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Comprehensive Laboratory Evaluations and a Proposed Mix Design Procedure for Cement-Stabilized Cohesive and Granular Soils

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Embankment subgrade soils classifying as A-4 to A-7-6 according to the AASHTO Soil Classification System can exhibit low bearing strength, high volumetric instability, and freeze-thaw susceptibility. These characteristics of soil are frequently identified as main factors leading to accelerated damage of pavement systems. Cement stabilization has been widely used to improve these soils conditions. The present study aims to help designers and practitioners better understand how cement stabilizations can influence soil index properties and mechanical properties before and after saturation. In this study, a total of 28 cohesive and granular soil materials obtained from nine construction sites were tested using 4–12% type I/II Portland cement contents. Specimens were prepared using a 2 inch by 2 inch compaction apparatus and tested for 28-day unconfined compressive strength (UCS) with and without vacuum saturation. Results indicated that statistically significant relationships exist between soil index properties, UCS, and cement content. Based on the laboratory test results, a laboratory evaluation procedure for cement stabilization mix design for both granular and cohesive soils is proposed.

Keywords: soil stabilization, cement stabilization, unconfined compressive strength, fines content, Atterberg limits, AASHTO group index

INTRODUCTION

Embankment subgrade soils classifying as A-4 to A-7-6 according to the AASHTO Soil Classification System can exhibit low bearing strength, high volumetric instability, and freeze-thaw susceptibility, which are frequently identified as main factors leading to accelerated damage of pavement systems (White and Bergeson, 2001; White et al., 2004, 2008, 2018; Zhang et al., 2016, 2019; Li et al., 2020). Soil stabilization with cement has been studied during the past six decades over a variety of soil types (Balmer, 1958; Mitchell, 1976; Uddin et al., 1997; Lo and Wardani, 2002; Lorenzo and Bergado, 2004; Sariosseiri, 2008; Sariosseiri et al., 2011; Sarkar et al., 2012;

Rashid et al., 2014; Riaz et al., 2014; Yang et al., 2018; Li et al., 2020). Previous research indicated that Portland cement stabilized materials generally show superior performance than any other chemical stabilizer (Parsons and Milburn, 2003; Henry et al., 2005; Zhang et al., 2016, 2019; Li et al., 2017, 2018, Li C. et al., 2019). Multiple regression analysis is a valuable tool applied in geotechnical engineering (Li S. et al., 2019). Horpibulsuk (2012) reported the effectiveness of various percentages cement mixture on the specimen's strength development. Three strength development zones were presented: active, inert, and deterioration zone. In the active zone, the pores smaller than 0.1 micron significantly decreased due to cement hydration process, so the strength increased significantly. However, as content of cement additives increased, the desired water was not adequate for hydration, so the strength and quantity of cementitious materials decreased. Various studies have previously developed similar relationships between cement dosage and modified soil strength and other engineering properties, such as liquid limit, plasticity index, etc (Qubain et al., 2006; Sariosseiri et al., 2011; Du et al., 2013; Rashid et al., 2014). Spangler and Patel (1950) showed that the plastic limit was increased as cement content increased, and plasticity index was decreased as cement admixture content increased because the liquid limit was decreased.

To understand how the cement content can influence the strength and soil index properties of both cohesive and granular materials, the present study conducted a comprehensive laboratory evaluation. A total of 28 granular and cohesive materials were tested using 4–12% type I/II Portland cement contents. The laboratory results were analyzed using multi-variate statistical analysis to assess influence of the cement content and soil index properties on post-stabilization material properties. Based on the laboratory test and statistical analysis results, a laboratory testing and evaluation procedure for cement stabilization mix design for both granular and cohesive soils is proposed.

MATERIALS AND METHODS

In this study, a total of 28 granular and cohesive materials obtained from nine construction sites were tested using 4–12% type I/II Portland cement contents. **Table 1** summarizes the parent materials, particle size analyses, Atterberg limits, and soil classifications test results of the materials. The cohesive soils were collected from 25 test beds of eight project sites, and the parent materials of the cohesive soils were either glacial till or loess. The cohesionless granular soils were collected from three test beds of one project site, and their parent material was alluvium material.

TESTING AND ANALYSIS METHODS

To classify the materials tested in this study, particle size analysis was conducted in accordance with ASTM D422-63 (2007) (ASTM, 2007). The distribution of particle sizes larger than 75 μm (opening size of the No. 200 sieve) was determined by sieving, and the distribution of particle sizes smaller than 75 μm was determined by the hydrometer method. Atterberg limit testing was conducted in accordance with ASTM D4318-10 (2000) (ASTM, 2000) using the wet preparation method. Liquid limit tests were performed using the multipoint method. Based on these results, each sample was classified according to the AASHTO Soil Classification System and Unified Soil Classification System (USCS).

