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Construction Quality: Laboratory Compaction Tests are Not the Compaction Standard

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Abstract

Standard laboratory compaction tests for soil, a three-phase material, are often viewed as the compaction standard for earthen fills. However, these lab tests were developed to simulate the compaction energy of and locate the compaction curve for a particular compactor-soil-lift combination. The resultant compaction curves were intended to serve as reference standards for curve location, to enable the compaction standard in construction specifications. Because these tests were not designed to be a compaction standard, its reference must be investigated. In this comprehensive field study, two CL soils (liquid limit of 42 (CL-A) and 48 (CL-B)) were field compacted (to locate the site-specific compaction curve, SSCC) and several properties (dry unit weight-moisture relationship, maximum dry unit weight, optimum moisture content, void ratio and air void content) were compared to the Standard Proctor (SP) and Modified Proctor (MP) tests for the same soils. In the field, the CL soils were compacted at 200 mm (8-in) lift thickness using a popular compactor. Nuclear density gauges were used to measure the lift densities and moisture contents. The dry unit weight-moisture content relationships for SP and SSCC didn't overlap at all. This supports the basis of the SP compaction test as only a reference standard for the field specified compaction standard. For the soil-compactor-lift combinations studied, the SSCC overlapped with part of the wet-side curve of MP, indicating that an actual dry-side condition in the field would be mistakenly viewed as a wet-side condition per lab reference standards. The maximum dry unit weight of SSCC compacted CL soils were 8 to 9 pcf higher than the SP compacted soils. All the other properties studied showed notable differences between the field compaction and laboratory compaction. The void ratio and air void contents had the highest differences in the SP and SSCC compacted CL soils.

Introduction

Compaction characteristics of soils (three phase materials), depends on several factors like moisture content, given energy, air content and soil physical properties which affects the degree of saturation at the optimum compaction. In the case of fine-grained soils that interact with water, the density and other properties achieved by compaction depends not only on the water content and compaction effort but also on the type of soil (Vipulanandan et al. 2004, 2007).

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Numerous laboratory and field investigations have been made to understand the principles of compaction, since the 1930's (Nagaraj et al. 2006).

Many researchers have tried to develop correlations to predict the laboratory compaction parameters by simulating the standard Proctor compaction test using a smaller compaction apparatus or by performing mathematical modeling (Diaz-Zorita et al. 2001, Sridharan et al. 2005, and Nagaraj et al. 2006).

Correlations are important in estimating the engineering properties of compacted soil particularly for a project where there is a financial limitation, a lack of test equipment, or limited time. Index tests can be easily performed and are required for cohesive soils in all soil exploration programs. It is therefore useful to estimate the engineering properties of soils by using other soil parameters that can be easily obtained. Sridharan et al. (2005) modeled a mini compaction aspirator which involves only about 1/10th volume of the soil required for the standard proctor test was used to simulate the Proctor compaction test for fine grained soils with particle size less than 2 mm. Further, the effort and time required to perform the compaction test using this apparatus is considerably less. From this study on red earth, kaolinite, and black cotton soil, he identified that the compaction curves obtained from the proposed an apparatus for different blows that have almost the same degree of saturation at the peak point for a given soil. Degree of saturation at peak points was found to be about 85, 96, and 95 % respectively.

According to Nagaraj et al. 2006, with an increase in compactive effort on a fine-grained soil, different compaction curves are obtained, each with its own values of optimum water content and maximum dry unit weight. It has also been established that with an increase in the compactive effort the maximum dry unit weight increases that is accompanied by a decrease in the optimum water content. These changes in the maximum dry unit weight and optimum water content which increases in compactive effort are marked up to a specific level of the compactive effort, but tend to be less pronounced with each additional increment in energy and finally leveling, where further increase in dry unit weight becomes negligible with higher compactive effort.

Sivrikaya et al. (2008) performed a study on estimating compaction behavior of fine-grained soils based on compaction energy. In his study, the correlation between optimum moisture content (w_{opt}) and plastic limit (w_{PL}) of fine soils was developed based on 130 data samples for standard compaction and 60 data samples for modified compaction (Table 1).

