FIELD COMPACTION VERIFICATION USING A NEW SURFACE PENETROMETER (SP-CIGMAT) DURING CONSTRUCTION

C. Vipulanandan , Ph.D., P.E.
Professor and Director of Center for Innovative Grouting Materials and Technology (CIGMAT) and
Texas Hurricane Center for Innovative Technology (THC-IT),
Department of Civil and Environmental Engineering,
University of Houston, Houston, Texas 77204-4003.
Phone: (713) 743-4278; email: cvipulanandan@uh.edu;
URL: http://cigmat.cive.uh.edu

Abstract

The need for better characterizing the properties of field compacted soils during construction is important in ensuring the quality of construction. Standard laboratory compaction tests for soil, a three-phase material, are often viewed as the compaction standard for earthen fills. However, these laboratory tests were developed to simulate the compaction energy of a particular compactor-soil-lift combination. For this study, a field compacted CL soil (liquid limit of 42) with several properties (dry unit weight-moisture relationship, maximum dry unit weight, optimum moisture content, void ratio and air void content) was compared to the Standard Proctor (SP) and Modified Proctor (MP) tests. In the field, the CL soil was compacted at 200 mm (8-in) lift thickness using a popular compactor. Nuclear density gauges was used to measure the lift densities and moisture contents. The dry unit weight-moisture content relationships for SP and field compacted curve didn't overlap at all. The maximum dry unit weight of field compacted CL soil was 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 field compacted CL soil. A new surface penetrometer (SP-CIGMAT) was developed and used to evaluate compacted soil undrained shear strength (s_u) and CBR during the construction. This device can be easily attached to any construction vehicle to perform tests on compacted soils during construction. Based on the limited field data and laboratory tests, non-linear and linear correlations between the SP-CIGMAT deflection and compacted soil properties have been developed.

Introduction

For site investigation, in-situ tests are increasingly used to determine the soil properties for geotechnical analysis and design. The penetrometers evolved from the need for acquiring data on sub-surface soils that were not sampled easily by any other means (Sanglerat 1972). Hence static and dynamic penetration resistances have been used to classify and characterize subsoils.

Compaction characteristics of soils (three phase materials), depends on several factors including the soil type, moisture content and compaction energy (Vipulanandan et al. 2004, 2007). 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 soils based on soil properties. 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 used only about 1/10th volume of the soil required for the standard proctor test. This test was used to simulate the Proctor compaction test for fine grained soils with particle size less than 2 mm.

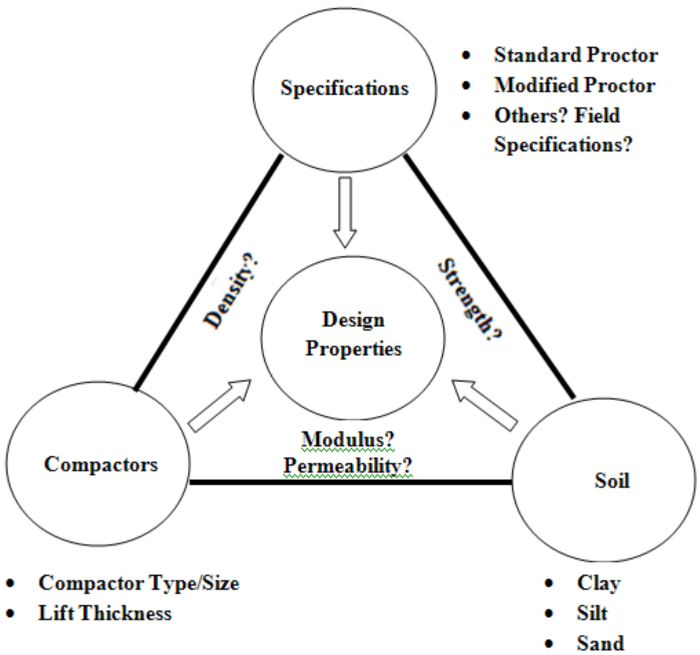

Figure 1. Major Components in Field Compaction

Based on past studies, 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 tends 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.