Soil Compaction Test

The relationship between the moisture and dry unit weight of embankment materials was determined in accordance with ASTM D698 (2013) (ASTM, 2013) and ASTM D1557 (2009) (ASTM, 2009). Appropriate methods were chosen based on the grain size distributions for each sample. The tests were performed at five moisture contents, and the optimum moisture-density characteristics were obtained by fitting the data to the Li and Sego Fit model as described in Eq. 1

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

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, S_m = maximum degree of saturation, w_m = moisture content at S_m, and n and p are shape factors.

ISU 2 Inch by 2 Inch Test

ISU 2 inch by 2 inch compaction apparatus is described in O'Flaherty et al. (1963). The test procedure was used to prepare 50.8 mm (2 inch) diameter by 50.8 mm (2 inch) height samples for unconfined compressive strength (UCS) testing. Standard Proctor optimum moisture content for each sample was determined based on the Li and Sego Fit model, and each sample was compacted at that moisture content. For cement treated materials, the optimum moisture content was determined using Eq. 2 with a water to cement (w/c) ratio of 0.25:

$$w_{\text{opt soil+cement}} = \left[\left(\%\text{ cement added by weight}\right) \times \left(w/c\ \text{ ratio}\right)\right] + w_{\text{opt soil}} \tag{2}$$

The test procedure involved placing loose material in the compaction apparatus and dropping a 2.27 kg hammer from a drop height of about 0.31 m in a 50.8 mm diameter steel mold. O'Flaherty et al. (1963) provided guidance on the number of blows required to obtain standard Proctor densities for different soil types, 6, 7, 14 drop-hammer blows for AASHTO soil types A-7/A-6, A-4, and A-3/A-2/A-1, respectively. 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.

After compaction, the 2 inch by 2 inch specimens were sealed using plastic wrap and aluminum foil, and were placed in sealed plastic bag. According to Winterkorn and Pamukcu (1990), cement stabilized specimens cured for 7 days at 43°C can be used to simulate 28 day curing strength. Unstabilized specimens were

TABLE 1 | Soil index properties of the granular and cohesive subgrade materials tested in this study.

Construction site	Parent material	Gravel content (>4.75 mm) (%)	Sand content (4.75 mm—75 μm) (%)	Silt content (75 μm—2 μm) (%)	Clay content (< 2 μm) (%)	Liquid limit, LL (%)	Plastic limit, PL (%)	Plastic Index, PI (%)	AASHTO classification	USCS classification
1# TB1	Glacial till	0.4	11.6	66.4	21.6	49	28	21	A-7-6 (21)	CL
1# TB2	Glacial till	3.9	25.8	34.7	35.6	45	34	11	A-7-5 (8)	CL
1# TB3	Glacial till	2.6	28.7	45.8	22.9	36	20	16	A-6 (9)	CL
1# TB4	Glacial till	1.8	24.6	50.9	22.7	34	17	17	A-6 (11)	CL
2# TB1	Glacial till	2.0	27.5	37.3	33.2	44	31	13	A-7-5 (9)	CL
2# TB2	Glacial till	5.0	31.6	31.9	31.5	40	19	21	A-6 (11)	CL
2# TB3 (Gray)	Glacial till	0.7	18.7	39.1	41.5	54	20	34	A-7-6 (28)	CH
2# TB3 (Brown)	Glacial till	0.6	29.2	33.7	36.5	40	20	20	A-6 (13)	CL
3# TB1	Weathered loess	0.7	46.0	26.4	26.9	31	25	6	A-4 (1)	CL-ML
4# TB1	Glacial till	1.8	37.6	32.9	27.7	31	12	19	A-6 (8)	CL
4# TB2	Glacial till	1.3	42.6	30.9	25.2	34	16	18	A-6 (7)	CL
4# TB3	Glacial till	11.3	36.1	31.2	21.4	33	11	22	A-6 (7)	CL
4# TB4	Glacial till	1.1	39.9	35.6	23.4	32	16	16	A-6 (6)	CL
4# TB5	Glacial till	2.0	40.3	34.8	22.9	30	16	14	A-6 (5)	CL
5# TB1	Manufactured materials	7.3	10.1	56.2	26.4	43	18	25	A-7-6 (20)	CL
5# TB2	Manufactured materials	5.3	25.5	48.0	21.2	42	19	23	A-7-6 (14)	CL
6# TB1	Alluvium	0.2	78.4	15.5	5.9	NP	NP	NP	A-2-4	SM
6# TB2	Alluvium	0.0	83.2	12.6	4.2	NP	NP	NP	A-2-4	SM
6# TB3	Alluvium	1.7	81.1	11.6	5.6	NP	NP	NP	A-2-4	SM
7# TB1	Loess	0.1	1.0	72.9	26.0	39	32	7	A-4 (10)	CL-ML
7# TB2	Loess	1.0	24.3	45.5	29.2	35	24	11	A-6 (8)	CL
7# TB3	Loess	2.0	29.2	45.9	22.9	28	17	11	A-6 (5)	CL
8# TB1	Loess	0.1	3.1	70.6	26.2	38	34	4	A-4 (7)	CL-ML
8# TB2	Loess	3.9	6.4	34.9	54.8	36	31	5	A-4 (6)	CL-ML
9# TB1	very deep loess	0.0	8.8	68.8	22.4	32	25	7	A-4 (7)	CL-ML
9# TB2	Very deep loess	0.0	1.3	73.3	25.4	35	27	8	A-4 (9)	CL
9# TB3	Very deep loess	0.1	4.2	69.6	26.1	35	23	12	A-6 (12)	CL
9# TB4	Very deep loess	0.0	6.4	72.0	21.6	31	24	7	A-4 (7)	CL-ML

