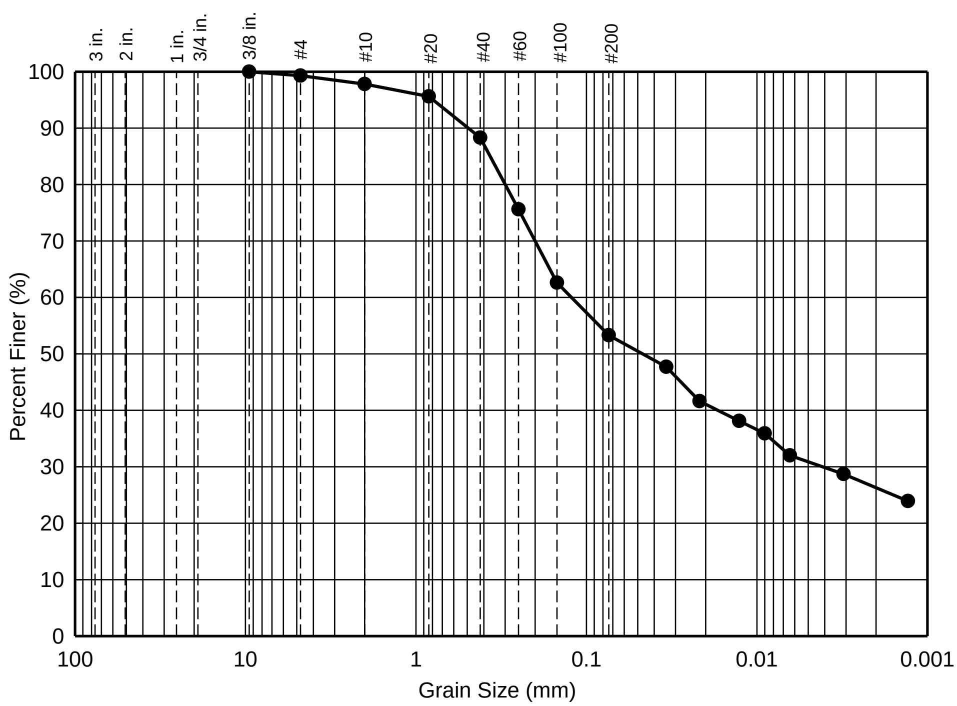

Figure 8. Grain size distribution of embankment materials obtained from Linn County 79

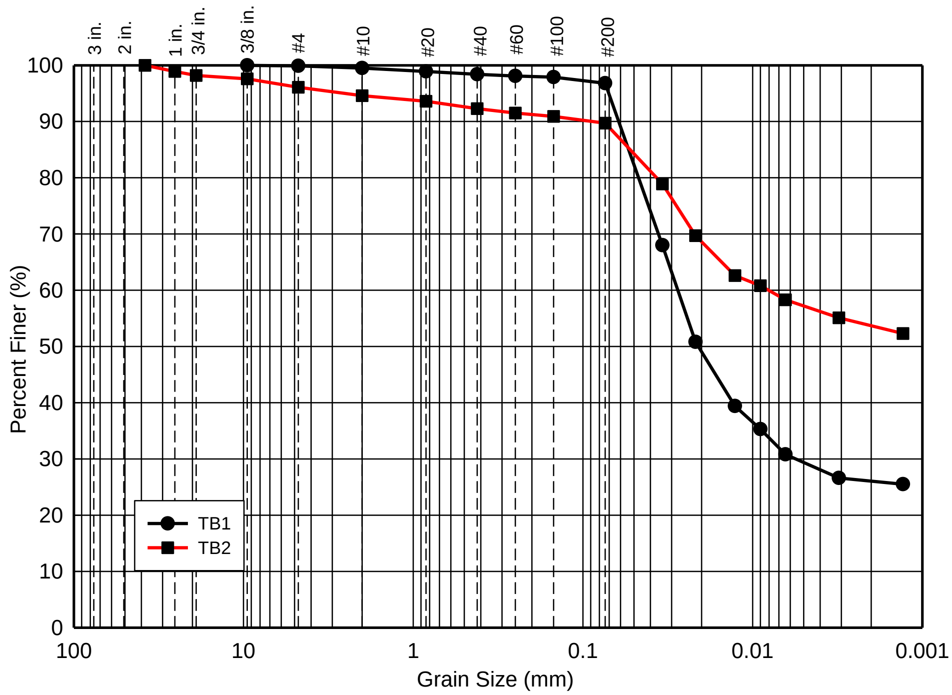

Figure 9. Grain size distribution of embankment materials obtained from Mills County

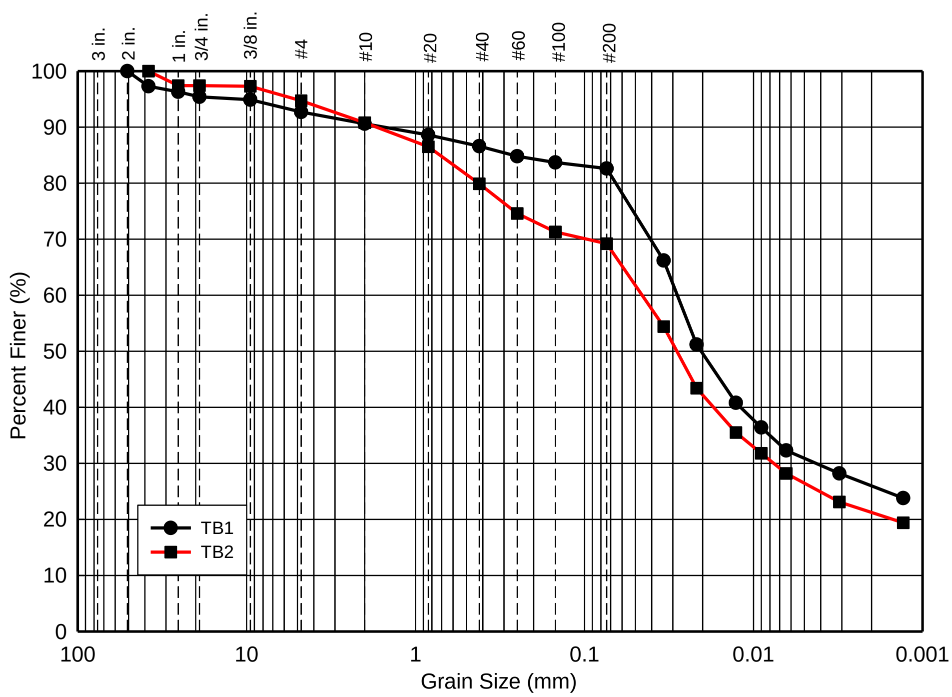

Figure 10. Grain size distribution of embankment materials obtained from Pottawattamie County

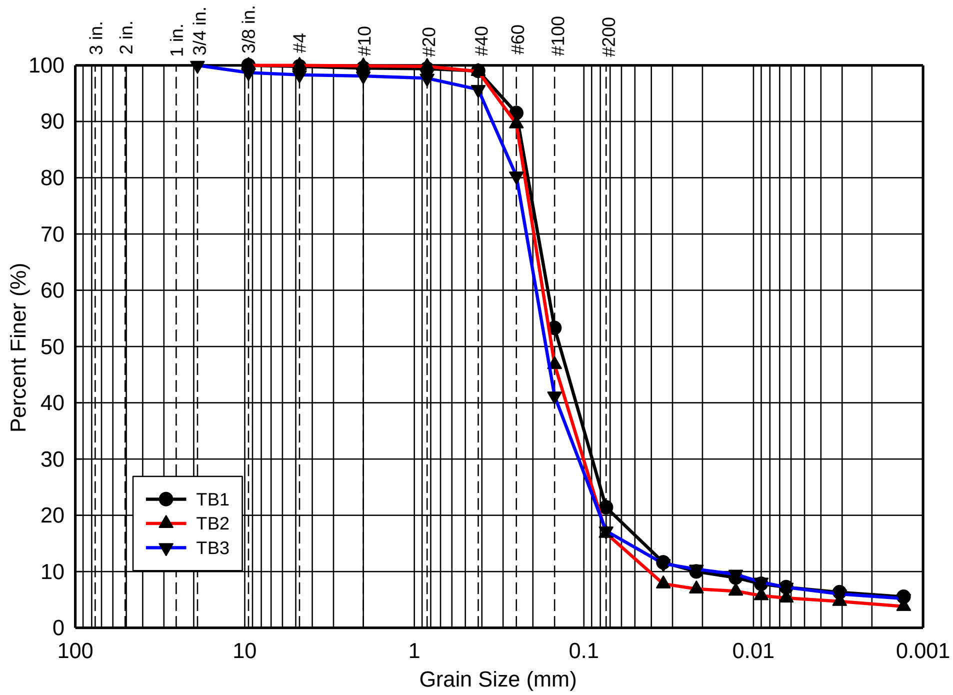

Figure 11. Grain size distribution of embankment materials obtained from Woodbury County I-29

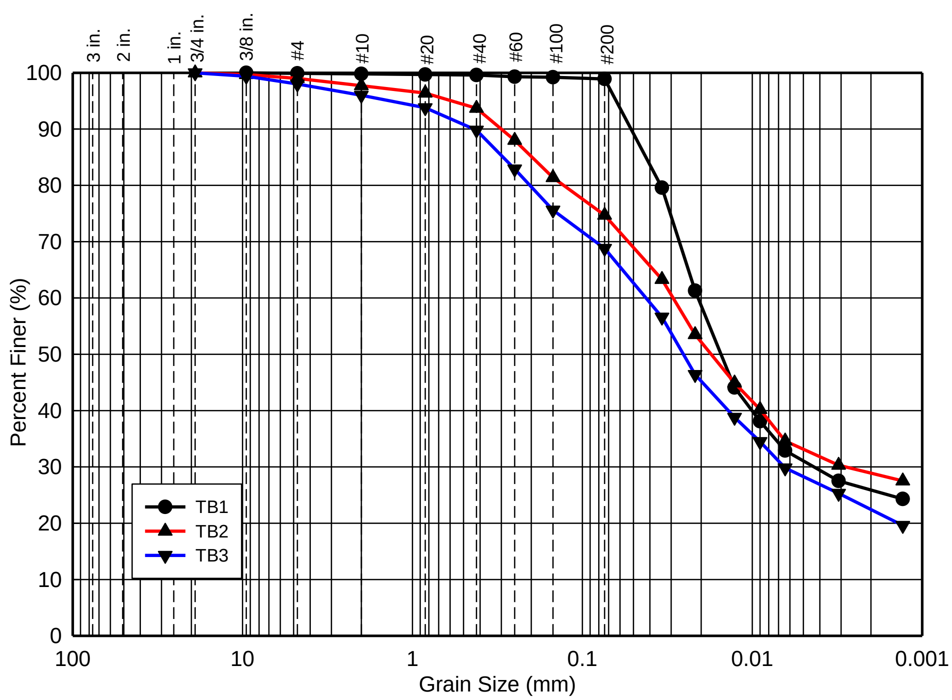

Figure 12. Grain size distribution of embankment materials obtained from Scott County

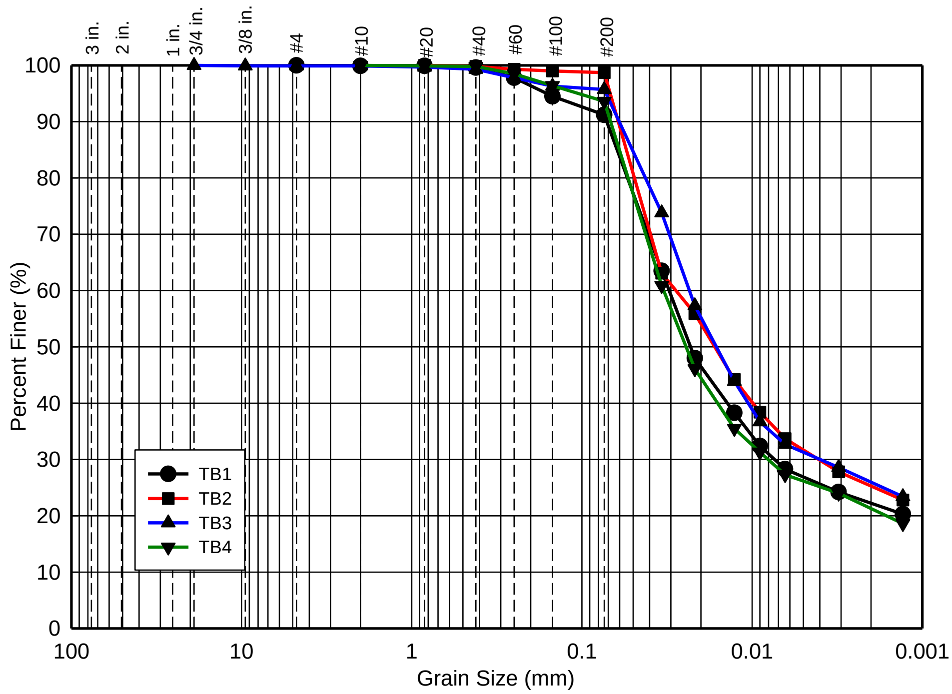

Figure 13. Grain size distribution of embankment materials obtained from Woodbury County US 20

CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents the results obtained from laboratory tests and statistical analysis. A summary of the F_{200}, Atterberg limits, GI, and Iowa DOT material suitability classification results for materials stabilized with different cement contents are presented in Table 9. Detailed results are provided in Appendix A. In the following sections of this chapter, the results and analysis are separately for F_{200}, Atterberg limits, GI, and UCS, to present the influence of cement stabilization on these properties.