Table 1. Relations between compaction parameters and physical properties of fine soil (SI units) (Sivrikaya et al. 2008)

Properties	Testing Method	Relations	Equation Number
Optimum Moisture Content, Plastic Limit	Standard Proctor Compaction	$w_{opt} = 0.94 w_P$	(1)
Max Dry unit weight, Optimum Moisture Content		$\gamma_{dry/\max} = 21.97 - 0.27 w_{opt}$	(2)
Max Dry unit weight, Optimum Moisture Content		$\gamma_{dry/\max} = 23.45 e^{-0.018 w_{opt}}$	(3)
Optimum Moisture Content, Plastic Limit	Modified Proctor Compaction	$w_{opt} = 0.69 w_P$	(4)
Optimum Moisture		$w_{opt} = 0.35 w_L$	(5)

Content, Liquid Limit		
Max Dry unit weight, Optimum Moisture Content	$\gamma_{dry/\max} = 22.33 - 0.285 w_{opt}$	(6)
Max Dry unit weight, Optimum Moisture Content	$\gamma_{dry/\max} = 23.72 e^{-0.0184 w_{opt}}$	(7)

Field Compaction Control

Quality control procedures usually include the field measurement of dry unit weight ($\gamma_{d/Field}$) and a comparison with the laboratory maximum density ($\gamma_{d/Lab}$) values that is expected to be attainable in the field for the material and the applied compactive effort, based on laboratory compaction tests. The ratio ($\gamma_{d/Field}$)/ ($\gamma_{d/Lab}$) = RC (usually expressed as a percentage) is the relative compaction and is often used as the criterion for compaction, where ($\gamma_{d/Lab}$) is the maximum dry unit weight of the soil for a given laboratory compaction standard. Also there are several other methods that have been used to control the field compaction: the air voids method of evaluating the field compaction (Mokwa et al, 2007), the rapid estimation of field compaction parameters by that proposed by Nagaraj et al (2006), and by using other field instrumentations.

In this study, the air voids method was employed to determine the field compaction control that should be implied for these remolded fill soil materials. Based on the basic geotechnical phase relations between the each component in a soil mix (Air, Water, and Soil), the following relations can be identified:

Air voids, N_a:

$$N_a = \frac{V_a}{V_t} = \frac{V_a}{V_s + V_w + V_a} \qquad (8)$$

And;

$$N_a = \left[1 - \frac{\gamma_{dry}}{\gamma_w}\left(\frac{1}{G_s} + w\right)\right] \qquad (9)$$

So,

$$\gamma_{dry} = \frac{(1 - N_a).\gamma_w}{\left(w + \frac{1}{G_s}\right)} \qquad (10)$$

Where, V_a is the volume of air in the phase; Vs is the volume of the solid; V_w is volume of water; V_t is the total volume; γ_{dry} is the dry unit weight of the soil; γ_w is the unit weight of water; G_S is Soil specific gravity; and *w* is the moisture content.

Field Applications

Engineered soils are mostly used as fill materials for embankments, pavement subgrades, earth dam construction, and retaining wall backfills. But, when the fill materials are used in the field construction there should be a method to achieve the required quality. Because of that, the laboratory determined properties are used in the quality checking and assurance work. A similar study was performed by Mokwa et al (2007); in his study, earthwork compaction at field was controlled by using the soil air voids method.

The soil air voids method represents an alternate approach to the traditional Proctor method of field compaction control. The air voids evaluation procedure is based on the premise that the future performance of a compacted layer of soil can be evaluated by comparing the measured air voids with a predetermined limiting value of 10 % of air voids (Fig. 1). In theory, a field inspector can rapidly determine if a soil layer meets the specified compaction criteria without obtaining a soil sample for laboratory Proctor compaction testing. The air voids method has not gained widespread acceptance after being introduced to the engineering community in the 1940's. The air voids approach is simple because to evaluate the suitability of a compacted layer, the inspector only needs to plot a data point on the appropriate air voids graph (Fig. 1).