(a) Dry density-Moisture Content Space

As shown in Fig 2, a soil that was at either point #1 or point #2 could be compacted using different methods to reach the point #3 where the dry density and moisture content are the same. For example, point#3 could be on the wet side of optimum of the compaction curve for path 1 compaction and be on the dry side of the optimum based for compaction path 2. Hence for point #3, the mechanical properties will be based on the energy/stress path the soil was subjected too during the compaction. Although the same dry density and moisture content were achieved the soil structure in the compacted soil will be different based on the energy used for compaction.

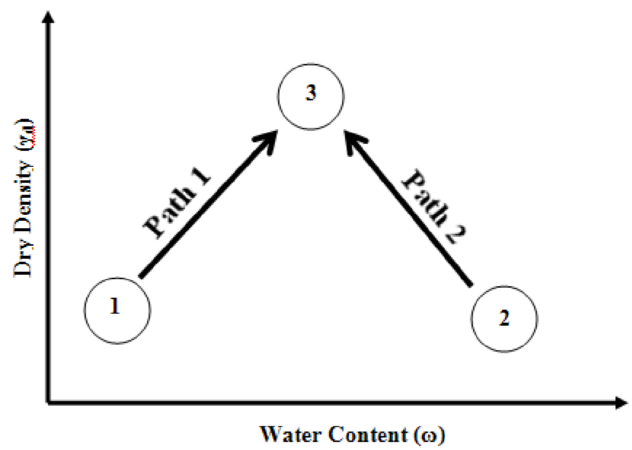

Figure 2. Compacted Soil Properties Depend on the Energy/Stress Path of Compaction

(b) Field Compaction Quality

Engineered soils are compacted to be 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, as shown in Fig.3 (acceptable region). Because of that, the laboratory determined properties are used in the quality checking and assurance work. In theory, a field inspector can rapidly determine if a soil layer meets the specified compaction criteria (dry density and/or moisture content) without obtaining a soil sample for laboratory Proctor compaction testing.

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 (less than 10%) 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.