Table 9. Summary of soil index properties and Iowa DOT suitability classifications at different cement contents

County and Test Bed	Cement content (%)	F_{200} (%)	LL (%)	PI (%)	GI	Iowa DOT Suitability
Polk TB1	0	88	49	21	21	suitable
	4	74.1	41	13	10	suitable
	8	64.5	40	8	5	suitable
	12	53.1	40	0	0	suitable
Polk TB2	0	70.3	45	11	8	suitable
	4	59.3	43	13	7	suitable
	8	47.9	41	10	3	suitable
	12	45.7	38	0	0	suitable
Polk TB3	0	68.7	36	16	9	suitable
	4	58.5	34	6	2	suitable
	8	41.1	35	0	0	suitable
	12	32.3	36	0	0	suitable
Polk TB4	0	73.6	34	17	11	suitable
	4	61.9	36	0	0	suitable
	8	40.6	38	0	0	suitable
	12	40.4	34	0	0	suitable
Warren TB1	0	70.5	44	13	9	suitable
	4	60.4	38	14	7	suitable
	8	36.8	41	0	0	suitable
	12	27.4	38	0	0	suitable
Warren TB2	0	63.4	40	21	11	select
	4	55.7	39	15	6	select
	8	34.4	38	0	0	suitable
	12	25.7	34	0	0	suitable
Warren TB3	0	80.6	54	34	28	unsuitable
	4	70.7	42	17	11	suitable
	8	51.8	44	12	4	suitable
	12	31	40	0	0	suitable

County and Test Bed	Cement content (%)	F_{200} (%)	LL (%)	PI (%)	GI	Iowa DOT Suitability
Linn 79 TB1	0	53.3	31	6	1	suitable
	4	40.8	29	12	1	suitable
	8	28.6	28	0	0	suitable
	12	21.2	29	0	0	suitable
Linn 77 TB1	0	60.6	31	19	8	select
	4	49.9	34	16	5	select
	8	38.8	33	10	1	suitable
	12	29.4	33	0	0	suitable
Linn 77 TB2	0	56.1	34	18	7	select
	4	51.3	34	12	3	select
	8	41	32	0	0	suitable
	12	22.4	31	0	0	suitable
Linn 77 TB3	0	52.6	33	22	7	select
	4	43.1	32	11	2	select
	8	20.4	32	0	0	suitable
	12	15.8	35	0	0	suitable
Linn 77 TB4	0	59	32	16	6	select
	4	48	43	16	5	select
	8	37	43	14	1	select
	12	33.6	39	0	0	suitable
Linn 77 TB5	0	57.7	30	14	5	select
	4	52.9	34	15	5	select
	8	31.2	33	9	0	suitable
	12	23.4	33	0	0	suitable
Pottawattamie TB1	0	82.6	43	25	20	suitable
	4	78.6	39	9	8	suitable
	8	52.3	40	7	2	suitable
	12	37.5	36	0	0	suitable
Pottawattamie TB2	0	69.2	42	23	14	suitable
	4	60.5	36	5	2	suitable
	8	42.5	36	4	0	suitable
	12	35.3	37	0	0	suitable
Mills TB1	0	96.8	38	4	7	suitable
	4	88	35	8	8	suitable
	8	49.8	34	2	0	suitable
	12	34.5	36	0	0	suitable
Mills TB2	0	89.7	36	5	6	suitable
	4	72.6	34	5	4	suitable
	8	48.3	34	2	0	suitable
	12	29.4	35	0	0	suitable

County and Test Bed	Cement content (%)	F_{200} (%)	LL (%)	PI (%)	GI	Iowa DOT Suitability
Scott TB1	0	98.9	39	7	10	suitable
	4	85.2	34	8	7	suitable
	8	52.1	34	3	0	suitable
	12	34.9	35	0	0	suitable
Scott TB2	0	74.7	35	11	8	suitable
	4	61	33	6	2	suitable
	8	46.9	32	0	0	suitable
	12	40	34	0	0	suitable
Scott TB3	0	68.8	28	11	5	suitable
	4	56.4	31	9	3	suitable
	8	37.9	31	1	0	suitable
	12	25.1	33	0	0	suitable
Woodbury (US20) TB1	0	91.2	32	7	7	suitable
	4	65.4	33	7	4	suitable
	8	53.9	33	2	0	suitable
	12	39	34	0	0	suitable
Woodbury (US20) TB2	0	98.7	35	8	9	suitable
	4	76.3	41	10	8	suitable
	8	50.5	40	5	1	suitable
	12	33.8	43	0	0	suitable
Woodbury (US20) TB3	0	95.7	35	12	12	suitable
	4	69.8	40	9	6	suitable
	8	43.2	40	6	1	suitable
	12	32.4	41	0	0	suitable
Woodbury (US20) TB4	0	93.6	31	7	7	suitable
	4	79.1	32	6	4	suitable
	8	51.6	32	1	0	suitable
	12	32.9	33	0	0	suitable
Woodbury (I29) TB1	0	21.4	NV	0	0	suitable
	4	9.3	NV	0	0	suitable
	8	9	NV	0	0	suitable
	12	8.6	NV	0	0	select
Woodbury (I29) TB2	0	16.8	NV	0	0	suitable
	4	7.7	NV	0	0	suitable
	8	7.1	NV	0	0	suitable
	12	7.4	NV	0	0	suitable
Woodbury (I29) TB3	0	17.2	NV	0	0	suitable
	4	8.2	NV	0	0	suitable
	8	9.5	NV	0	0	suitable
	12	8.3	NV	0	0	select

Fines Content (F_{200})

Results of F_{200} versus cement content are presented in Figure 14 and Figure 15. The results indicated that F_{200} decreased with increasing cement content. Statistical analysis was conducted to predict F_{200} after treatment as a function of cement content, F_{200} before treatment, and Atterberg limits. Results are summarized in Table 10. Cement content, F200 before treatment, and LL were found to be statistically significant. PI and PL parameters were not statistically significant. Measured versus predicted F_{200} (after treatment) results from the multi-variate model are presented in Figure 16. The model showed an R^2 of about 0.9 and RMSE of about 7%.

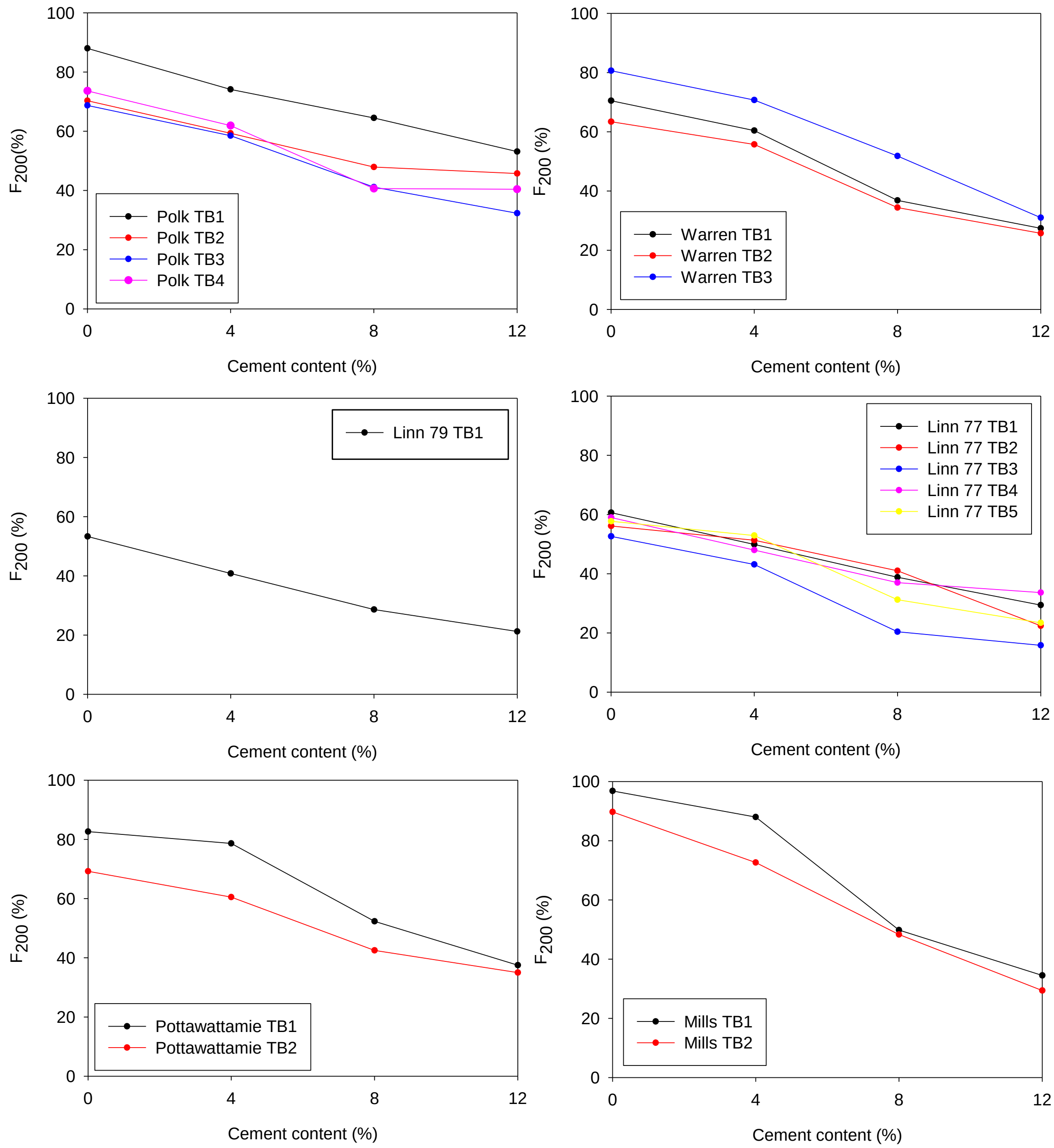

Figure 14. F_{200} versus cement content

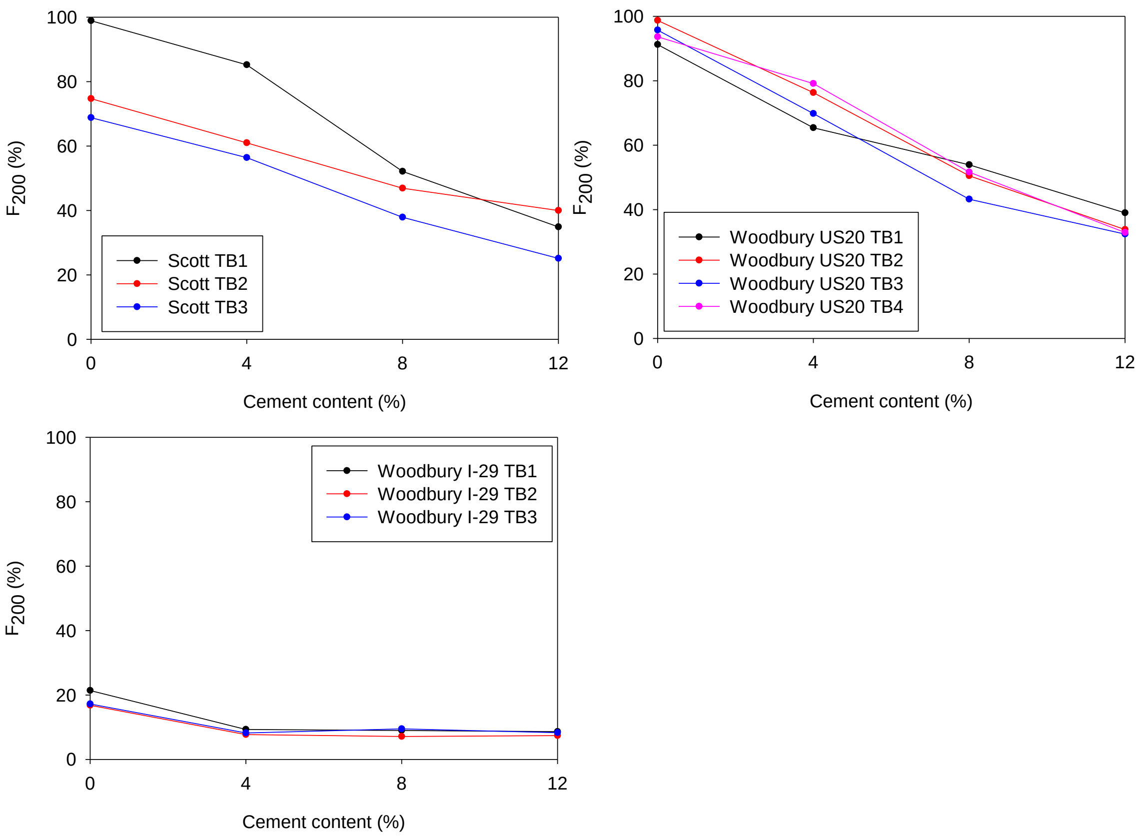

Figure 15. F_{200} versus cement content (continued)