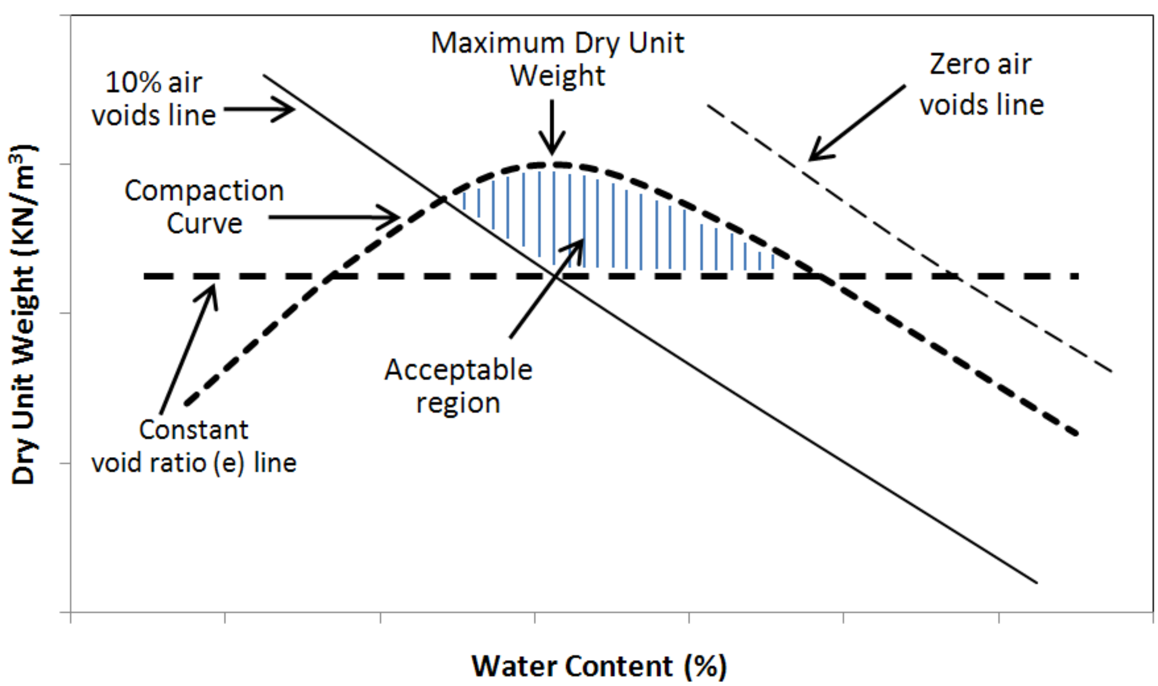

Figure 1. Typical acceptable zone for compacted soils

Objectives

The objective of this study was to compare the differences in field and laboratory compacted CL soils. Specific objectives are as follows: (a) to conduct a field study to determine the compacted soil parameters; (b) to perform laboratory compaction tests on CL soils; and (c) to quantify the differences in the important soil parameters.

Materials and Methods

(i) Moisture Content

Several methods are used for determining soil moisture content in both the field and the laboratory (Das 2000: Holtz et al. 1981). The following is a brief summary of the tests used in this study.

(a) Laboratory Water Content of Soil and Rock (ASTM D 2216-98) Equivalent Method: AASHTO T 265.

This method is widely known in geotechnical practice as the "Oven Dry Method". The underlying principle behind this test is to determine both the weight of solids and the weight of water contained in a given soil sample. The sample is placed inside a conventional oven at 110°C for a period of 24 hours. The wet and dry weights of the sample are determined before and after drying. The apparatus consists of a drying oven, balances and specimen containers. The oven dry method has traditionally been accepted as the baseline standard for geotechnical applications. The main limitation of this method is the amount of time required to perform this test. According to the ASTM D 2216-98, the accuracy of this method is 0.1 %.

(b) Field Method using Nuclear Method (Shallow Depth) (ASTM D 3017-01) Equivalent Method: AASHTO T 310

The shallow depth nuclear method calls for a fast neutron source to be applied to the surface of the soil. Using a surface slow neutron detector, the slowing ratio of the fast neutron is measured. Using this ratio and the calibration data, the moisture content of the soil is calculated. The hydrogen present in water is the main factor in this test. The apparatus is highly sensitive to water contained in the top 2 to 3 inches of soil. Hydrogen in forms other than water will cause readings to be larger than that of the true value. Some chemical elements such as boron, chlorine, and minute quantities of cadmium cause measurements to be lower than the true value.

(ii) Unit Weight

(a) Nuclear Method (shallow depth) (ASTM D3017-01) Equivalent Method:AASHTO T 310

The shallow depth nuclear method is the same as the regular nuclear method, but either the source and detector remains on the surface (Backscatter Method) or one of them is at the surface while the other is at a known depth of up to 300 mm (Direct Transmission Method). The same limitations apply as with the other nuclear methods. According to the ASTM D 3017-01, the accuracy of this method is 0.3 lbf /ft^3.

(iii) Compaction Tests

(a) Standard Compaction Mold (ASTM D 698-00)

Compaction tests are the most commonly performed soil test. The strength of the soil is indirectly illustrated from the compaction characteristic of the soil. It could be performed at field as well as in the laboratory. The relations between moisture content and the dry unit weight are determined from the compaction test. From the test the optimum moisture content and the maximum dry unit weight are obtained for particular soil. The field density test expresses the degree of compaction at the location. The standard Proctor compaction test procedures are based on the ASTM D 698-00a (2002).