FIGURE 1 | Vacuum saturation of cement stabilized specimens.

tested shortly after compaction (no curing). Three samples were prepared at each cement content.

UCS Test

The cured specimens were tested for UCS accordance with ASTM D 1633 (2014) (ASTM, 2014b). The standard requires use of either 101.6 mm diameter by 116.4 mm height Proctor samples with a height to diameter ratio (h/d) of 1.15 or 71.1 mm diameter by 142.2 mm height samples with a h/d ratio of 2.0. Instead, 2 inch by 2 inch. specimens were used in this study which have a h/d ratio of 1.0. Based on laboratory evaluations, White et al. (2005) concluded that the UCS determined from 2 inch by 2 inch 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. The ASTM D1633 (2014) (ASTM, 2014b) also provides a similar guidance in relating UCS on samples with h/d = 2 multiplying a factor of 1.10 to samples with h/d = 1.15 for conversion.

The cured specimens were tested in unsaturated and saturated condition. The specimens were saturated using the vacuum saturated method as described in ASTM C593 (2014) (ASTM, 2014a). The specimens were placed on a perforated Plexiglas plate in a vacuum vessel as shown in **Figure 1**, and the chamber was evacuated to 609 MmHg for 30 minutes. Then the vacuum vessel was flooded to a depth sufficient to cover the soil specimens. After 1 h 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 kPa.

Multiple Regression Analysis

The multiple regression analysis was performed to evaluate that how the cement content and pre-treatment soil index properties can influence the soil index properties and UCS of the soils. Regression analyses were performed by incorporating the parameters as independent variables into a general multiple linear regression model as shown in Eq. 3.

$$\text{Predicted parameter} = b_0 + b_1X_1 + b_2X_2 \cdots b_nX_n \quad (3)$$

where

Predicted parameters = UCS, PI, GI, and F_{200},

b_0 = intercept,

b_n = regression coefficients, and X_n = various parameters (cement content, LL, F_{200}, clay content, PI, and sand content).

Statistical significance of each variable was assessed based on p and t values. A statistical analysis software, JMP 10 was used to generate the statistical models based on testing data. The criteria for identifying the significance of a parameter was: p value < 0.05 = significant, <0.10 = possibly significant, >0.10 = not significant, and t- value < -2 or $> +2$ = significant. The p-value indicated the significance of a parameter and the t-ratio value indicates the relative importance. The best fit model was determined based on the strength of the regression relationships assessed by the coefficient of determination (R^2) values.

LABORATORY TEST RESULTS

In the following sections, the results and analysis are separately for F_{200}, Atterberg limits, GI, and UCS, to present the influence of cement stabilization on these properties.

Fines Content (F_{200})

Results of F_{200} versus cement content are presented in **Figure 2**. The results indicated that F_{200} of both the cohesive and granular soils greatly decreased with increasing cement content due to the fine soil particles of the materials were bonded by the cement hydration and pozzolanic reactions.