Table 10. Multi-variate analysis results to predict F_{200} after cement stabilization

Parameter	Value	t Ratio	Prob> |t|	R^2	RMSE
Intercept	18.92	3.96	< 0.0001	0.898	6.588
Cement Content (%)	-3.74	-24.88	< 0.0001		
F_{200} before treatment (%)	0.607	13.23	< 0.0001		
LL (%)	0.306	2.79	0.0064		
Prediction expression	F_{200} after treatment (%) = 18.92 - 3.74 x cement content (%) + 0.607 x F_{200} (%) + 0.306 x LL (%)				

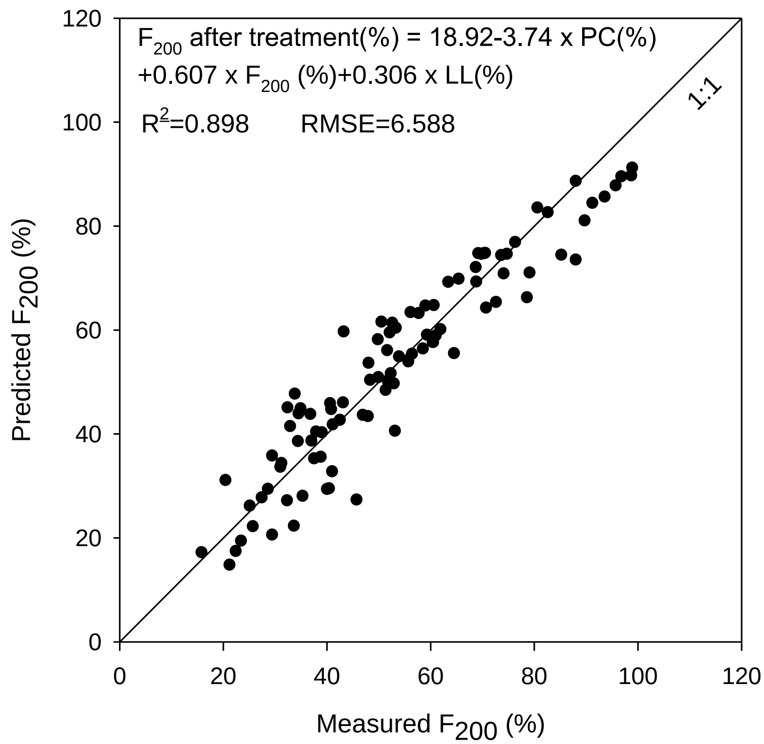

Figure 16. Comparison of measured F_{200} and predicted F_{200}

Atterberg Limits

Plasticity charts showing relationship between LL and PI for unstabilized and stabilized soils with 4%, 8%, and 12% cement content are shown in Figure 16 to Figure 20, respectively. F_{200} versus of PI results are shown in Figure 21. LL and PI versus cement content are presented in Figure 22 to Figure 24.

With the exception of a few materials (Polk TB4, Linn 79, Linn 77 TB4), the LL and PI of all materials decreased with increasing cement content. The one untreated soil classified as "unsuitable", classified as "suitable" after stabilized with cement. Some of the "select" untreated soils classified as "suitable" after stabilized with cement, because of reduction in PI. All of the soils classified as "suitable" at 12% cement content because of no plasticity.

Statistical analysis was conducted to predict PI after treatment as a function of cement content, cement content, clay content, silt content, and LL. Results are summarized in Table 11. Cement content and clay content were found to be statistically significant, while the remaining parameters were not statistically significant. Measured versus predicted PI (after treatment) results from the multi-variate model are presented in Figure 25. The model showed an R^2 of about 0.5 and RMSE of about 5%.