Modified Compaction Test (ASTM D 1557-00)

This method of compaction is done for specific conditions where the compaction energy requirement is higher. Both small (4" diameter mold) and the large mold (6" diameter mold) could be used based on the soil particle sizes. During the compaction procedure a 10 lbm rammer was allowed to fall from a height of 18 inches. The small mold was compacted using 5 layers with 25 blows per layer, while the 6 inch mold was compacted using 56 blows per layer. According to the ASTM D1557-00, the moisture content and dry unit weight reported to the accuracy of 0.5 % and 0.5 lbf /ft^3 respectively.

(iv) Physical Properties

(a) Atterberg Limits (ASTM D 4318-84)

The Atterberg limit test (Liquid limit, Plastic limit, Plasticity Index) is done to the soils which are finer than No. 40 sieve size. The liquid limit is the moisture content of the soil when it starts to behave like viscous fluid. The liquid limit was determined using the Casagrandy apparatus. The method used in this study was the multiple point method, where at least four points for blow count and corresponding moisture content data were determined experimentally. The plastic limit is the minimum moisture content at the soil can be remolded without any cracks and volume change in it. The testing procedures were confirmed accordingly the ASTM D 4318-84.

(b) Specific Gravity Test (ASTM D 854)

Specific gravity test is used to determine the specific gravity of the average soil particle which is in the soil mixture. According to the above ASTM procedures, this method is suitable for the soil which passes the sieve no. 4, and the material which has specific gravity higher than 1. During the specific gravity test removal of air from the phycnometer is the significant part to determine the accurate result. There are two methods used to remove the air from the soil, one is direct heating the water soil mixture until the air bubbles removed from the phycnometer and the second method is applying suction to the soil water mixture. In this study, both methods were used.

(v) Field Test Program

A field test program was conducted to determine the compaction of soil using the Caterpillar 815F (weight 45,765; drum diameter 3.88 ft. drum width 3.25 ft.) Field study was performed at the ESOL proving ground facility located in Waller, Texas. About 200 cubic yard of each CL soil was stockpiled on the site for testing. The test pads were 16 ft. x 250 ft. and were prepared by removing the top 18 inches of native soil and placing a geotextile layer at the bottom and refilling it back with borrowed soils which were well compacted to have leveled test pads. Compaction of the two CL soils were studied for 8-in lifts and unit weight and moisture contents were measured at least at five locations along the test pad after each pass of the 815F compactor. The compaction was continued until the measured unit weight approached an asymptotic level (Langston and Tritico 1995). For each CL soil, compaction tests were performed at least at 6 moisture contents.

Discussion

(a) Physical Properties

At least 10 samples were randomly collected from each CL soil stockpile to measure the physical properties and the results are summarized in Table 2. Compared to CL-A soil, CL-B soil had greater variation in its index properties (based on coefficient of variation (COV)).

Table 2. Summary of Physical Properties of Soils

Soil		LL	PL	PI	Specific Gravity	Remarks
CL-A	Mean	42	16	26	2.69	Lesser variation in the soil properties compared to CL-B. Compared to CL-B, the soil has less LL and PI
	Standard deviation	2.2	2.2	2.2	0.016	
	COV (%)	5.3	13.8	11.6	0.60	
CL-B	Mean	48	17	31	2.69	Greater variation in the soil properties. Has greater LL and PI compared to CL-A.
	Standard deviation	6.3	6.7	6.7	0.024	
	COV	13.1	39.4	21.6	0.893	

Compaction Study

The test results from the laboratory and field compaction (Site Specific Compaction Curve (SSCC)) studies for the two selected soils are shown in Figs. 2 and 3.

(i) Soil CL-A

Dry Unit Weight – Moisture Content (γ_d-w) Relationship: The relationship of standard Proctor (SP) test was not even close to the field compacted results (SSCC) and there was no overlapping of results at all (Fig. 1). The modified Proctor (MP) test had a region of overlap with the SSCC on the wet side of the compaction curve (Fig. 1), but mismatch for the rest of the curve/relationship.