Statistical analysis was conducted to predict F_{200} after treatment as a function of cement content, F_{200} before treatment, and Atterberg limits. Cement content, F_{200} before treatment, and LL were found to be statistically significant as shown in **Table 2**. PI and PL parameters were not statistically significant. The measured versus predicted F_{200} of soils after cement treatment from the multi-variate model are presented in **Figure 3**. The model showed an R^2 of about 0.9 and RMSE of about 7%.

Atterberg Limits

The F_{200} versus PI results of the untreated and cement treated soils with 4, 8, and 12% cement content are shown in **Figure 4**. The test results show that both of the PI and F_{200} decreased as the cement content increased. For soils treated with 12% cement, the PI values are zero, which indicates that the treated soils become to non-plastic.

Statistical analysis was conducted to predict PI after treatment as a function of cement content, clay content, silt content, and LL. Results are summarized in **Table 3**. 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 5**. The model showed an R^2 of about 0.5 and RMSE of about 5%.

AASHTO Group Index (GI)

For a majority of the soils, the GI values decreased with increasing cement content. Statistical analysis was conducted

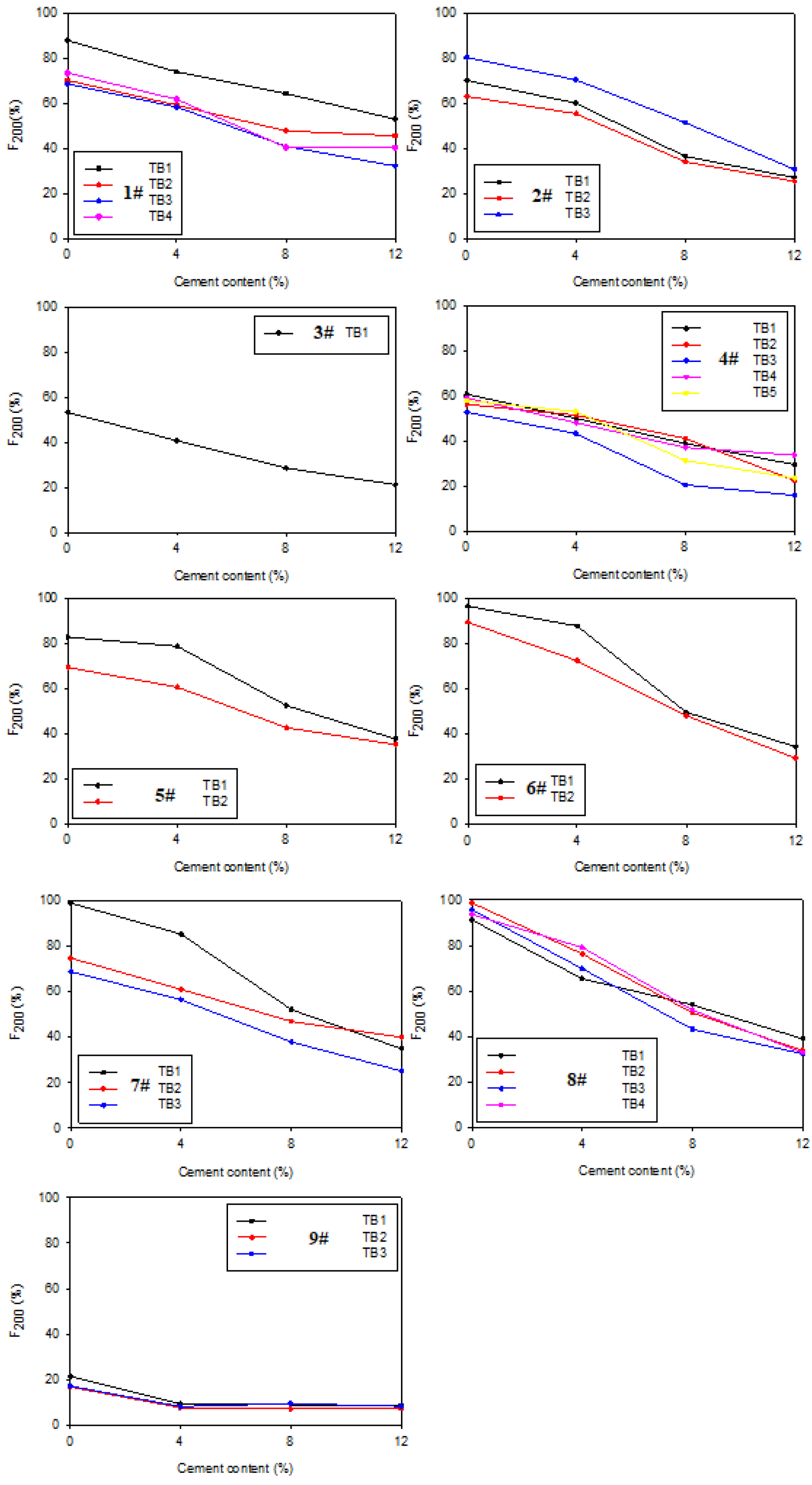

FIGURE 2 | F_{200} versus cement content.