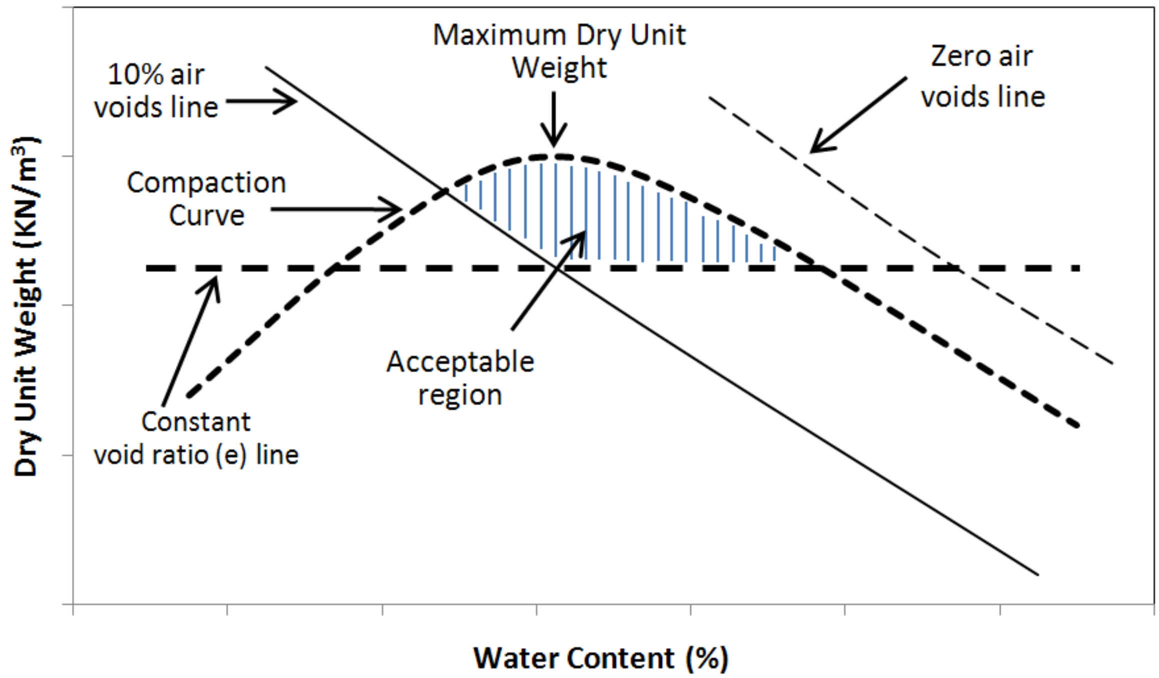

Figure 3. Typical acceptable zone for compacted soils

(c)Surface Applications

As is well known, one of the most important parameters in Pavement Management System (PMS) is both the functional and structural capacity of the pavement network (Chen et al. 2005). Currently there is no standard field test to determine the strength of base and subgrade soils for construction quality control/assurance purposes; though many transportation agencies only use density and moisture measurement. The Falling Weight Deflectometer (FWD), Geogauge, Dirt Seismic Pavement Analyzer (DSPA), and laboratory repetitive triaxial tests have been used to determine the pavement layer modulus (Nazarian et al. 2002; Rahim and George 2002; Sawangsuriya et al. 2002). However, the limitations of each method are equally real. As many different sets of layer moduli would satisfy the same FWD deflection bowl, practicing pavement engineers struggle to identify the correct set. Also, the FWD often is unable to determine the extent of a weak base/subgrade layer due to a thick concrete layer that carries most of the load away. Laboratory repetitive triaxial tests are seldom used to determine the layer moduli for routine design or QC/QA tests in current DOT environments (Rahim and George 2002; Chen et al. 2001b). Seismic tests are quick and easy, but the seismically determined modulus is very high due to the high frequencies and miniscule loads used. The Geogauge is highly sensitive to the surface preparation, and it only gives a composite stiffness that includes all layers to some uncertain depth (Chen 2005).

(d) In-Situ Tests

Compacted soils are the soils in which the in-situ structure of the soil is modified by compaction. The main objective of compaction is to improve the performance of a material by increasing its strength, stiffness and durability. There are many situations where the compacted soils are used such as construction of new embankment, road, earth dam, building foundation and retaining wall back fills soils.

In order to inspect and verify the quality and construction of compacted soils, nondestructive testing devices are extremely attractive owing to the rapidity in performing the tests. Researchers have used Dynamic Cone Penetrometer (DCP), California Bearing Ratio (CBR) and Falling Weight Deflectometer (FWD) for evaluating earth structures, backfills for pipelines, pavements and subgrade soils (Kleyn (1983), Chen et al. (2005) and Misra (2006).

The advantages of in situ testing include the following: (*i*) disturbance is often less than in sampling and testing, and (*ii*) results can be viewed in real time and used to modify field compaction procedure.

Objectives

The objective of this study was to compare the differences in field and laboratory compacted CL soil and to evaluate the performance of a surface penetrometer (SP-CIGMAT) to characterized the compacted soil during construction.

Materials and Methods

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.) 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 several 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.

<u>Discussion</u>

<u>(a) Physical Properties</u>

At least 10 samples were randomly collected from each CL soil stockpile to measure the physical properties and the results are summarized in Table 1 for one CL soil selected for this paper.

Table 2. Summary of Physical Properties of Soils

Soil Type		LL	PL	PI	Specific Gravity	Remarks
CL	Mean	42	16	26	2.69	Lesser variation in the soil properties compared to other CL soils selected for the field study. Also had less LL and PI to other CL soils
	Standard deviation	2.2	2.2	2.2	0.016	
	COV (%)	5.3	13.8	11.6	0.60	

<u>Compaction Study</u>

The test results from the laboratory and field compaction (FC)) studies for the selected CL soil is shown in Figs. 4.

(i) Soil CL

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 and there was no overlapping of results at all (Fig. 4). 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.

<u>(a) Optimum Conditions</u>

Maximum Dry Unit Weight $(\gamma_d)_{max}$: As summarized in Table 2 and shown in Fig. 4, 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 FC–γ_{dmax} was 1.7 pcf or -1.4% lower than the modified compaction γ_{dmax}.

Optimum Moisture Content $(w)_{opt}$: As summarized in Table 3 and shown in Fig. 4, 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 FC–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%.