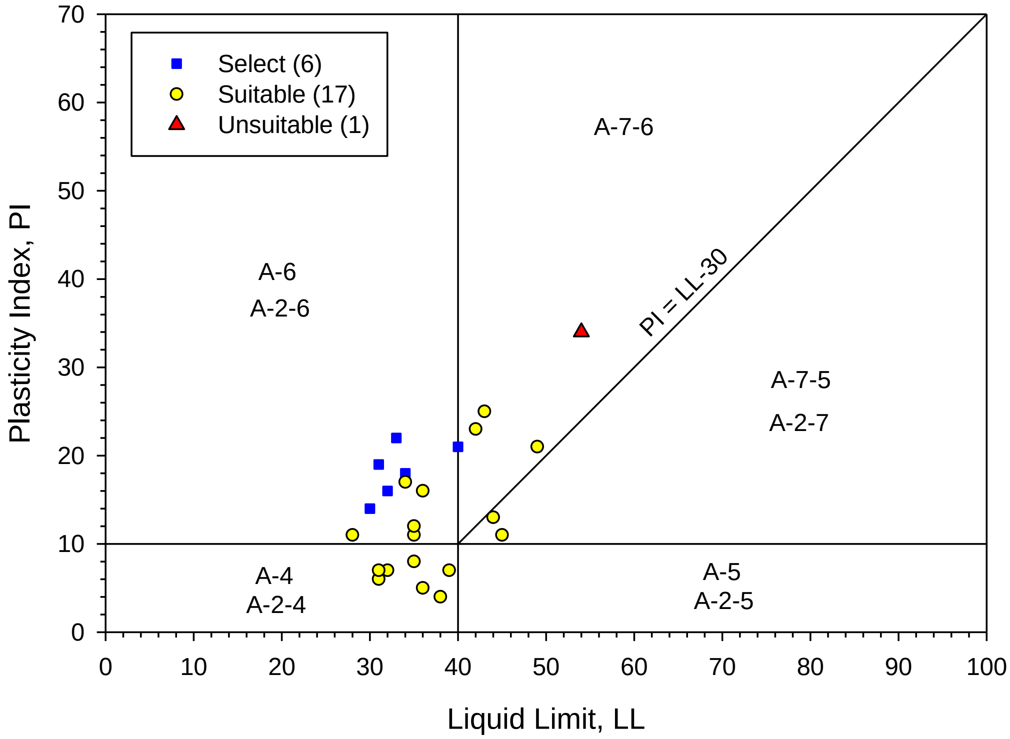

Figure 17. Plasticity chart with results of unstabilized soils

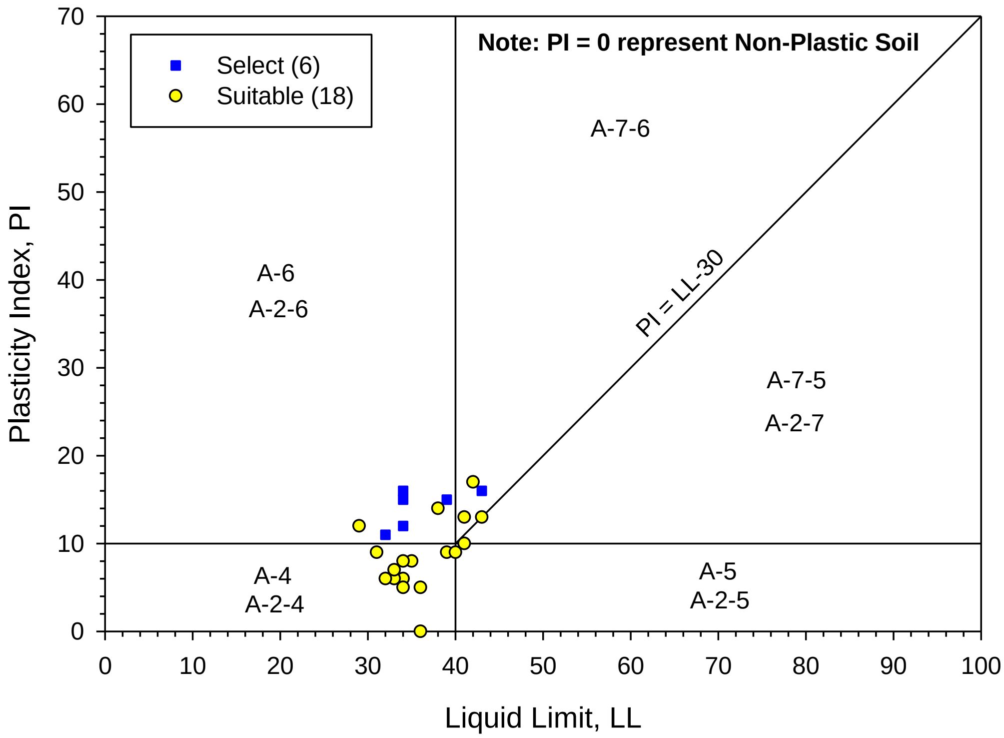

Figure 18. Plasticity chart with results of 4% cement stabilized soils

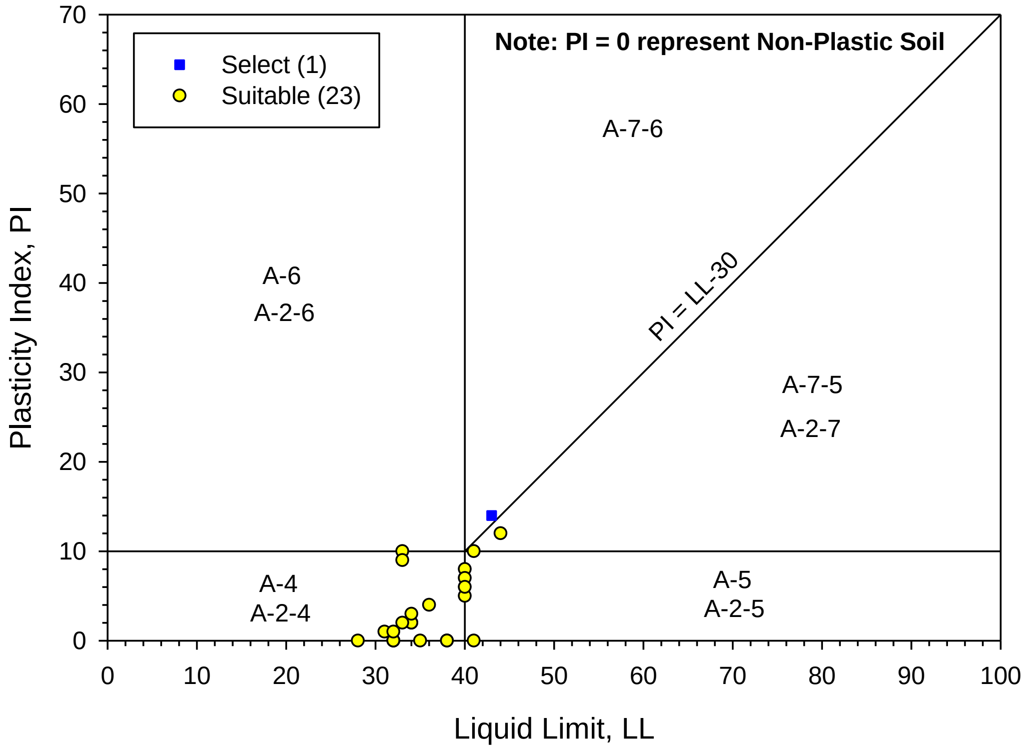

Figure 19. Plasticity chart with results of 8% cement stabilized soils

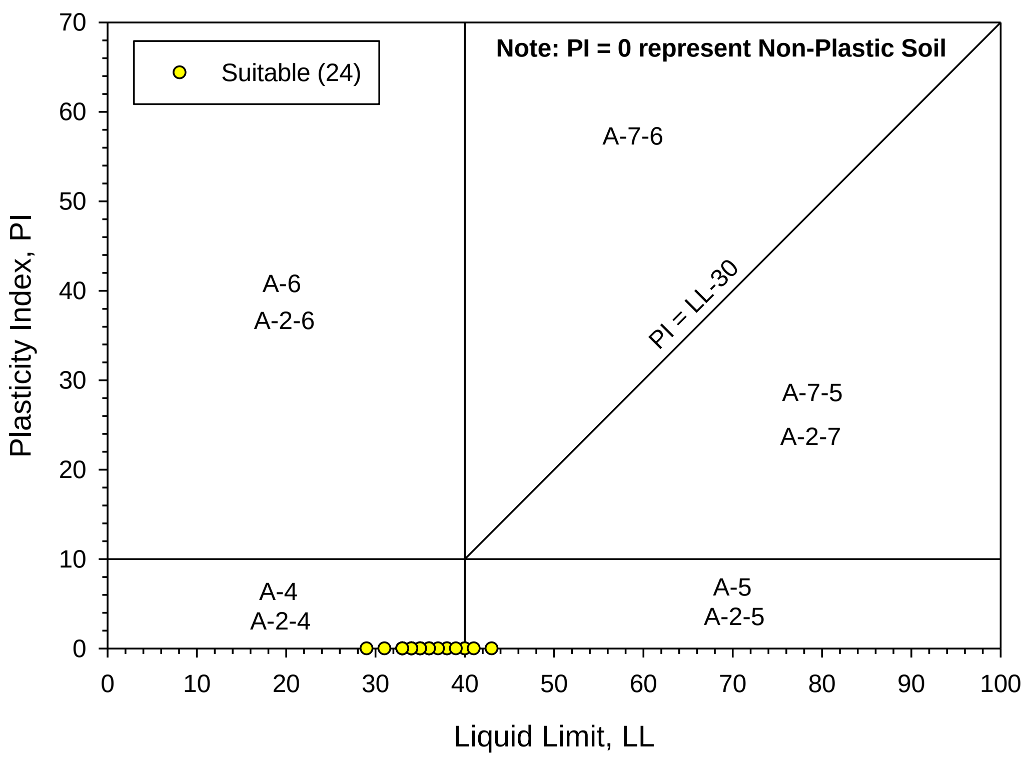

Figure 20. Plasticity chart with results of 12% cement stabilized soils

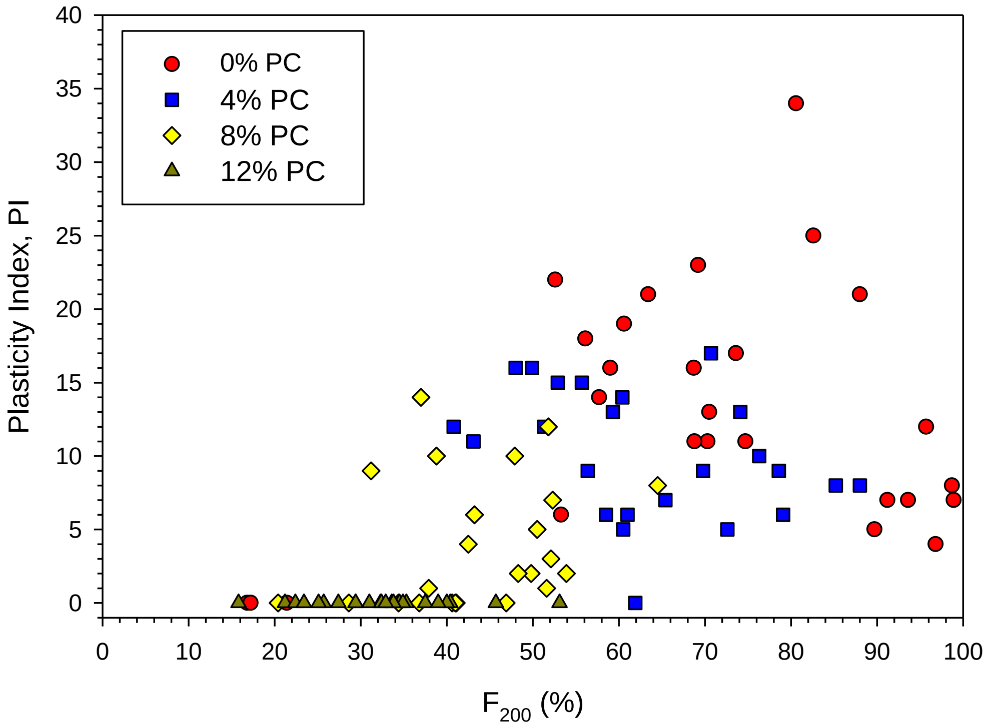

Figure 21. PI versus F200 for unstabilized and stabilized soils

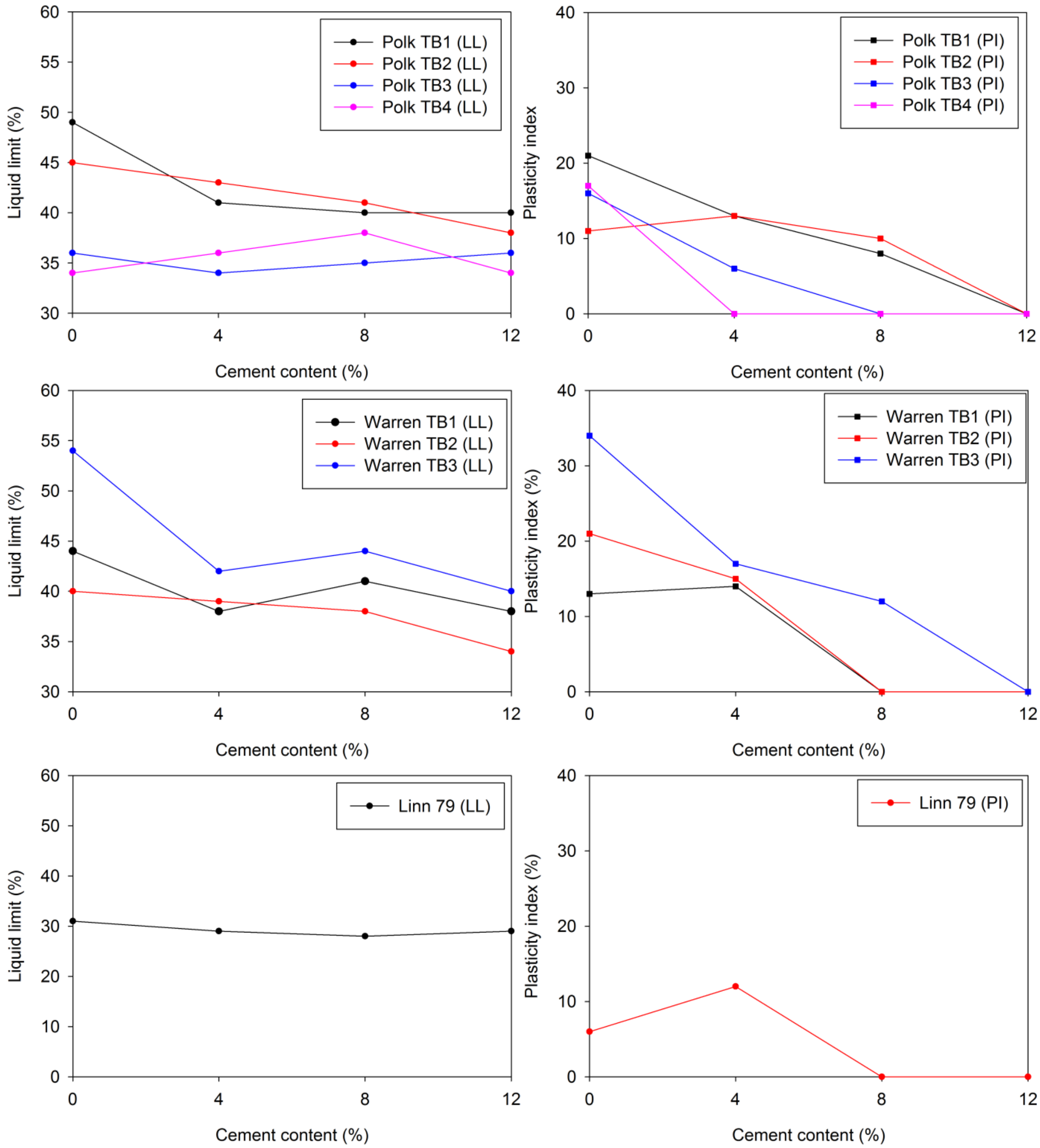

Figure 22. LL and PI versus cement content

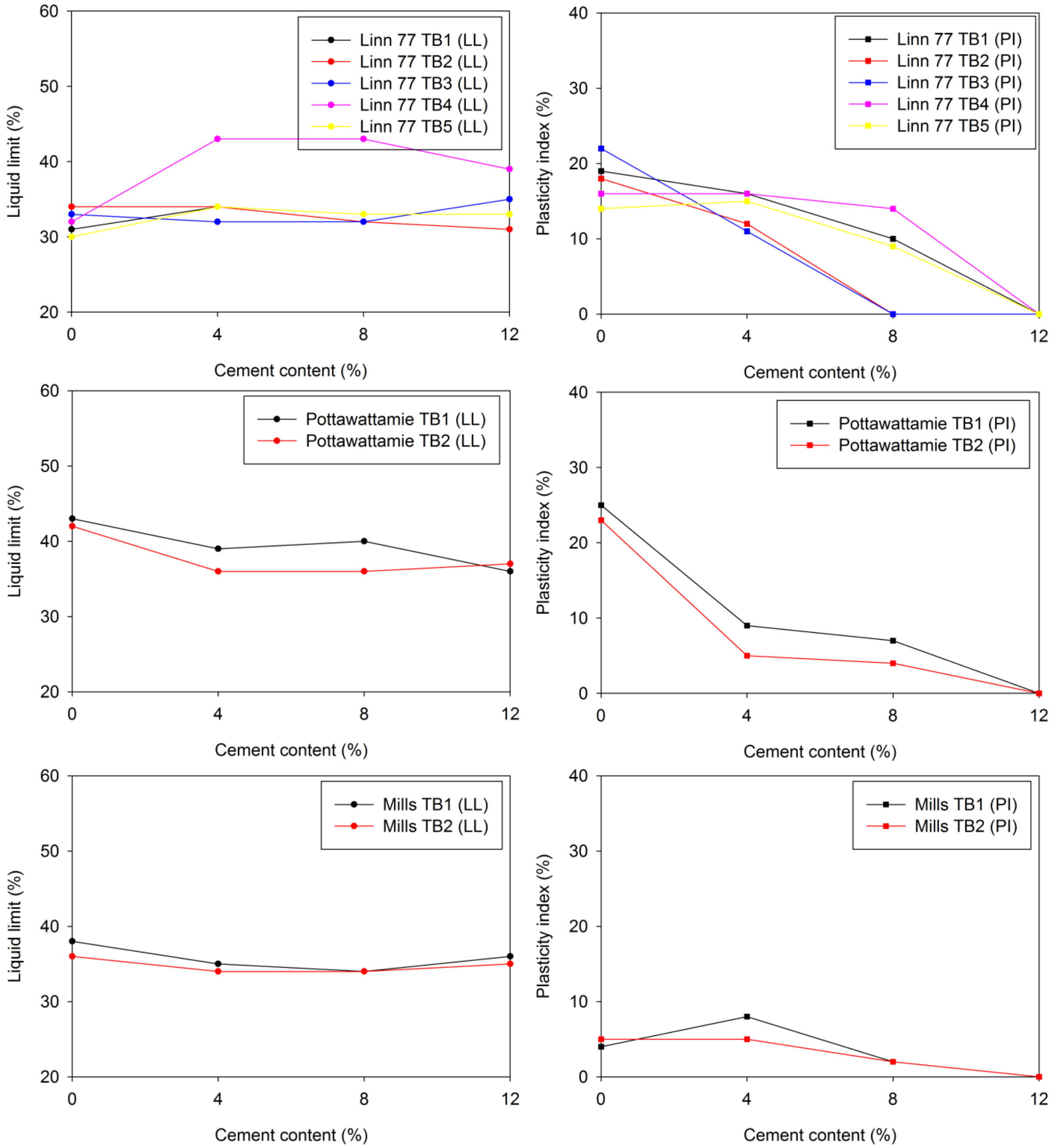

Figure 23. LL and PI versus cement content (continued)