(a) Optimum Conditions

Maximum Dry Unit Weight $(\gamma_d)_{max}$: As summarized in Table 3 and shown in Fig. 2, the maximum dry unit weight of the field compacted soil was 9.5 pcf, or 8.5% higher than the standard compaction. The relative compaction (RC) was 1.08. The SSCC–γ_{dmax} was 1.7 pcf or -1.4% lower than the modified compaction $\gamma_{dmax.}$ Equations (2) and (3) over predicted the maximum unit weight of standard compaction by 3 pcf. Equations (6) and (7) over predicted the maximum unit weight of modified compaction by 1.6 and 3 pcf respectively.

Optimum Moisture Content $(w)_{opt}$: As summarized in Table 3 and shown in Fig. 2, the w_{opt} of the field compacted soil was 11.8% which was -2.6% lower than the standard compaction. In reality this will save using excess water in the field for compaction. The SSCC–w_{opt} was 1.5% higher than the modified compaction w_{opt}. Equation (1) predicted the SP-w_{opt} to be 15% and the actual value was 14.6%. Equations (4) and (5) predicted the MP-w_{opt} to be 11% and 14.7% respectively. So Equation (4) better predicted the moisture content of MP-w_{opt}.

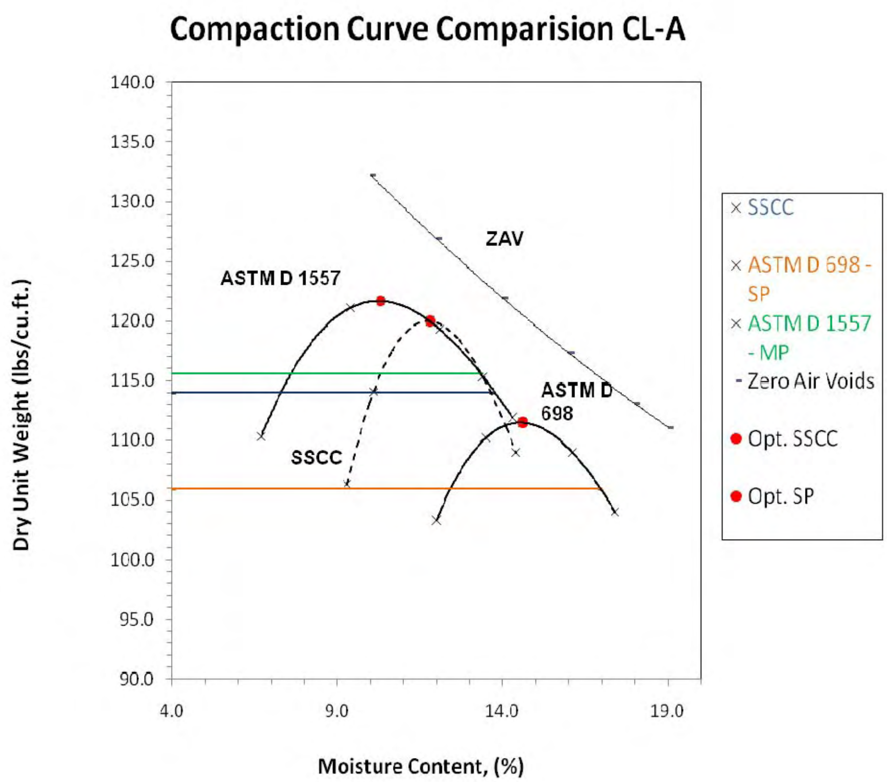

Figure 2. Laboratory and Field Compaction Results for CL-A Soil

Degree of Saturation (S): As summarized in Table 3, the S for SSCC was the maximum with 79.6% and the modified compaction had the lowest with 73.1%.

Void Ratio (e): As summarized in Table 3, the void ratio of the SP was the highest with 0.51. The void ratio for SSCC and MP were 0.40 and 0.38 respectively. Hence the SSCC–e was 21.5% lower than the SP-e. The void ratio showed the second largest percentage difference in the properties investigated between the SSCC and SP compacted soils.

Air Void Ratio (N_a): As summarized in Table 3, the N_a of the SSCC was the lowest with 5.82. The N_a for SP and MP were 7.49 and 7.41 respectively. Hence the SSCC– N_a was 28.7% lower than the SP-N_a. The air void ratio showed the highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

(b) 95% of Optimum-Dry Condition

Dry Unit Weight (γ_d): As summarized in Table 2 and shown in Fig. 1, the 95% of optium dry unit weight of the SSCC compacted soil was 8.1 pcf, or 7.6% higher than the SP. The relative compaction (RC) was 1.08. The SSCC–γ_d was 1.6 pcf or -1.4% lower than the MP-γ_d.