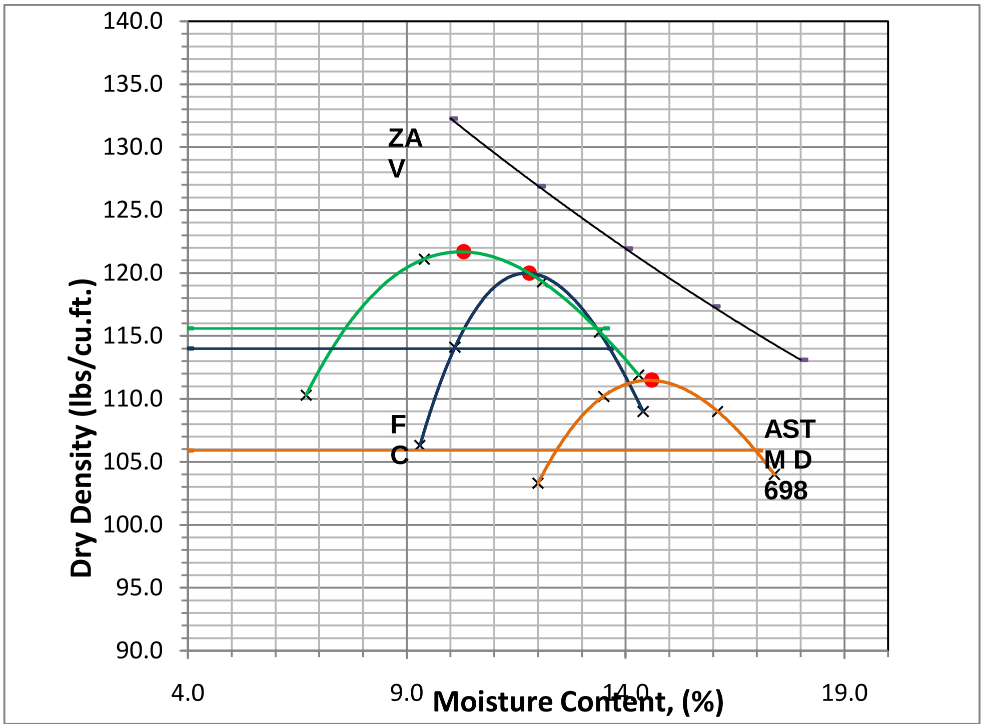

Figure 4. Laboratory and Field Compaction Results for a CL Soil

Degree of Saturation (S): As summarized in Table 2, the S for FC 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 FC and MP were 0.40 and 0.38 respectively. Hence the FC–e was 21.5% lower than the SP-e. The void ratio showed the second largest percentage difference in the properties investigated between the FC and SP compacted soils.

Air Void Ratio (N_a): As summarized in Table 3, the $\mathbf{N_a}$ of the FC was the lowest with 5.82. The N_a for SP and MP were 7.49 and 7.41 respectively. Hence the FC– 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 FC and SP compacted soils.

<u>**(b) 95% of Optimum-Dry Condition**</u>

Dry Unit Weight (γ_d): As summarized in Table 2 and shown in Fig. 4, the 95% of optium dry unit weight of the FC 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 2 and shown in Fig. 4, the w for the 95% FC compacted soil was 10.1% which was -2.4% lower than the SP. The FC– ẉ was 2.5% higher than the MP-w.

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

Air Void Ratio (N_a): As summarized in Table 3, the N_a of the FC was the lowest with 13.63. The N_a for SP and MP were 15.70 and 17.03 respectively. Hence the FC– 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 FC and SP compacted soils.

Table 2. Summary of Compacted Properties of CL Soil

Compaction Method		Moisture Content(%)	Dry Unit Weight (lb/cu.ft)	Degree of Saturation (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
Field Compaction (FC)	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

(c) 95% of Optimum-Wet Condition

Dry Unit Weight (γ_d): As summarized in Table 2 and shown in Fig. 4, 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 FC–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% FC compacted soil was 13.6% which was -3.3% lower than the SP. The FC–w was 0.3% higher than the MP-w.

Degree of Saturation (S): As summarized in Table 3, the S for FC 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 2, the void ratio of the SP was the highest with 0.59. The void ratio for FC and MP were 0.47 and 0.45 respectively. Hence the FC–e was 20% lower than the SP-e. The void ratio showed the highest percentage difference in the properties investigated between the FC and SP compacted soils.