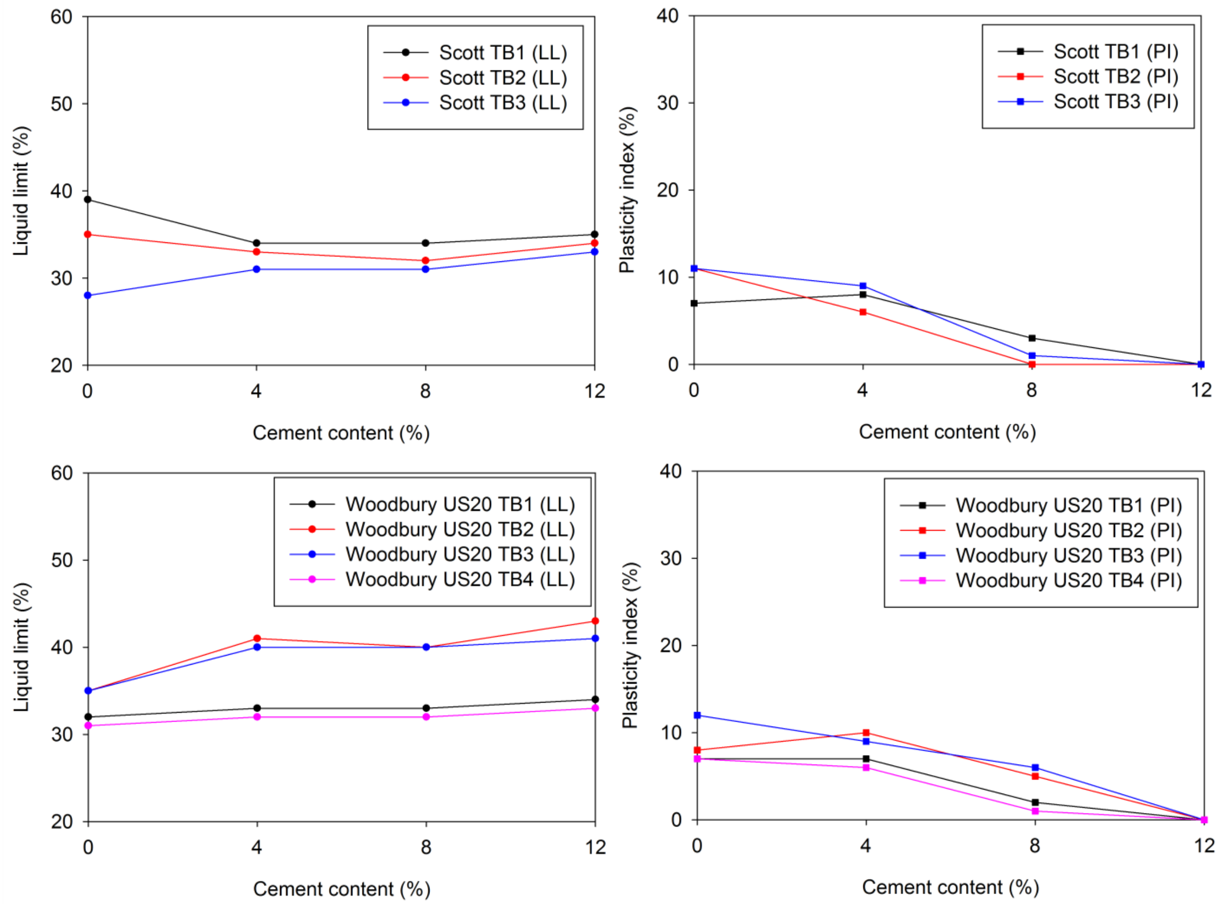

Figure 24. LL and PI versus cement content (continued-2)

Table 11. Multi-variate analysis results to predict PI after cement stabilization

Parameter	**Value**	**t Ratio**	**Prob> |t|**	**R^2**	**RMSE**
Intercept	8.664	5.85	< 0.0001	0.509	5.101
Cement Content (%)	-1.102	-10.04	< 0.0001		
Clay content (%)	0.172	3.49	0.0007		
Prediction expression	F_{200} after treatment (%) = 8.664 – 1.102 x cement content (%) + 0.172 x Clay content (%)				

Note: Silt content, sand content, and LL were not statistically significant

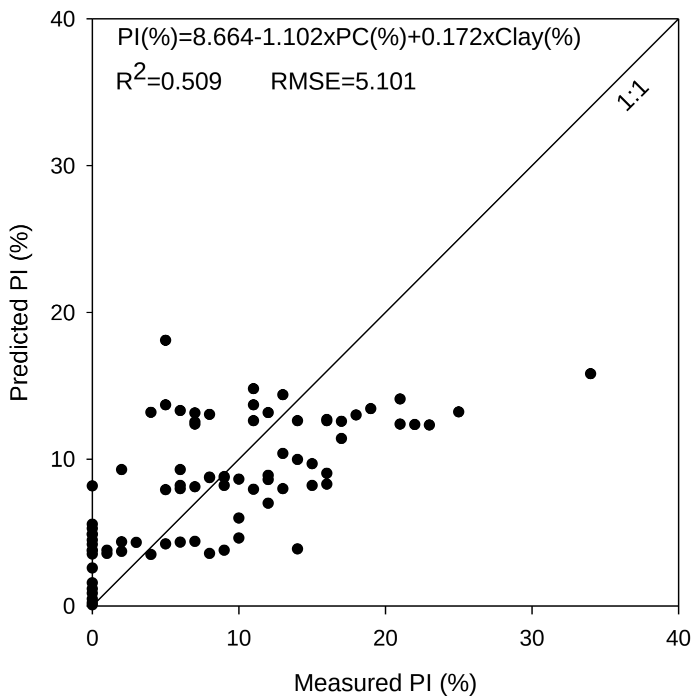

Figure 25. Comparison of measured PI and predicted PI

AASHTO Group Index

GI versus cement content results are presented Figure 26 to Figure 27. For a majority of the soils, the GI values decreased with increasing cement content. Statistical analysis was conducted to predict GI after treatment as a function of cement content, clay content, silt content, F_{200}, LL, and PI. Results are summarized in Table 12. Cement content, F_{200}, LL, and PI were found to be statistically significant, while the remaining parameters were not statistically significant. Measured versus predicted GI (after treatment) results from the multi-variate model are presented in Figure 28. The model showed an R^2 of about 0.7 and RMSE of about 3.

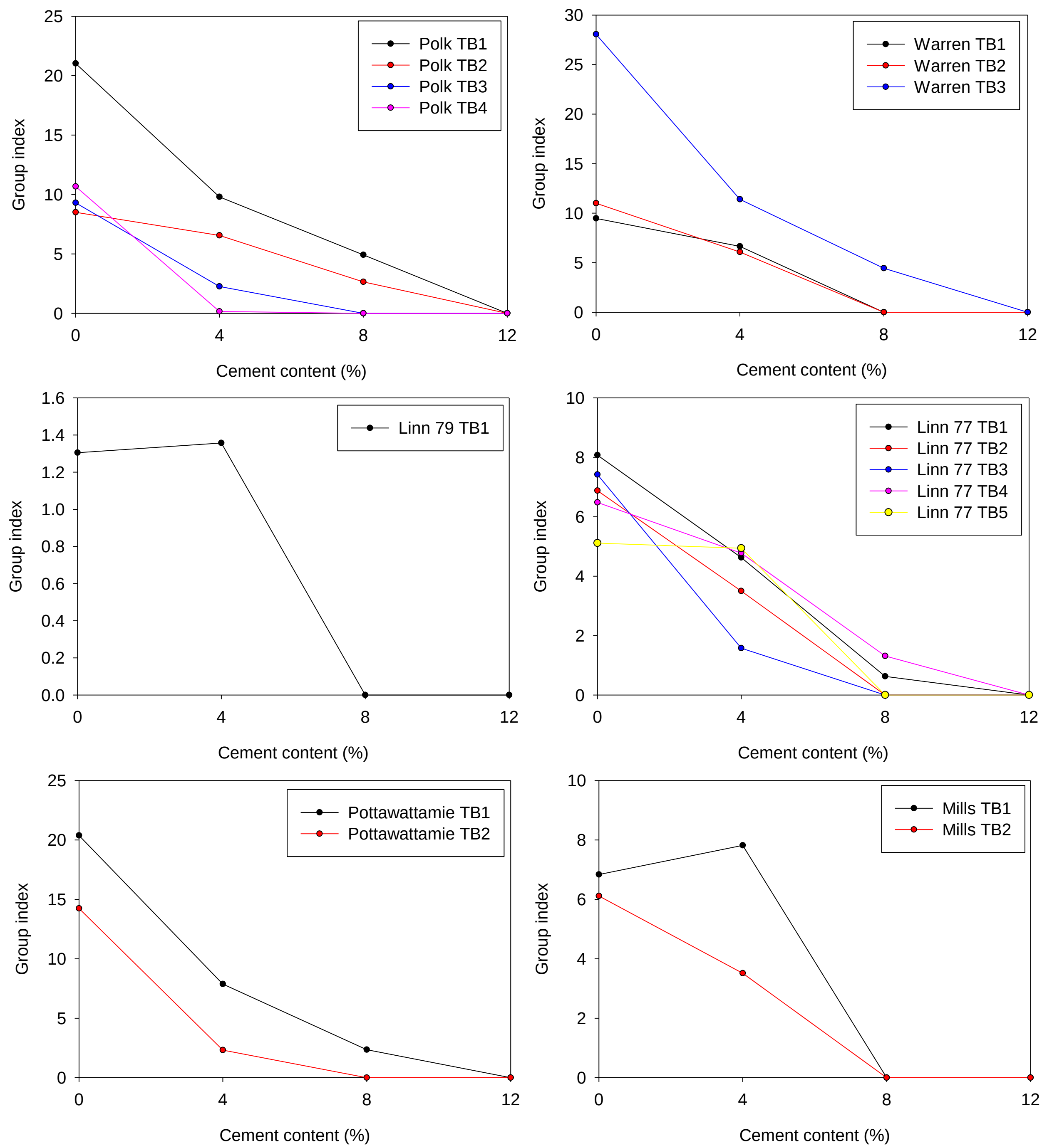

Figure 26. AASHTO group index versus cement content

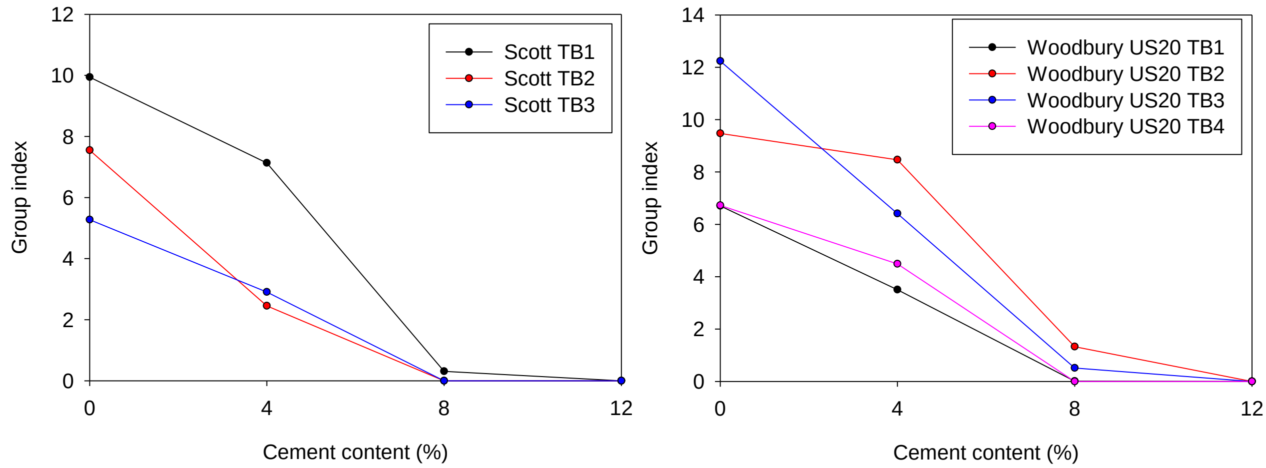

Figure 27. AASHTO group index versus cement content (continued)

Table 12. Multi-variate analysis results to predict GI after cement stabilization

Parameter	Value	t Ratio	Prob> |t|	R^2	RMSE
Intercept	-4.540	-2.23	0.0281	0.708	2.774
Cement Content (%)	-0.844	-13.33	<0.0001		
F_{200} (%)	0.069	2.85	0.0055		
LL (%)	0.157	2.98	0.0164		
PI (%)	0.172	2.45	0.0037		
Prediction expression	GI = - 4.540 – 0.844 x cement content (%) + 0.069 x F_{200} (%) + 0.157 x LL (%) + 0.172 x PI (%)				

Note: Silt content and clay content were not statistically significant.

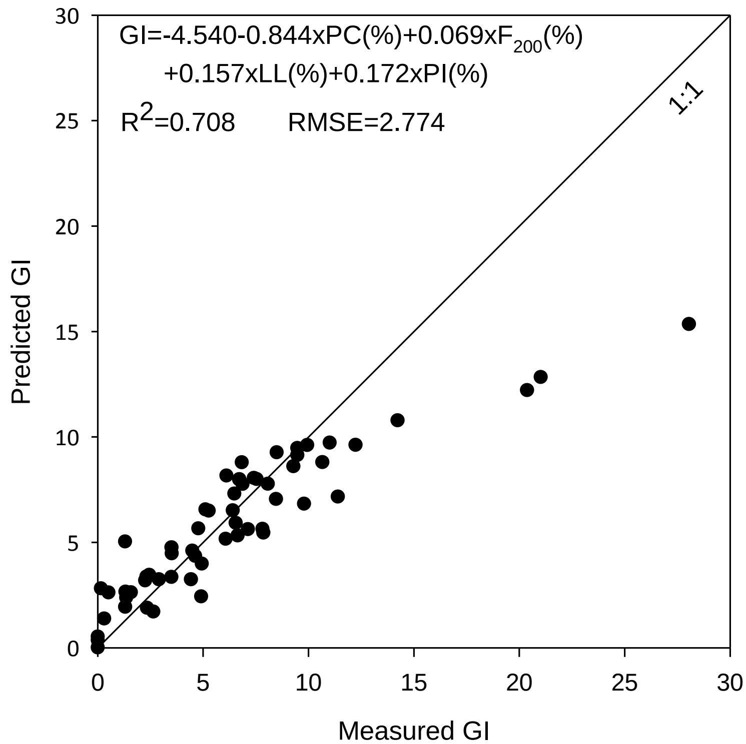

Figure 28. Comparison of measured group index and predicted group index

Unconfined Compressive Strength

Figure 29 to Figure 31 present the results of unsaturated and vacuum saturated UCS of the materials at different cement contents. A linear regression line is fit to the data to define the relationship between UCS and cement content. Results indicated increasing UCS with increasing cement content, as expected. For a majority of the unstabilized materials, the soil specimens became fragile after vacuum saturation and could not be retrieved from the vessel. For those soils, UCS of 0 psi is reported herein. Vacuum saturated stabilized specimens resulted in UCS measurements that were on average about 1.5 times lower than the unsaturated specimens. The ratio of unsaturated and vacuum saturated UCS of stabilized specimens ranged from about 1.1 to 2.5.