Moisture Content (w): As summarized in Table 3 and shown in Fig. 2, the w for the 95% SSCC compacted soil was 10.1% which was -2.4% lower than the SP. The SSCC– w was 2.5% higher than the MP-w.

Degree of Saturation (S): As summarized in Table 3, the S for SSCC and SP were the same of 57.5% and the modified compaction had the lowest with 45.2%.

Void Ratio (e): As summarized in Table 3, the void ratio of the SP was the highest with 0.59. The void ratio for SSCC and MP were 0.47 and 0.45 respectively. Hence the SSCC–e was 20% lower than the SP-e. The void ratio showed the highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

Air Void Ratio (N_a): As summarized in Table 3, the $\mathbf{N_a}$ of the SSCC was the lowest with 13.63. The N_a for SP and MP were 15.70 and 17.03 respectively. Hence the SSCC– N_a was 15% lower than the SP-N_a. The air void ratio showed the second highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

Table 3. Summary of Compacted Properties of CL-A Soil

Compaction Method		Moisture Content(%)	Dry Unit Weight (lb/cu.ft)	Degree of Saturatio n (S) (%)	Void Ratio (e)	Air Voids (%)
Standard Proctor (SP)	Optimum	14.6	111.5	77.7	0.51	7.49
	95% Dry	12.5	105.9	57.5	0.59	15.70
	95% Wet	16.9	105.9	77.7	0.59	8.23
Site Specific Compaction Curve (SSCC)	Optimum	11.8	120.0	79.6	0.40	5.82
	95% Dry	10.1	114.0	57.5	0.47	13.63
	95% Wet	13.6	114.0	77.4	0.47	7.24
Modified Proctor (MP)	Optimum	10.3	121.7	73.1	0.38	7.41
	95% Dry	7.6	115.6	45.2	0.45	17.05
	95% Wet	13.3	115.6	79.2	0.45	6.49

(b) 95% of Optimum-Wet Condition

Dry Unit Weight (γ_d): As summarized in Table 3 and shown in Fig. 2, the 95% of optimum wet unit weight of the SSCC compacted soil was 8.1 pcf, or 7.6% higher than the SP. The relative compaction (RC) was 1.08. The SSCC–γ_d was 1.6 pcf or -1.4% lower than the MP-γ_d.

Moisture Content (w): As summarized in Table 3 and shown in Fig. 2, the w for the 95% SSCC compacted soil was 13.6% which was -3.3% lower than the SP. The SSCC–w was 0.3% higher than the MP-w.

Degree of Saturation (S): As summarized in Table 3, the S for SSCC and SP were very close and was about 77.5% and the modified compaction had the highest of 79.2%.

Void Ratio (e): As summarized in Table 3, the void ratio of the SP was the highest with 0.59. The void ratio for SSCC and MP were 0.47 and 0.45 respectively. Hence the SSCC–e was 20% lower than the SP-e. The void ratio showed the highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

Air Void Ratio (N_a): As summarized in Table 3, the $\mathbf{N_a}$ of the SSCC was the lowest with 7.24. The N_a for SP and MP were 8.23 and 6.49 respectively. Hence the SSCC–N_a was 12% lower than the SP-N_a. The air void ratio showed the second highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

(i) Soil CL-B

Dry Unit Weight – Moisture Content (γ_d-w) Relationship: The relationship of SP test was not even close to the SSCC compacted results and there was no overlapping of results at all (Fig. 3), similar to what was observed for CL-A soil. The modified Proctor (MP) test had a region of overlap with the SSCC on the wet side of the compaction curve (Fig. 2), but mismatch for the rest of the curve/relationship.

(a) Optimum Conditions

Maximum Dry Unit Weight (γ_d)$_{max}$: As summarized in Table 4 and shown in Fig. 3, the maximum dry unit weight of the field compacted soil was 9.1 pcf, or 8.4% higher than the SP. The relative compaction (RC) was 1.08. The SSCC–γ_{dmax} was 2 pcf or -1.7% less than the MP compaction γ_{dmax}. Equations (2) and (3) over predicted the maximum unit weight of SP compaction by 3.7 and 3.3 pcf respectively. Equations (6) and (7) over predicted the maximum unit weight of MP compaction by 2.2 and 3.3 pcf respectively.