Air Void Ratio (N_a): As summarized in Table 3, the N_a of the FC was the lowest with 7.24. The N_a for SP and MP were 8.23 and 6.49 respectively. Hence the FC–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 FC and SP compacted soils.

NEW SURFACE PENETROMETER (SP-CIGMAT)

In this study CIGMAT Down-Hole Penetrometer (DHP-CIGMAT) was modified to CIGMAT Surface Penetrometer (SP-CIGMAT) and used for measuring the strength and modulus of compacted soils. Tests were performed on compacted soils varying from soft to very stiff clay, silty soils and sandy soils (CL, CH and SC). Total of 19 field tests were performed with Shelby tube sampling the soil for the unconfined compression test.

Field Tests

SP-CIGMAT field tests were performed to investigate the relationship between penetrometer deflection (δ_{max}) and compressive strength (σ_u), modulus (E) and CBR value of compacted soil layers which were 8 and 12 inches depths. In these field tests CH, CL and SC were the major soils. SP-CIGMAT was mounted to the sampling rigs, which were used to obtain samples using 3 inch Shelby Tubes (Area ratio<10%) (Figure 5). The location of tests were selected close enough to have similar properties with samples, but also far enough not to effected by opened hole.

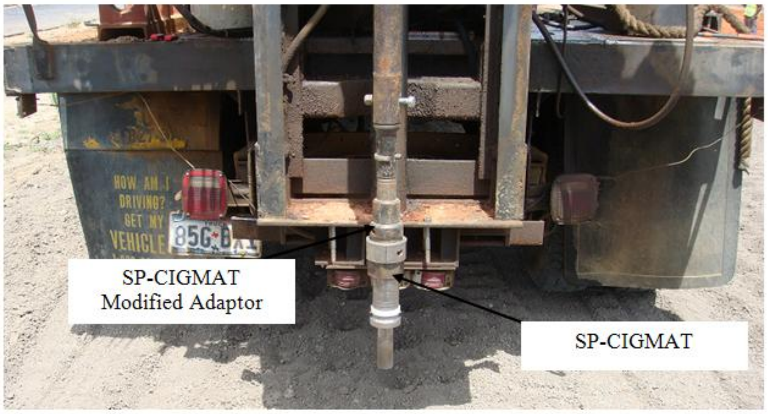

Figure 5. SP-CIGMAT Mounted on a Soil Sampling Rig

<u>Shear Strength</u>

The bearing capacity theory with non-linear relationship, where relationship between soft rock/stiff clay unconfined compressive strength (σ_u, psi) and ultimate strength (q_{ult}, psi) was suggested by Zhang and Einstein (1998) and Vipulanandan et al. (2007) was used and is as follows:

$$q_{ult} = \alpha_q (\sigma_u)^m \quad , \qquad (1)$$

where, magnitudes of parameters m and α_q depend on the type of soft rock/stiff clay and unconfined compressive strength (σ_u, psi = $2S_u$)). This relationship can be used to relate the undrained shear strength of soil (S_u) to the penetrometer deflection (δ_{max}). The relationship for penetrometer deflections (δ_{max}) and the shear strength (S_u) is as follows:

$$S_u = 56.4 * \delta_{max}^{1.78} \quad N= 19 , R^2=0.72. \quad (2)$$

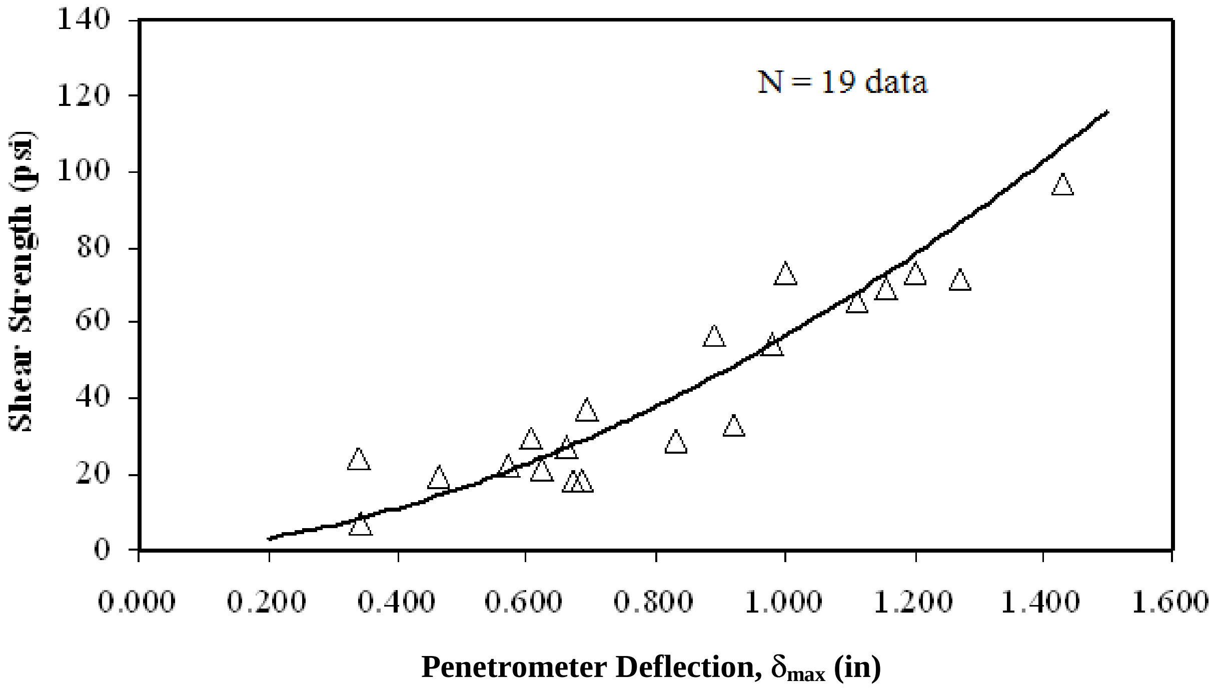

Figure 6. Relationship between SP-CIGMAT deflections (δ_{max}) and Shear Strength (S_u)

<u>California Bearing Capacity Ratio</u> (CBR)

Present design approaches of subgrades for pavement design use CBR values to determine the resilient modulus. Hence it was of interest to determine the correlation between CBR and SP-CIGMAT penetrometer deflection. Compacted field samples were collected in CBR molds and test were performed in the laboratory. Total of 7 CBR tests were performed and the relationship for penetrometer deflections (δ_{max}) and the CBR was as follows:

$$CBR = 33\ \delta_{max} , \quad N =7 , \quad R^2 \text{ of } 0.78. \quad (3)$$

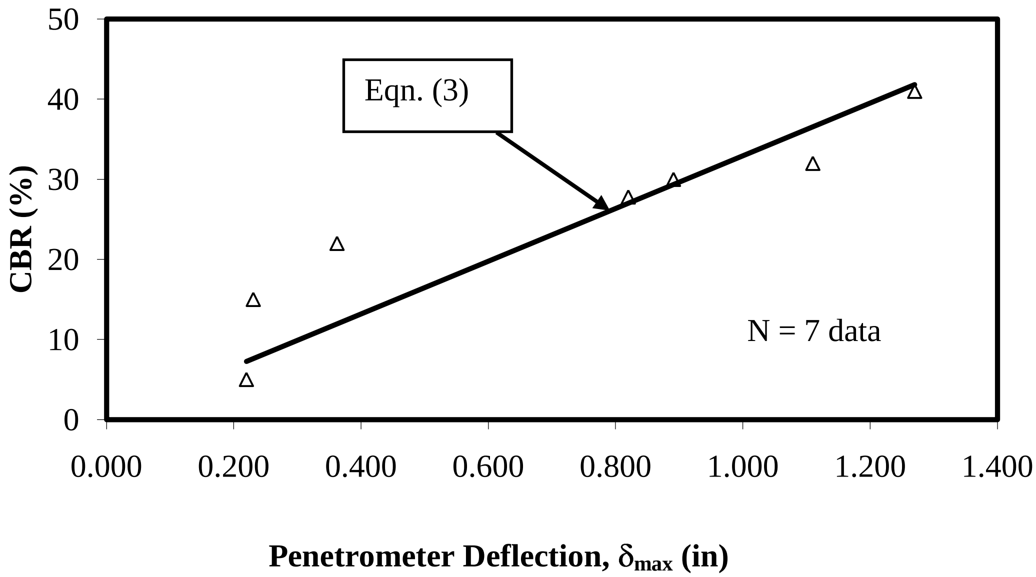

Figure 7. Relationship between SP-CIGMAT deflection and CBR value

CONCLUSIONS

Based on the comprehensive field and laboratory compaction studies following conclusions are advanced:

1. Field compacted (FC) dry density-moisture content relationship was different from the laboratory compaction test results. Hence the laboratory relationships cannot represent the field compacted relationship.

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

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

4. SP-CIGMAT deflection correlated well with the undrained shear strength of field compacted soils. The relationship was nonlinear.

5. SP-CIGMAT deflection correlated well with the undrained shear strength of field compacted soils. The relationship was linear.

ACKNOWLEDGEMENT

This project was supported by ESOL-Earthworks Solutions LLC. The sponsor is not responsible for any of the conclusions made in this study.

REFERENCES

ASTM, (2008) "ASTM D 698 Standard Proctor method, Annual Book of ASTM

Chen, D.H., Lin, D.F., Liau,P. and Bilyeu, J. (2005) "A Correlation between Dynamic Cone Penetrometer Values and Pavement Layer Moduli." Geotechnical Testing Journal, 28(1), 42-49.

Das B. M, (2000), Fundermental of Geotechnical Engineering, Brooks/Cole, Thomson Learning, USA, ISBN 0-534-37114-0.

Holtz, R., and Kovac, W.D, (1981), An introduction to Geotechnical Engineering, Pentice Hall, Inc.

Langston, R. and Tritico, P. (1995), Practice Improvements for The Design and Construction of Earth Fills, Proceedings, ASCE –Texas Section.

Mokwa, R. L., and Fridleifsson, S., (2007), Earthwork Compaction Evaluation using Soil Air Voids, Canadian Geotechnical Journal, Vol. 44: pp.151-159.

Nagaraj T. S., Lutenegger, A. J., Pandian, N. S., and Manoj, M., (2006), Rapid Estimation of Compaction Parameters for Field Control, Geotechnical Testing Journal, Vol. 29: No.6, pp. 1 -10.

Sivrikaya, O., Togrol.E, and Kayadelen,C., (2008), Estimating Compaction Behavior of Fine-Grained Soils based on Compaction Energy, Canadian Geotechnica Journal, Vol.45: pp. 877-887

Sridharan, A., and Sivapullaiah, P. V., (2005), Mini Compaction Test Apparatus for Fine Grained Soils, Geotechnical Testing Journal, Vol. 28: No.3, pp.1-7.

Sridharan, A., El-Shafi, A. and Miura, N., (2002), Mechanisms Controlling the Undrained Shear Strength Behavior of Remolded Ariake Marine Clays, Marine Georesources and Geotechnology, Vol. 20: pp.21-50.

Vipulanandan, C., Guezo, Y.J., and Bilgin, O., (2007), Geotechnical Properties of Marine and Deltaic Soft Clays, Proceedings, Geo Denver, Denver, USA

Vipulanandan, C., Kim, M.S., and Harendra, S., (2007), Microstructural and Geotechnical Properties of Houston-Galveston Area Soft Clays, Proceedings, New Peaks in Geotechnics, ASCE Geo Institute, Denver, Colorado.

Vipulanandan, C., Mo, Y.L., Puppala, A.J., Jao, M., and Fang, Li., (2004), Correlation of Texas Cone Penetrometer Test Values and Shear Strength of Texas Soils, Project Proposal for TxDOT Research Project No. 0-4862, Houston, Texas.

Zhang, Z., Tao, M., and Tumay, M., T., (2005), Absorbed Energy and Compacted Cohesive Soil Performance, Geotechnical Testing Journal, Vol. 28: No.4, pp. 1-6.

Zhang, L. and Einstein, H. H., (1998). "End Bearing Capacity of Drilled shafts in Rock." Journal of Geotechnical and Geoenvironmental Engineering, Vol. 124, No. 7, pp. 574-584.