TABLE 2 | Multi-variate analysis results to predict F_{200} after cement stabilization.

Parameter	Value	*t* Ratio	Probability > | *t*|	R^2	RMSE
Intercept	18.92	3.96	<0.0001	0.90	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 × cement content (%) + 0.607 × F_{200} (%) + 0.306 × LL (%)				

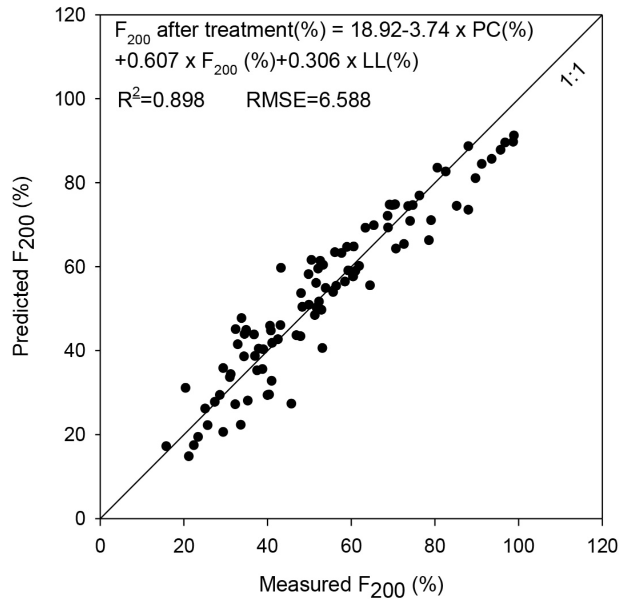

FIGURE 3 | Comparison of measured F_{200} and predicted F_{200} of the cement treated soils.

on the laboratory test results 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 4**. 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 6**. The model showed an R^2 of about 0.7 and RMSE of about 3.

Unconfined Compressive Strength

The results of unsaturated and vacuum saturated UCS of the materials at different cement contents are used for determining relationships between the cement content and pre- and post-saturation strength of the materials.

Results indicated that 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 kPa 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 also conducted to predict unsaturated and vacuum saturated UCS as a function of cement content, sand

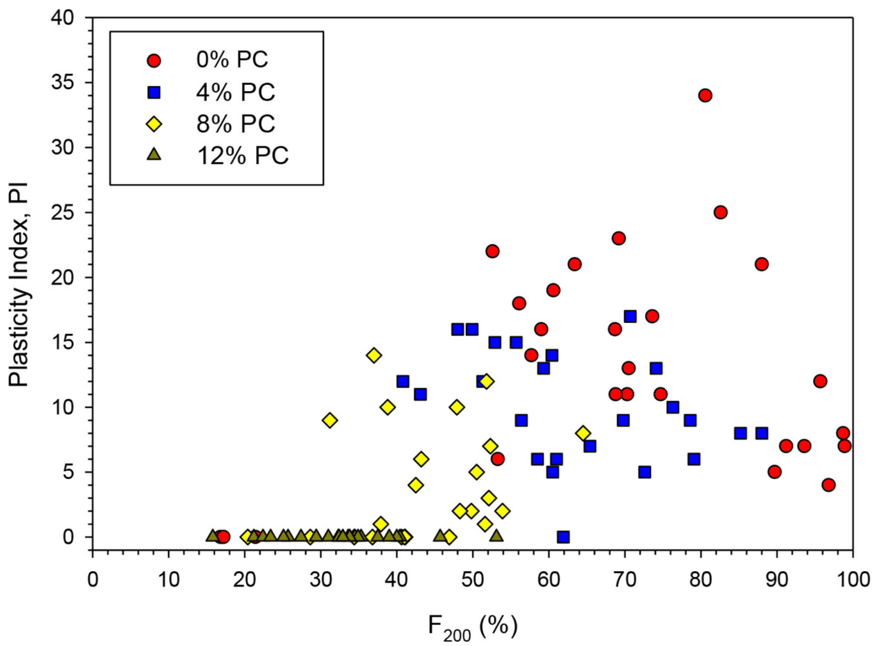

FIGURE 4 | PI versus F_{200} for the untreated and cement treated soils.