Optimum Moisture Content (w)$_{opt}$: As summarized in Table 4 and shown in Fig. 3, the w_{opt} of the field compacted soil was 12.7% which was -3.3% lower than the SP compaction. In reality this will save using excess water in the field for compaction. The SSCC–w_{opt} was 1.6% higher than the MP compaction w_{opt}. Equation (1) predicted the SP-w_{opt} to be 16%, which agreed with the experimental results. Equations (4) and (5) predicted the MP-w_{opt} to be 11.7% and 16.8% respectively with the actual value being 11.1%. Equation (4) better predicted the MP-w_{opt}.

Degree of Saturation (S): As summarized in Table 4, the S for SSCC was the maximum with 79.9% and the modified compaction had the lowest with 74%.

Void Ratio (e): As summarized in Table 4, the void ratio of the SP was the highest with 0.55. The void ratio for SSCC and MP were 0.43 and 0.40 respectively. Hence the SSCC–e was 21.9% lower than the SP-e. The void ratio showed the highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

Air Void Ratio (N_a): As summarized in Table 4, the $\mathbf{N_a}$ of the SSCC was the lowest with 6.01. The N_a for SP and MP were 7.54 and 7.47 respectively. Hence the SSCC–N_a was 20.3% lower than the SP-N_a. The air void ratio showed the second highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

(b) 95% of Optimum-Dry Condition

Dry Unit Weight (γ_d): As summarized in Table 4 and shown in Fig. 3, the 95% of optimum dry unit weight of the SSCC compacted soil was 8.6 pcf, or 8.3% higher than the SP. The relative compaction (RC) was 1.08. The SSCC–γ_d was 1.9 pcf or -1.7% lower than the MP-$\gamma_{d.}$.

Moisture Content (w): As summarized in Table 4 and shown in Fig. 3, the w for the 95% SSCC compacted soil was 11.1% which was -2.4% lower than the SP. The SSCC– w was 2.7% higher than the MP-w.

Degree of Saturation (S): As summarized in Table 4, the S for SSCC and SP were 59.4 and 57.8% respectively. The modified compaction had the lowest with 47.3%.

Void Ratio (e): As summarized in Table 4, the void ratio of the SP was the highest with 0.63. The void ratio for SSCC and MP were 0.50 and 0.48 respectively. Hence the SSCC–e was 20.6% lower than the SP-e. The void ratio showed the second highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

Air Void Ratio (N_a): As summarized in Table 4, the $\mathbf{N_a}$ of the SSCC was the lowest with 13.59. The N_a for SP and MP were 20.24 and 17.03 respectively. Hence the SSCC–N_a was 32.8% lower than the SP-N_a. The air void ratio showed the highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

(b) 95% of Optimum-Wet Condition

Dry Unit Weight (γ_d): As summarized in Table 4 and shown in Fig. 3, the 95% of optimum dry unit weight of the SSCC compacted soil was 8.6 pcf, or 8.3% higher than the SP. The relative compaction (RC) was 1.08. The SSCC–γ_d was 1.9 pcf or -1.7% lower than the MP-$\gamma_{d.}$.

Moisture Content (w): As summarized in Table 4 and shown in Fig. 3, the w for the 95% SSCC compacted soil was 14.5% which was -4.3% lower than the SP. The SSCC–w was almost the same as the MP-w.

Degree of Saturation (S): As summarized in Table 4, the S for SSCC and SP were 77.6 and

80.5% respectively. The modified compaction had a S of 81.1%.

Void Ratio (e): As summarized in Table 4, the void ratio of the SP was the highest with 0.63. The void ratio for SSCC and MP were 0.50 and 0.48 respectively. Hence the SSCC–e was 20.6% lower than the SP-e. The void ratio showed the highest percentage difference in the properties investigated between the SSCC and SP compacted soils.

Air Void Ratio (N_a): As summarized in Table 4, the N_a of the SSCC was the lowest with 7.50%. The N_a for SP and MP were 7.54 and 6.11 respectively. Hence the SSCC–N_a was similar to the SP-N_a. The air void ratio showed the lowest percentage difference in the properties investigated between the SSCC and SP compacted soils.