Statistical analysis was conducted to predict unsaturated and vacuum saturated UCS as a function of cement content, sand content, clay content, silt content, F_{200}, LL, and PI. Results are summarized in Table 13 and Table 14. Cement content, sand content, F_{200}, and LL were found to be statistically significant, while the remaining parameters were not statistically significant. Measured versus predicted UCS results from the multi-variate model are presented in Figure 32 and Figure 33. The models showed an R^2 of about 0.85 and RMSE of about 75 psi for vacuum saturated UCS and 97 psi for unsaturated UCS.

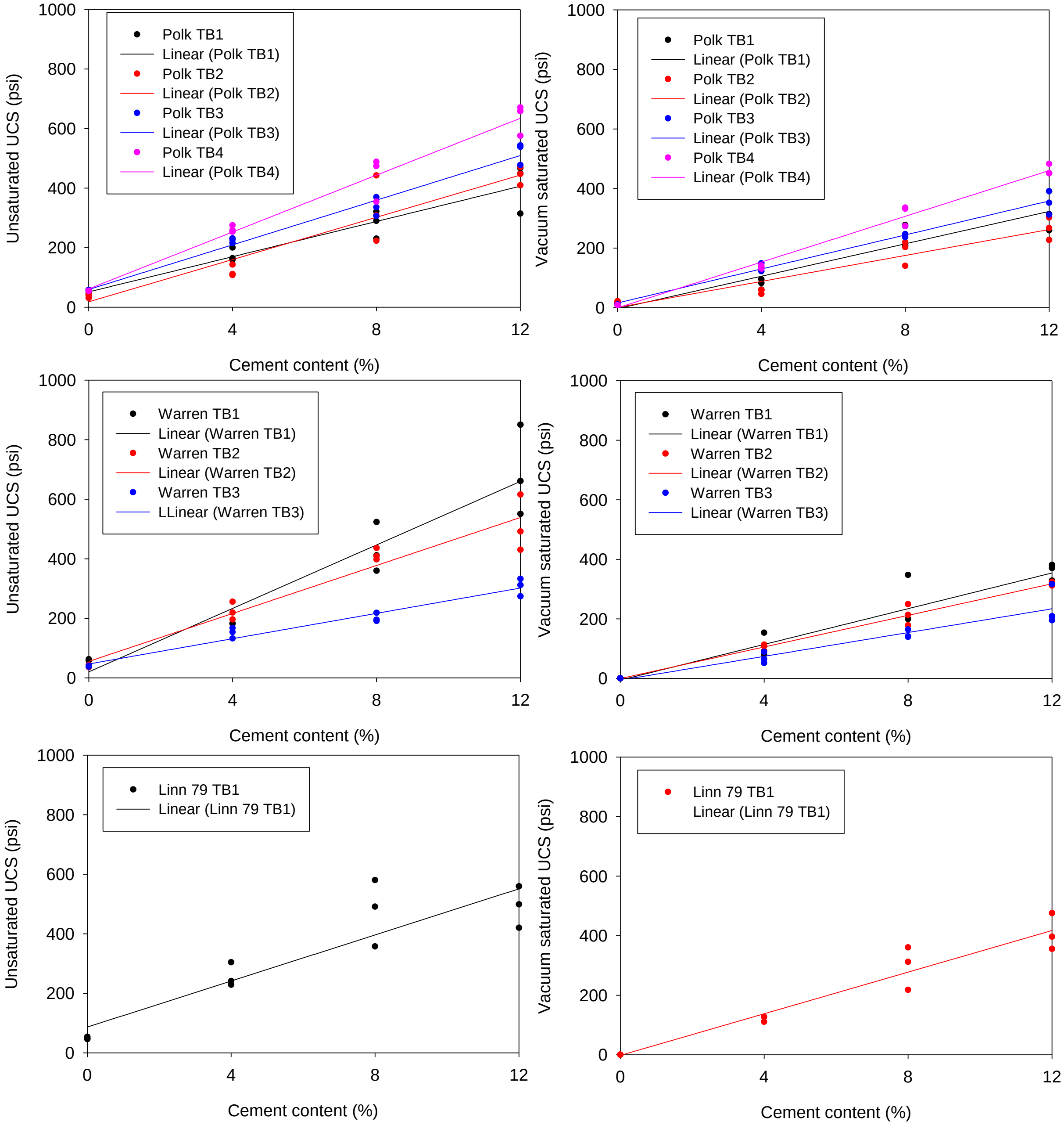

Figure 29. Unsaturated and vacuum saturated UCS versus cement content

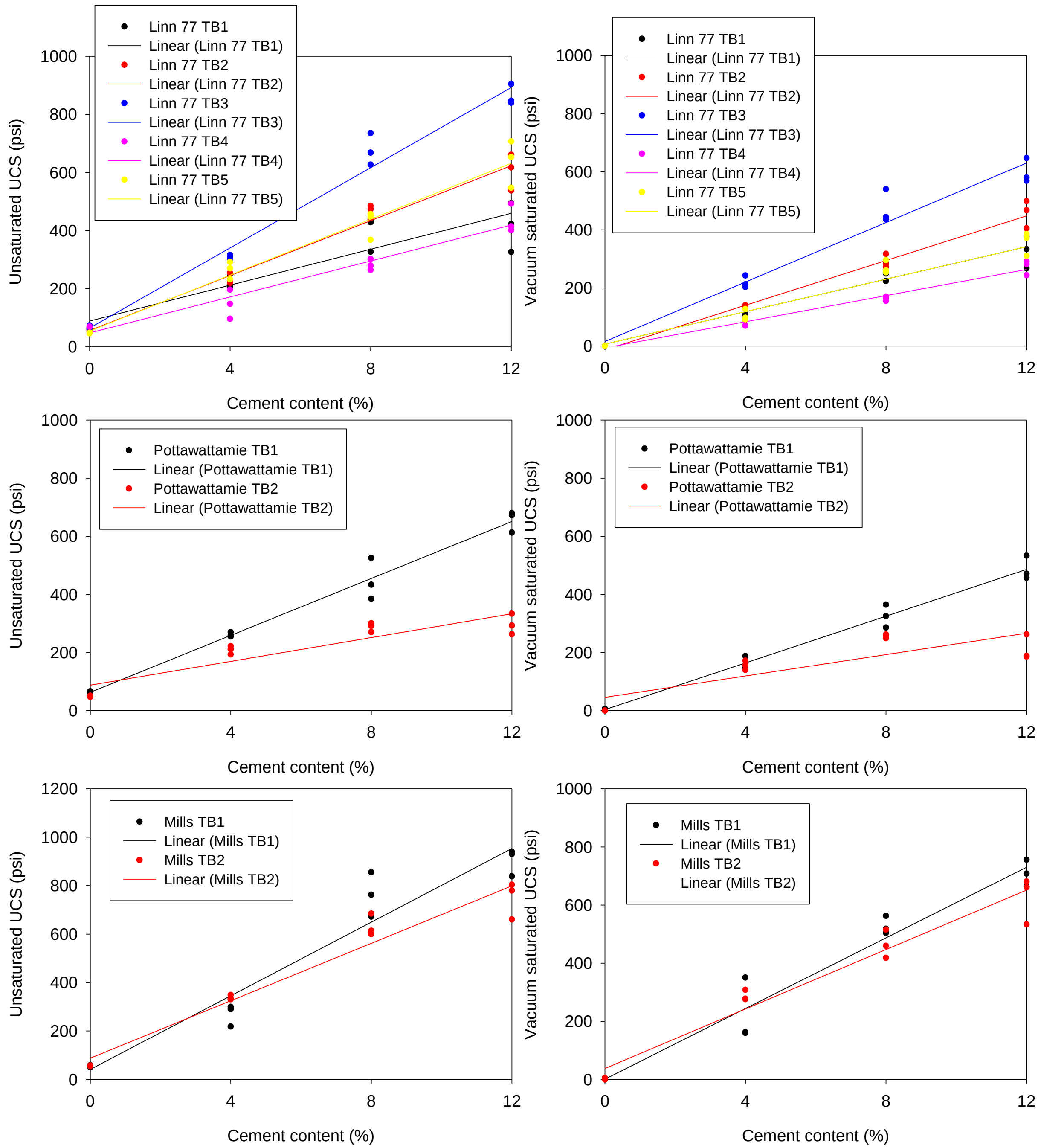

Figure 30. Unsaturated and vacuum saturated UCS versus cement content (continued)

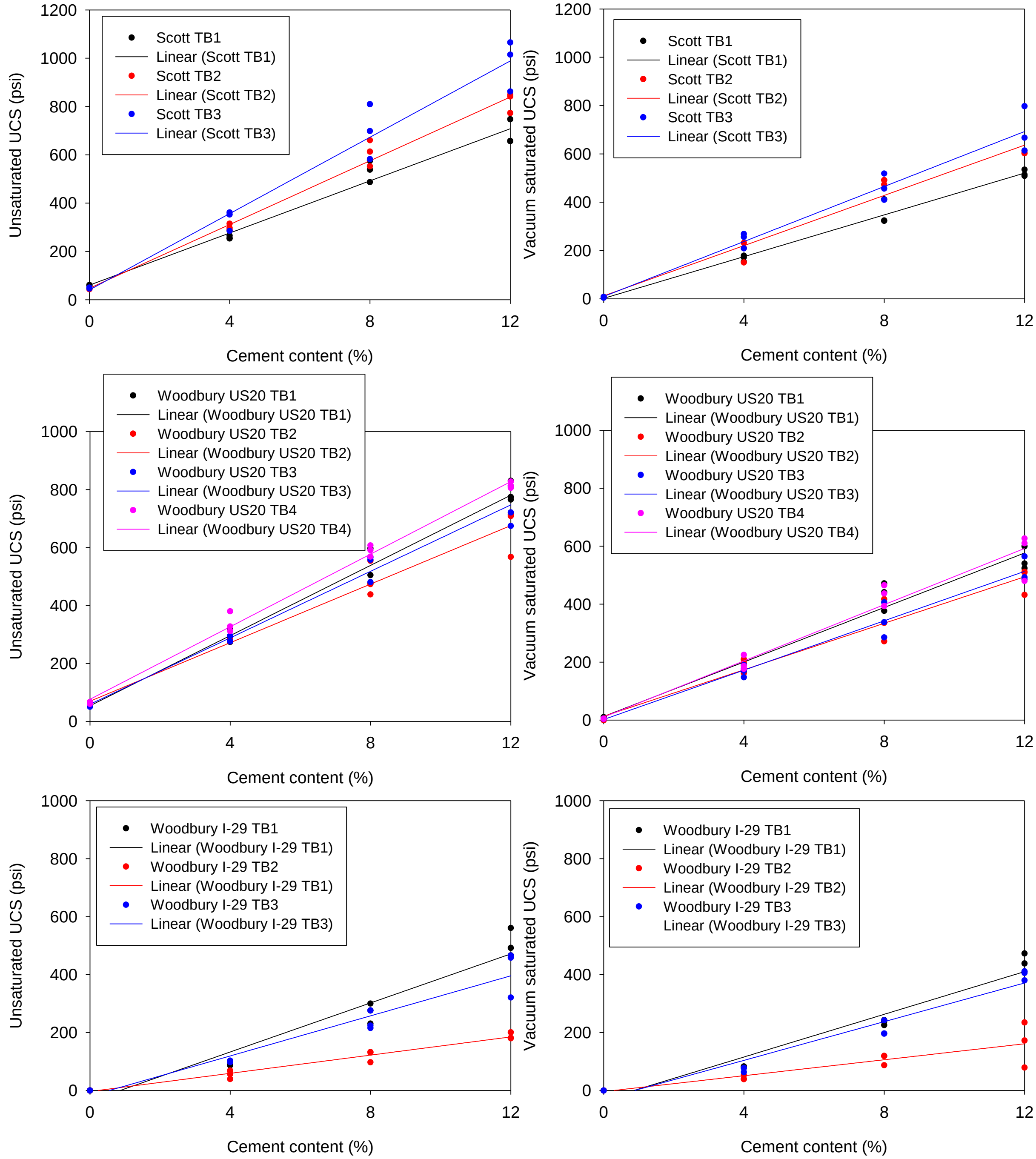

Figure 31. Unsaturated and vacuum saturated UCS versus cement content (continued-2)

Table 13. Multi-variate analysis results to predict unsaturated UCS

Parameter	Value	t Ratio	Prob> |t|	R^2	Root Mean square error
Intercept	1465.38	3.61	0.0005	0.848	97.418
Cement content (%)	48.69	21.90	<0.0001		
Sand (%)	-13.26	-3.13	0.0023		
F_{200} (%)	-9.24	-2.35	0.0209		
LL (%)	-11.28	-6.77	<0.0001		
Prediction expression	UCS (psi) = 1465.38 + 48.69 x cement content (%)- 13.26 x Sand (%) - 11.28 x LL (%) - 9.24 x F_{200} (%)				

Note: Silt content and clay content were not statistically significant.