TABLE 3 | Multi-variate analysis results to predict PI after cement stabilization.

Parameter	Value	*t* Ratio	Probability > | *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	PI after treatment (%) = 8.664–1.102 × cement content (%) + 0.172 × Clay content (%)				

Silt content, sand content, and LL were not statistically significant.

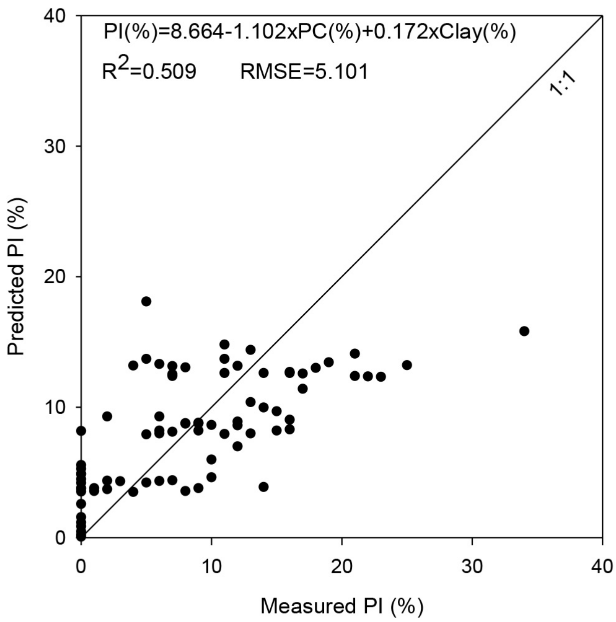

FIGURE 5 | Comparison of measured PI and predicted PI of the cement treated soils.

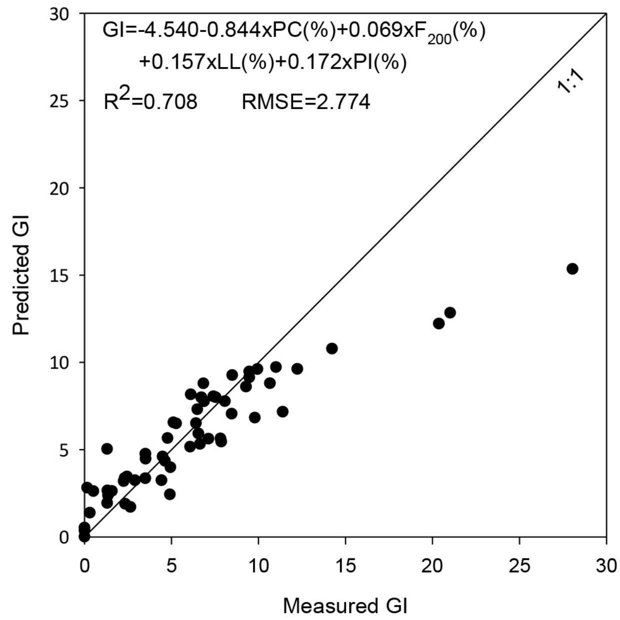

FIGURE 6 | Comparison of measured group index and predicted group index.

content, clay content, silt content, F_{200}, LL, and PI. Results are summarized in **Tables 5**, **6**. The 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 7**. The models showed an R^2 of about 0.855 and RMSE of about 515 kPa for vacuum saturated UCS and 672 kPa for unsaturated UCS.

TABLE 4 | Multi-variate analysis results to predict GI after cement stabilization.

Parameter	Value	*t* Ratio	Probability >| *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 cement content (%) + 0.069 × F_{200} (%) + 0.157 × LL (%) + 0.172 × PI (%)				

Silt content and clay content were not statistically significant.

PROPOSED TESTING AND EVALUATION PROCEDURE

Based on the test results and experience obtain from this laboratory evaluation, a mix design procedure is proposed for sampling and testing, and requirements of cement stabilized soils.

TABLE 5 | Multi-variate analysis results to predict unsaturated UCS.

Parameter	Value	*t* Ratio	Probability >| *t*|	R^2	RMSE
Intercept	1465.38	3.61	0.0005	0.855	671.675
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 (kPa) = 10103.4 + 335.7 × cement content (%)–91.4 × Sand (%)–77.8 × LL (%)–63.7 × F_{200} (%)				

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

TABLE 6 | Multi-variate analysis results to predict vacuum saturated UCS.