Table 4. Summary of Compacted Properties of CL-B Soil

Compaction Method		Moisture Content(%)	Dry Unit Weight (lb/cu.ft)	Degree of Saturation (S) (%)	Void Ratio (e)	Air Voids (%)
Standard Proctor (SP)	Optimum	16.0	108.5	78.7	0.55	7.54
	95% Dry	13.5	103.1	57.8	0.63	20.24
	95% Wet	18.8	103.1	80.5	0.63	7.54
Site Specific Compaction Curve (SSCC)	Optimum	12.7	117.6	79.9	0.43	6.01
	95% Dry	11.1	111.7	59.4	0.50	13.59
	95% Wet	14.5	111.7	77.6	0.50	7.50
Modified Proctor (MP)	Optimum	11.1	119.6	74.0	0.40	7.47
	95% Dry	8.4	113.6	47.3	0.48	17.03
	95% Wet	14.4	113.6	81.1	0.48	6.11

CONCLUSIONS

Based on the comprehensive field and laboratory compaction studies on two CL soils following conclusions were advanced:

1. **Dry Unit Weight – Moisture Content (γ_d-w) Relationship**: The relationship of SP test was not even close to the SSCC results and there was no overlapping of the results at all for both the soils. The modified Proctor (MP) test had a region of overlap with the SSCC on the wet side of the compaction curve, but mismatch for the rest of the curve/relationship. Hence the laboratory relationships cannot represent the field compacted relationship.

2. **Maximum Dry Unit Weight $(\gamma_d)_{max}$**: The maximum dry unit weight of the field compacted soil was 8 to 9.5 pcf, or about 8.5% higher than the standard compaction. The relative compaction (RC) was 1.08. The SSCC–γ_{dmax} was 1.7 pcf or -1.4% lower

than the modified compaction $\gamma_{dmax.}$ Equations in the literature over predicted the SP and MP unit weights by about 3 pcf.

3. **Optimum Moisture Content $(w)_{opt}$**: The w_{opt} of the field compacted soil was about 2.6% lower than the standard compaction. In reality this will save using excess water in the field for compaction. The SSCC–w_{opt} was 1.5% higher than the modified compaction $w_{opt.}$ Equation in the literature, based on the plastic limit, predicted the SP-w_{opt} and the MP-$w_{opt.}$

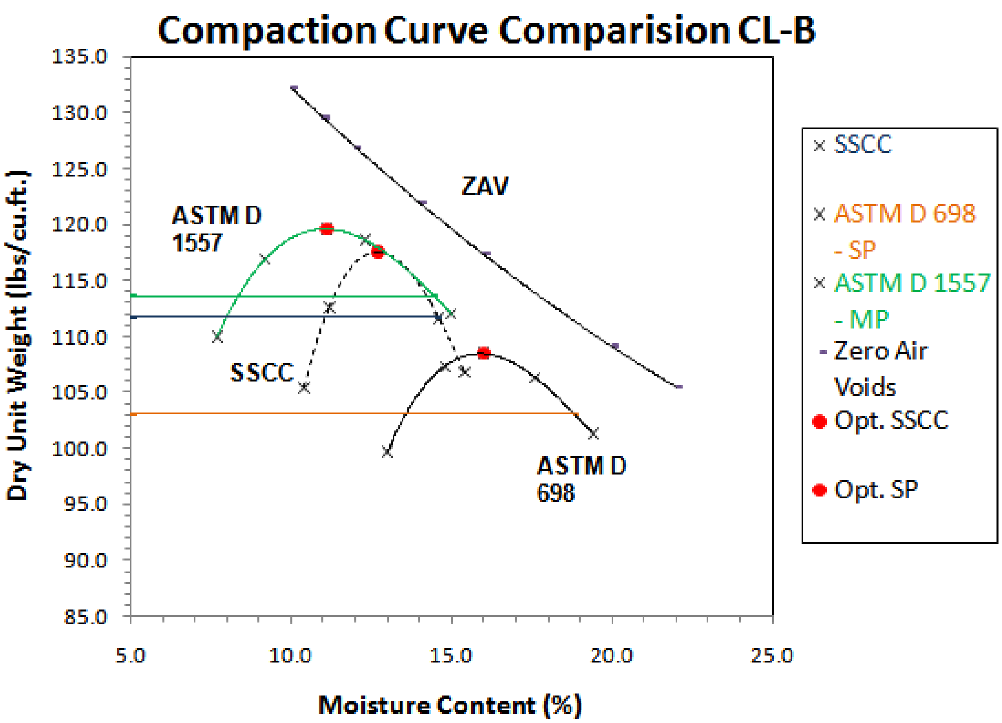

Figure 3. Laboratory and Field Compaction Results for CL-B Soil

4. **Degree of Saturation (S)**: Notable differences were observed in the degree of saturation based on the compaction methods.

5. **Void Ratio (e)**: The void ratio showed the highest or second highest percentage difference in the SSCC and SP compacted soils.

6. **Air Void Ratio (N_a)**: The air void ratio showed the highest or second highest percentage difference in the SSCC and SP compacted soils.

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