Table 14. Multi-variate analysis results to predict vacuum saturated UCS

Parameter	Value	t Ratio	Prob> |t|	R^2	Root Mean square error
Intercept	1151.32	3.7	0.0004	0.850	74.704
Cement content (%)	37.33	21.89	<0.0001		
Sand (%)	-11.40	-3.51	0.0007		
F_{200} (%)	-7.70	-2.56	0.0123		
LL (%)	-8.37	-6.55	<0.0001		
Prediction expression	UCS (psi) = 1151.323 + 37.329 x cement content (%) - 11.401 x Sand (%) - 8.372 x LL (%) - 7.703 x F_{200} (%)				

Note: Silt content and clay content were not statistically significant.

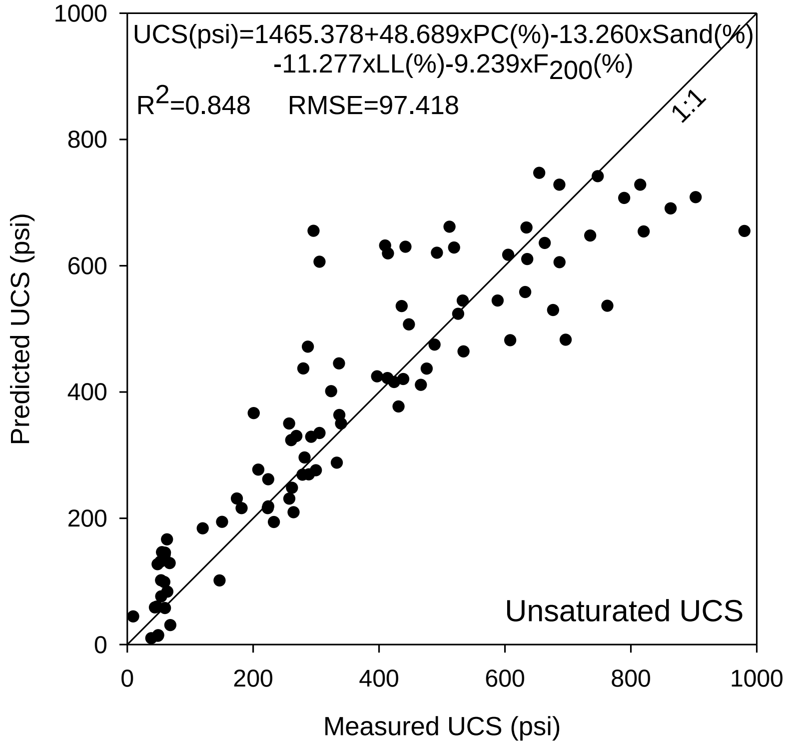

Figure 32. Comparison of measured unsaturated UCS and predicted unsaturated UCS

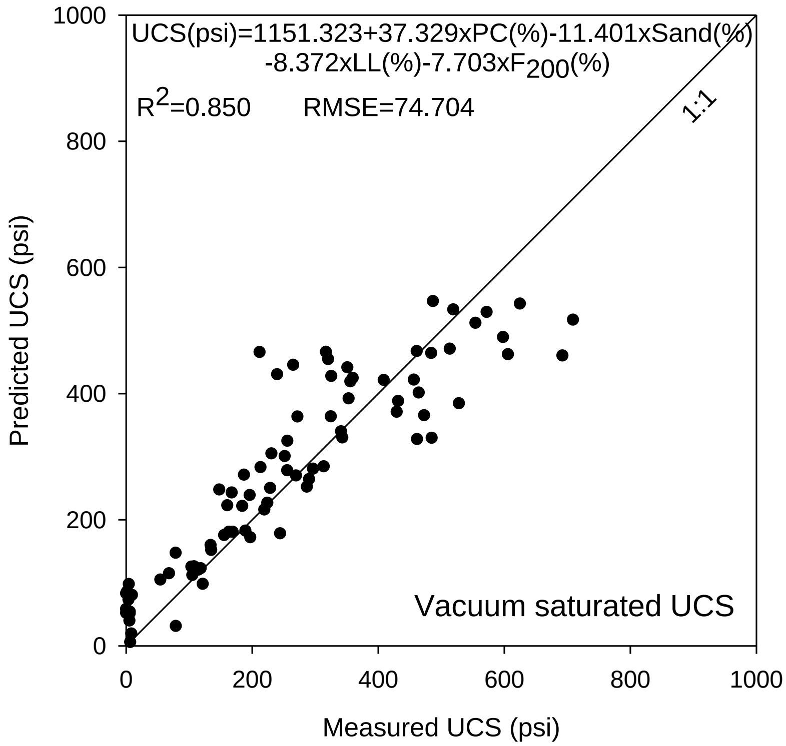

Figure 33. Comparison of measured vacuum saturated UCS and predicted UCS

CHAPTER 5: SUMMARY OF KEY FINDINGS

Results of a laboratory study focused on cement stabilization of 28 soils obtained from 9 active construction sites in Iowa are presented in this report. The materials consisted of glacial till, western Iowa loess, and alluvium sand. Type I/II portland cement was used for stabilization of these materials. 2 x 2 specimens of stabilized and unstabilized materials were prepared, cured, and tested for UCS with and without vacuum saturation. F_{200}, AASHTO group index (GI), and Atterberg limits were tested before and after stabilization. The results were analyzed using multi-variate statistical analysis to assess influence of the various soil index properties on post-stabilization material properties. Key findings from the test results and analysis are as follows:

- F_{200} of the material decreased with increasing cement content for a majority of the soils. The percent cement content, F_{200} before treatment, and liquid limit were found to be statistically significant in predicting the F_{200} after treatment. The multi-variate model showed an R^2 of about 0.9 and RMSE of about 7% in predicting the F_{200} after treatment.

- With the exception of a few materials, the liquid limit and plasticity index of all materials decreased with increasing cement content. The one untreated soil classified as “unsuitable”, classified as “suitable” after stabilized with cement. Some of the untreated soils that were classified as “select”, classified as “suitable” after stabilized with cement. The classifications changed because of reduction in plasticity index. All soils classified as “suitable” at 12% cement content because of no plasticity. The percent cement content and clay content parameters were found to be statistically significant in predicting the plasticity index of materials after stabilization. The multi-variate model showed an R^2 of about 0.5 and RMSE of about 5%.

- The GI values decreased with increasing cement content for a majority of the soils. The percent cement content, F_{200}, liquid limit, and plasticity index parameters were found to be statistically significant in predicting the group index values after treatment. The multi-variate model showed an R^2 of about 0.7 and RMSE of about 3.

- The UCS of specimens increased with increasing cement content, as expected. The average saturated UCS of the unstabilized materials varied between 0 and 57 psi. The average saturated UCS of stabilized materials varied between 44 and 287 psi at 4% cement content, 108 and 528 psi at t 8% cement content, and 162 and 709 psi at 12% cement content. The draft laboratory testing and evaluation procedure for cement stabilization mix design provided in Appendix B targets a 100 psi saturated unconfined compressive strength. The UCS of the saturated specimens was on average 1.5 times lower than of the unsaturated specimens.

- The percent cement content, sand content, fines content, and liquid limit were found to be statistically significant in predicting unsaturated and vacuum saturated UCS. The models showed an R^2 of about 0.85 and RMSE of about 75 psi for vacuum saturated specimens and 97 psi for unsaturated specimens.

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APPENDIX A: LABORATORY TEST RESULTS

Test Bed	Treated soil properties									Untreated soil properties					
	Cement content (%)	UCS (psi)		Atterberg limits			F_{200}	Group index	Iowa DOT Material Suitability	Gravel content (%)	Sand content (%)	Silt content (%)	Clay content (%)	USCS Classification	AASHTO Classification
		Unsaturated	Saturated	LL	PL	PI									
Polk TB1	0	50.4	8.5	49	28	21	88	21	suitable	0.4	11.6	66.4	21.6	CL	A-7-6(21)
	4	174.3	78.6	41	28	13	74.1	10	suitable						
	8	279.9	230.6	40	32	8	64.5	5	suitable						
	12	409.8	320.7	40	NP	0	53.1	0	suitable						
Polk TB2	0	36.8	18.7	45	34	11	70.3	8	suitable	3.9	25.8	34.7	35.6	CL	A-7-5(8)
	4	120.2	54.3	43	30	13	59.3	7	suitable						
	8	324	187.1	41	31	10	47.9	3	suitable						
	12	442	265.2	38	NP	0	45.7	0	suitable						
Polk TB3	0	9.6	56.9	36	20	16	68.7	9	suitable	2.6	28.7	45.8	22.9	CL	A-6(9)
	4	224.1	134.2	34	28	6	58.5	2	suitable						
	8	336.7	251.7	35	NP	0	41.1	0	suitable						
	12	519.4	351.2	36	NP	0	32.3	0	suitable						
Polk TB4	0	54.2	8.3	34	17	17	73.6	11	suitable	1.8	24.6	50.9	22.7	CL	A-6(11)
	4	261.8	135.1	36	NP	0	61.9	0	suitable						
	8	438.5	313.6	38	NP	0	40.6	0	suitable						
	12	634.4	461.2	34	NP	0	40.4	0	suitable						
Warren TB1	0	59.3	0	44	31	13	70.5	9	suitable	2	27.5	37.3	33.2	CL	A-7-5(9)
	4	181.9	107.9	38	24	14	60.4	7	suitable						
	8	431.1	228.6	41	NP	0	36.8	0	suitable						
	12	686.9	359.7	38	NP	0	27.4	0	suitable						
Warren TB2	0	38.3	0	40	19	21	63.4	11	select	5	31.6	31.9	31.5	CL	A-6(11)
	4	223.3	103.7	39	24	15	55.7	6	select						
	8	413.7	213.3	38	NP	0	34.4	0	suitable						
	12	512	317.2	34	NP	0	25.7	0	suitable						
Warren TB3	0	38.7	0	54	20	34	80.6	28	unsuitable	0.7	18.7	39.1	41.5	CH	A-7-6(28)
	4	150.8	68	42	25	17	70.7	11	suitable						
	8	201	147.8	44	32	12	51.8	4	suitable						
	12	305.6	239.7	40	NP	0	31	0	suitable						
Linn 79 TB1	0	48.9	0	31	25	6	53.3	1	suitable	0.7	46	26.4	26.9	CL-ML	A-4(1)
	4	257.7	118.4	29	17	12	40.8	1	suitable						
	8	475.8	296.5	28	NP	0	28.6	0	suitable						
	12	492.2	408.8	29	NP	0	21.2	0	suitable						
Linn 77 TB1	0	60	0	31	12	19	60.6	8	select	1.8	37.6	32.9	27.7	CL	A-6(8)
	4	224.2	114.7	34	18	16	49.9	5	select						
	8	397.1	255.5	33	23	10	38.8	1	suitable						
	12	414.3	325.6	33	NP	0	29.4	0	suitable						
Linn 77 TB2	0	53.1	0	34	16	18	56.1	7	select	1.3	42.6	30.9	25.2	CL	A-6(7)
	4	233.2	121.5	34	22	12	51.3	3	select						
	8	466.6	290.4	32	NP	0	41	0	suitable						
	12	605.3	456.7	31	NP	0	22.4	0	suitable						
Linn 77 TB3	0	67.5	0	33	11	22	52.6	7	select	11.3	36.1	31.2	21.4	CL	A-6(7)