Parameter	Value	*t* Ratio	Probability >| *t*|	R^2	RMSE
Intercept	1151.32	3.7	0.0004	0.856	515.071
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 (kPa) = 7938.1 + 257.4 × cement content (%)–78.6 × Sand (%)–57.7 × LL (%)–53.1 × F_{200} (%)				

Silt content and clay content were not statistically significant.

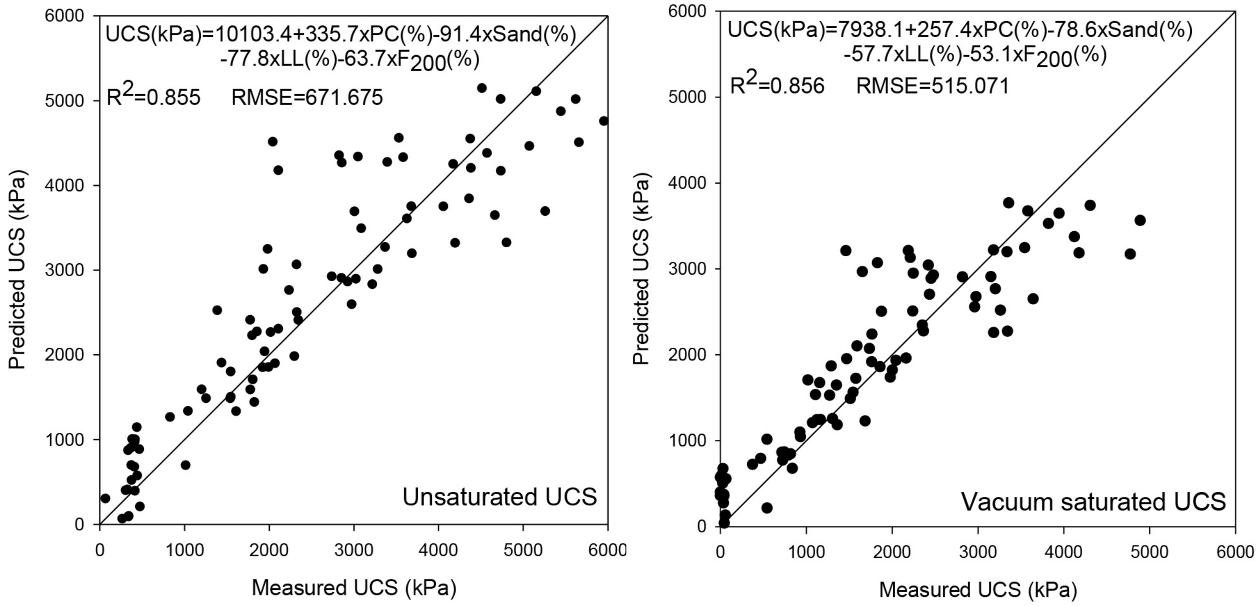

FIGURE 7 | Comparison of the measured and predicted UCS of unsaturated and vacuum saturated specimens.

Sampling and Materials

Each soil sample to be used in chemical stabilization shall be 35 kg. The cement used for stabilization shall meet the requirements of Type I or I/II.

Sample Preparation and Testing

The sulfate content of the soil shall be determined. 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 engineers.

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

1. Mix 1: Untreated soil.
2. Mix 2: 2% cement.
3. Mix 3: 4% cement.
4. Mix 4: 6% cement.
5. Mix 5: 8% cement.

To determine the quantity of cement to be added 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.

Moisture–Density Relationship

First, the moisture–density relationship of the different mixtures shall be determined. Then, UCS testing shall be performed at target moisture contents, as described below.

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 (2013) (ASTM, 2013). 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 (2019) (ASTM, 2019). All treated samples must be compacted within 1 h 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 ISU 2 inch by 2 inch. Moisture–Density Test Method, per Chu et al. (1995). In preparing samples using the 2 inch by 2 inch method, use the method of O'Flaherty et al. (1963) for guidance on the total number of drop-hammer blows depending on the soil type to obtain results similar to the standard Proctor test.