	4	305.6	219.3	32	21	11	43.1	2	select						
	8	676.6	472.9	32	NP	0	20.4	0	suitable						
	12	863.4	598	35	NP	0	15.8	0	suitable						
Linn 77 TB4	0	68.6	0	32	16	16	59	6	select	1.1	39.9	35.6	23.4	CL	A-6(6)
	4	146.8	78.8	43	27	16	48	5	select						
	8	281.9	163.1	43	29	14	37	1	select						
	12	436	271.9	39	NP	0	33.6	0	suitable						
Linn 77 TB5	0	47.1	0	30	16	14	57.7	5	select	2	40.3	34.8	22.9	CL	A-6(5)
	4	264.4	105.2	34	19	15	52.9	5	select						
	8	424.2	269.6	33	24	9	31.2	0	suitable						
	12	635.5	355.8	33	NP	0	23.4	0	suitable						
Pottawattamie TB1	0	63.9	5.3	43	18	25	82.6	20	suitable	7.3	10.1	56.2	26.4	CL	A-7-6(20)
	4	260.7	160.6	39	30	9	78.6	8	suitable						
	8	447.6	324.9	40	33	7	52.3	2	suitable						
	12	654.6	486.8	36	NP	0	37.5	0	suitable						
Pottawattamie TB2	0	49.3	0	42	19	23	69.2	14	suitable	5.3	25.5	48	21.2	CL	A-7-6(14)
	4	208.4	155.5	36	31	5	60.5	2	suitable						
	8	287.2	255.8	36	32	4	42.5	0	suitable						
	12	296	211.9	37	NP	0	35.3	0	suitable						
Mills TB1	0	53.9	0	38	34	4	96.8	7	suitable	0.1	3.1	70.6	26.2	CL-ML	A-4(7)
	4	268.8	224	35	27	8	88	8	suitable						
	8	762.9	528.1	34	32	2	49.8	0	suitable						
	12	903.1	709.1	36	NP	0	34.5	0	suitable						
Mills TB2	0	55.4	1.7	36	31	5	89.7	6	suitable	3.9	6.4	34.9	54.8	CL-ML	A-4(6)
	4	337.1	286.9	34	29	5	72.6	4	suitable						
	8	632.4	464.3	34	32	2	48.3	0	suitable						
	12	747.7	624.8	35	NP	0	29.4	0	suitable						
Scott TB1	0	59.2	5.8	39	32	7	98.9	10	suitable	0.1	1	72.9	26	CL-ML	A-4(10)
	4	257.3	167.7	34	26	8	85.2	7	suitable						
	8	533.2	353	34	31	3	52.1	0	suitable						
	12	686.7	519	35	NP	0	34.9	0	suitable						
Scott TB2	0	44	6.6	35	24	11	74.7	8	suitable	1	24.3	45.5	29.2	CL	A-6(8)
	4	299.8	197.2	33	27	6	61	2	suitable						
	8	608.6	484.9	32	NP	0	46.9	0	suitable						
	12	820.7	605.9	34	NP	0	40	0	suitable						
Scott TB3	0	48.4	5.8	28	17	11	68.8	5	suitable	2	29.2	45.9	22.9	CL	A-6(5)
	4	333	244.3	31	22	9	56.4	3	suitable						
	8	696.6	461.5	31	30	1	37.9	0	suitable						
	12	980.6	692.4	33	NP	0	25.1	0	suitable						
Woodbury (US20) TB1	0	60.2	9.3	32	25	7	91.2	7	suitable	0	8.8	68.8	22.4	CL-ML	A-4(7)
	4	292.3	184.4	33	26	7	65.4	4	suitable						
	8	525.8	429.3	33	31	2	53.9	0	suitable						
	12	789.7	554.3	34	NP	0	39	0	suitable						
Woodbury (US20) TB2	0	59.7	0	35	27	8	98.7	9	suitable	0	1.3	73.3	25.4	CL	A-4(9)
	4	278.6	189.4	41	31	10	76.3	8	suitable						

	8	488.4	341	40	35	5	50.5	1	suitable						
	12	663.3	484	43	NP	0	33.8	0	suitable						
Woodbury (US20) TB3	0	52.9	3.8	35	23	12	95.7	12	suitable	0.1	4.2	69.6	26.1	CL	A-6(12)
	4	288.7	169	40	31	9	69.8	6	suitable						
	8	534.4	343	40	34	6	43.2	1	suitable						
	12	735.7	513.7	41	NP	0	32.4	0	suitable						
Woodbury (US20) TB4	0	63.3	4.4	31	24	7	93.6	7	suitable	0	6.4	72	21.6	CL-ML	A-4(7)
	4	339.8	196	32	26	6	79.1	4	suitable						
	8	588.6	431.6	32	31	1	51.6	0	suitable						
	12	815	572.2	33	NP	0	32.9	0	suitable						
Woodbury (I29) TB1	0	0	0	NV	NP	NP	21.4	0	suitable	0.2	78.4	15.5	5.9	SM	A-2-4
	4	94.7	81.7	NV	NP	NP	9.3	0	suitable						
	8	268.6	234.9	NV	NP	NP	9	0	suitable						
	12	506.2	439.8	NV	NP	NP	8.6	0	select						
Woodbury (I29) TB2	0	0	0	NV	NP	NP	16.8	0	suitable	0	83.2	12.6	4.2	SM	A-2-4
	4	54.6	43.8	NV	NP	NP	7.7	0	suitable						
	8	120.2	108.2	NV	NP	NP	7.1	0	suitable						
	12	187.4	161.7	NV	NP	NP	7.4	0	suitable						
Woodbury (I29) TB3	0	0	0	NV	NP	NP	17.2	0	suitable	1.7	81.1	11.6	5.6	SM	A-2-4
	4	100	72.5	NV	NP	NP	8.2	0	suitable						
	8	238.3	211.4	NV	NP	NP	9.5	0	suitable						
	12	414.6	398.6	NV	NP	NP	8.3	0	select						

APPENDIX B: IOWA DOT PROPOSED INSTRUCTIONAL MEMORANDUM FOR CEMENT STABILIZATION OF SOILS

CEMENT STABILIZATION OF SOILS

GENERAL

This procedure describes procedures for sampling and testing, and requirements for submittal and approval of mix design for cement stabilized soils.

SAMPLING AND MATERIALS

Each soil sample to be used in chemical stabilization shall be 75 pounds (35 kg). This sample size will also provide for tests to be performed according to Materials IM 545.

The cement used for stabilization shall meet the requirements of Type I or I/II from Section 4101.

SAMPLE PREPARATION AND TESTING

Laboratory tests on untreated soil shall be performed according to Materials IM 545. The material suitability should be classified in accordance with Section 2102. Additionally, sulfate content of the soil shall be determined per AASHTO T290. If the soil consists of soluble sulfate content > 3,000 ppm or the material classifies as unsuitable, chemical stabilization shall not be performed unless consulted with the engineer.

For each soil type, prepare three samples each for the following four mixes:

- Mix 1: Untreated soil
- Mix 2: 2% cement
- Mix 3: 4% cement
- Mix 4: 6% cement.

To determine the quantity of cement to add to the soil, multiply the cement percentage by the dry weight of the soil. Use cement that is from the same source(s) that will be used during construction.

First, the moisture-density relationship of the different mixtures shall be determined. Then, unconfined compressive strength testing shall be performed at target moisture contents, as described below.

Moisture-Density Relationship

The moisture versus dry density relationship of untreated and cement-treated samples shall be determined using one of the following alternatives:

Alternative 1:

- *Untreated Samples:* The maximum dry density and optimum moisture content of the untreated samples shall be determined using standard Proctor test in accordance with ASTM D698-12 [Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lb/ft^3 (600 kN-m/m^3)). A minimum 3-point Proctor is recommended.
- *Treated Samples:* The maximum dry density and optimum moisture content shall be determined in accordance with ASTM D558-11 [Standard Test Methods for Moisture-Density (Unit Weight) Relations of Soil-Cement Mixtures]. All treated samples must be compacted within 1 hour of mixing. A minimum 3-point Proctor is recommended.

Alternative 2:

The maximum dry density and optimum moisture content of untreated and treated samples shall be determined using the Iowa State University 2” by 2” Moisture-Density Test Method, per O’Flaherty et al. (1963). In preparing samples using the 2” by 2” method, use the following table for guidance on the total number of drop-hammer blows depending on the soil type to obtain results similar to the standard Proctor test.

Total number of drop-hammer blows	Soil type (based on AASHTO system)
6	A7 and A6
7	A4
14	A3, A2, and A1

Alternative 3:

First, determine the optimum moisture content of the untreated soil using standard Proctor test in accordance with ASTM D698-12 [Standard Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort (12400 ft-lbf/ft^3 (600 kN-m/m^3))]. Then use the following equation to determine the optimum moisture content of treated samples, by using a water to cement (w/c) ratio of 0.25:

$$w_{\text{opt soil + cement}} = [(\text{% cement added by weight}) \times (\text{w/c ratio})] + w_{\text{opt soil}}$$

Unconfined Compressive Strength

The unconfined compressive strength (UCS) tests shall be conducted on compacted samples at respective optimum moisture contents for untreated and treated soils, in accordance with ASTM D1633-00 (2007) [Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders]. As an alternative, tests can be conducted on 2” by 2” samples prepared per Alternative 2 above.

For each mix, prepare three samples for UCS testing for a total of twelve samples. Wrap each sample immediately after compaction with a plastic wrap and aluminum foil and store in a moisture-proof and airtight bag. All treated samples shall be cured at 100^{o}F (38^{o}C) for 7 days. Untreated samples shall be cured for no more than 24 hours.

After curing, all samples shall be vacuum saturated in accordance with ASTM C593-06 (2011) Section 11 [Standard Specification for Fly Ash and Other Pozzolans for Use with Lime for Soil Stabilization]. For samples that become fragile and cannot be retrieved from water for UCS testing, report the UCS as 0 psi.

Target cement content determination

The data obtained from UCS testing shall be plotted on a graph with cement content on x-axis and saturated UCS on y-axis. The average UCS of three samples shall be reported on the y-axis. The cement content corresponding to a saturated UCS of 100 psi shall be determined. 0.5% cement shall be added to determine the target cement content for the field application, as illustrated in Figure 1.

Measurement of the *true* UCS is considered for specimens with height to diameter (h/d) ratio of 2.0. The Proctor size specimens prepared in accordance with ASTM D1633 have h/d = 1.15 and 2 x 2 specimens have h/d = 1.0. The UCS determined from these two sample sizes must be corrected as shown in Figure 2, to calculate the true UCS for sample with h/d = 2.0. The correction factors are based on a laboratory study on fly ash soil mixtures by White et al. (2005).

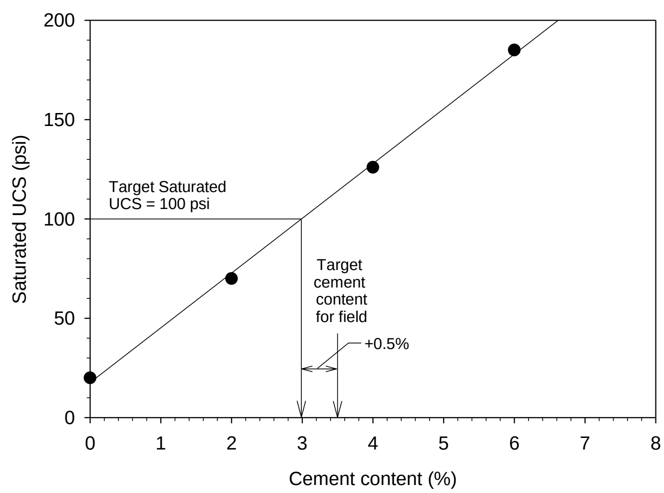

Figure 1. Determination of target cement content for field application

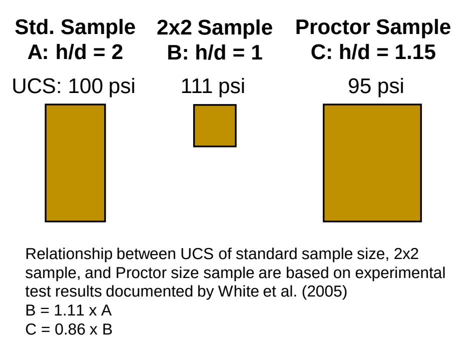

Figure 2. Correction factors for UCS determined from different sample sizes

REPORTS

Each report shall contain the following for untreated soil:

- Sample ID number and location
- Atterberg Limits
- Percent Gravel, Sand, Silt, and Clay
- Textural classification
- AASHTO classification
- Proctor density and optimum moisture
- Percent Carbon Content
- Sieve analysis (Percent Passing)
- Sulfate content

Additionally, each report shall contain the following for untreated and treated soils (for each soil type, there will be a total of twelve samples):

- Percent cement added in each mixture
- Maximum dry density and optimum moisture content, and the alternative procedure followed as described in this IM.
- Unconfined compressive strength – for each sample

Submit a graph similar to Figure 1 with average saturated UCS versus % of cement in the mixture with the recommended rate of chemical stabilization for review and approval by the Engineer.

REFERENCES

White, D.J., Harrington, D., and Thomas, Z. (2005). “Fly ash soil stabilization for non-uniform subgrade soils, Volume I: Engineering properties and construction guidelines.” Final report for Iowa Highway Research Board Project TR-461. Center for Portland Cement Concrete Pavement Technology (PCC Center), Ames, IA.

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