Alternative 3:

First, determine the optimum moisture content of the untreated soil using standard Proctor test in accordance with ASTM D698 (2013) (ASTM, 2013). 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:

$$w_{opt\ soil+cement} = \left[(\%\ cement\ added\ by\ weight) \times (w/c\ \ ratio)\right] + w_{opt\ soil} \tag{4}$$

Unconfined Compressive Strength

The UCS tests shall be performed on compacted samples at respective optimum moisture contents for untreated and treated soils, in accordance with ASTM D1633-00 (2014) (ASTM,

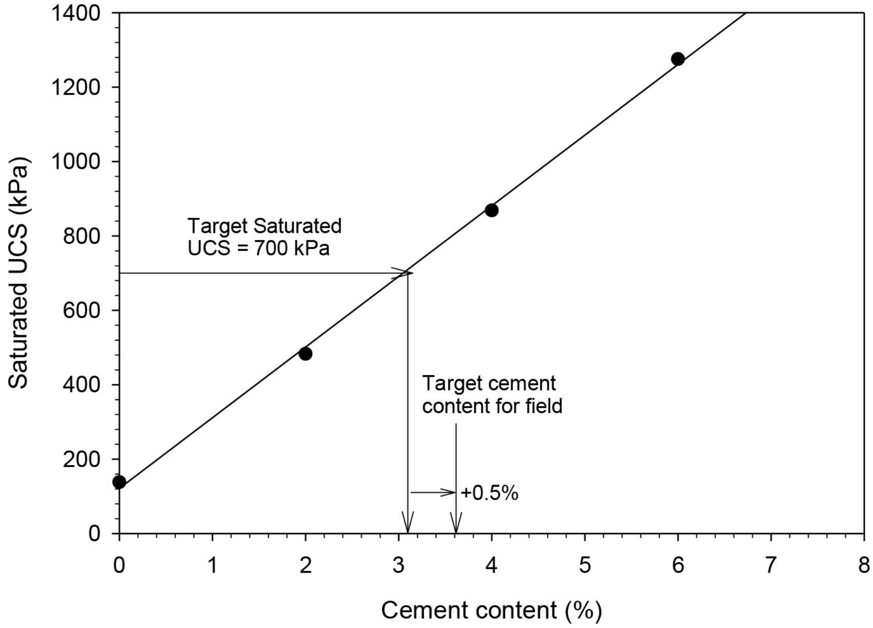

FIGURE 8 | Determination of target cement content for field application.

2014b). As an alternative, tests can be performed on 2 inch by 2 inch samples prepared per Alternative 2 above.

For each mix, prepare three samples for UCS testing for a total of 12 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 38°C for 7 days. Untreated samples shall be cured for no more than 24 h.

After curing, all samples shall be vacuum saturated in accordance with ASTM C593 (2014) (ASTM, 2014a). For samples that become fragile and cannot be retrieved from water for UCS testing, report the UCS as 0 kPa.

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 700 kPa shall be determined. A 0.5% cement shall be added to determine the target cement content for the field application, as illustrated in **Figure 8**.

SUMMARY AND CONCLUSION

Results of a laboratory study focused on cement stabilization of 28 soils obtained from 9 active construction sites are presented in this paper. The materials consisted of glacial till, loess, and alluvium sand. Type I/II Portland cement was used for stabilization of these materials. 2 inch by 2 inch specimens of treated and untreated specimens were prepared, cured, and tested for UCS with and without vacuum saturation. The F_{200}, Atterberg limits, and AASHTO GI were determined before and after treatment. The results were analyzed using multi-variate regression 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:

1. 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.
2. With the exception of a few materials, the liquid limit and plasticity index of all materials decreased with increasing cement content. 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%.
3. 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.
4. The UCS of specimens increased with increasing cement content, as expected. The average saturated UCS of the unstabilized materials varied between 0 and 400 kPa. The average saturated UCS of stabilized materials varied between 0.3 and 2,000 kPa at 4% cement content, 0.8 and 3700 kPa at 8% cement content, and 1.1 and 4,900 kPa at

12% cement content. The laboratory testing and evaluation procedure for cement stabilization mix design targets a 700 kPa saturated UCS. The UCS of the saturated specimens was on average 1.5 times lower than that of the unsaturated specimens.

5. 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 500 kPa for vacuum saturated specimens and 700 kPa for unsaturated specimens.

DATA AVAILABILITY STATEMENT

All datasets presented in this study are included in the article/supplementary material.

AUTHOR CONTRIBUTIONS

SL conducted the laboratory works and data analysis, and prepared the project report and manuscript. YY prepared part of the manuscript. CL, LY, PZ, LW, and TH reviewed the article and gave some valuable feedbacks. All authors contributed to the article and approved the submitted version.

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