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Compaction and mechanical properties of soils compacted in the gyratory compactor

Propiedades de compactación y mecánicas de suelos compactados en el compactador giratorio

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RESUMEN

En este artículo los autores presentan resultados de curvas de compactación de suelos finos que fueron determinadas con un compactador giratorio. Se muestra cómo varía la curva de compactación dependiendo de las variables controladas en el equipo giratorio durante la compactación (presión vertical, ángulo de giro y velocidad a la que se aplican los giros). Se llevaron a cabo comparaciones entre las curvas de compactación obtenidas por métodos tradicionales y las obtenidas con el compactador giratorio, encontrándose que la curva de compactación Proctor estándar se puede obtener si el suelo colocado en el equipo giratorio se densifica con 200 giros, con 1.25 grados de inclinación del molde y si se aplica una presión vertical de 200 kPa.Con respecto a la curva Proctor modificada, ésta no se logró obtener para ningún suelo con la combinación de variables estudiadas, al parecer se requiere de una presión vertical mayor a 800 kPa para alcanzar los pesos volumétricos secos de dicha curva. En la investigación también se estudió el efecto del tipo de compactación (dinámica y por medio del compactador giratorio) en el módulo de resiliencia y la resistencia en compresión simple de muestras compactadas en el óptimo, 2% debajo del óptimo y 2% por arriba del óptimo. Los resultados indicaron que ambos parámetros dependen del tipo de compactación cuando las muestras compactadas tienen un contenido de agua inferior al óptimo.

PALABRAS CLAVE: características de compactación, diseño de pavimento, compactador giratorio, módulo de resiliencia, compresión no confinada.

ABSTRACT

The authors present a series of compaction curves obtained in fine-grained soils through use of a gyratory compactor. The effect on compaction curves of variables such as vertical pressure, angle of gyration, and speed of gyration is shown. The curves obtained with the gyratory compactor were compared with those obtained using traditional methods of compaction (Proctor standard and modified compaction). It was observed that the standard compaction curve can be obtained with 200 gyrations, 1.25 degrees of angle of gyration, and a vertical pressure of 200 kPa. On the other hand, with the combination of variables studied in this research, modified compaction curves could not be reached. Tests were also performed to measure resilient modulus and unconfined compression strength on specimens prepared at optimum compaction conditions, 2% below the optimum and 2% above the optimum (for Proctor standard tests) using two methodsof compaction.The results indicate that unconfined compression strengths and resilient modulus are related to the compaction method when samples are compacted at water content below optimum.

***KEYWORDS:** compaction characteristics, pavement design, gyratory compactor, resilient modulus, unconfined compression.*

INTRODUCTION

Quality control of compacted materials has been one of the activities of major importance in the construction of earthwork projects. The process depends on the evaluation of fielddry density which is obtained after the material is compacted. The other parameter of importance is the maximum dry density measuredusing a standard test procedure (e.g., ASTM D698, ASTM D1557, AASHTO T99, or AASHTO T180).Even when standardtest procedures are followed,various authors have pointed out that impact compaction (Proctor tests) does not necessarily reproduce the same soil structure and compaction characteristics as the kneading process associated with field compaction equipment (Parsons et al., 2001; Holtz, 1990;Milberger and Dunlap 1966; Coyle and West 1956). Milberger and Dunlap (1966), and Ping et al.,(2003) stated that stress-strain curves differ ifspecimens are compacted with adynamic process in laboratory or if the curves are evaluated on undisturbed specimens. Lee et al.,(2007) evaluated properties such as unconfined compression, cohesion, and elastic modulus of samples compacted using different compaction methods. They found that specimens taken from field block samples show similar properties to specimens compacted in a gyratory compactor. It is not clear if the properties evaluated on specimens using the gyratory compactor and specimens compacted by traditional methods provide similar mechanical properties. It is important to develop accurate laboratory methods to better simulate the field compaction conditions since the goal of these methods is to adhere as closely as possible to field compaction conditions (Holtz, 1990, Ping et al., 2003).

The gyratory compactor has been shown to more closely simulate the compaction structure of hot asphalt mixes. This has led to the study of machines that better represent the field compaction of soils (Ping et al., 2003, Browne, 2006, Leet et al., 2007). The objective of this study was to evaluate the feasibility and applicability of the gyratory compactor as a means to: i.) evaluate the compaction characteristics of fine-grained soils, ii.) to evaluate the best set of variables to be controlled in the gyratory compactor in order to obtain the Proctor standard and modified compaction curves, and iii.) to compare results of resilient modulus and unconfined strength evaluated on specimens prepared by dynamic or gyratory compaction.

MATERIALS AND EQUIPMENT

Materials

The soils utilized in this study were collected in different regions of the State of Queretaro (Mexico).Index properties such as Atterberg limits (ASTM D 4318-10), specific gravity (ASTM D 854-10), and percent finer than 200 sieve (ASTM D 1140-00) were carried out; compaction properties were evaluated with the ASTM D698-12 and ASTM D1557-12 standards. Table 1 shows the properties of the studied soils.

Gyratory Compactor

The gyratory machine utilized in this research (distributed by IPC global) is a fully automated, servo-controlled, gyratory compactor which densifies the material by the simultaneous action of static compression and shearing action resulting from the mold being rotated through an angle about its longitudinal axis (Servopac manual, 1998). The variables that can be changed for compaction are: vertical pressure, angle of gyration, speed of gyration, and the number of gyrations applied to the specimen. The effect of these variables was studied in this research and the results are presented.

Table 1. *Index properties and compaction characteristics*

Soilclass.	Atterberglimits			G_s	% fines	% sand	Compaction characteristics (ASTM D698-12)		Compaction characteristics (ASTM D1557-12)	
	LL (%)	PL (%)	PI (%)				w_{opt} (%)	γ_{dmax} (kN/m³)	w_{opt} (%)	γ_{dmax} (kN/m³)
CH1	66	25	41	2.61	86.0	14.0	30.0	13.32	20.5	15.70
CH2	69	24	45	2.56	87.0	13.0	33.5	12.60	24.0	14.86
CH3	70	28	42	2.65	79.4	20.6	34.0	12.58	26.5	14.58
ML	44	33	11	2.56	87.0	13.0	32.0	13.00	24.5	14.60
SM	NP	NP	NP	2.52	37.0	63.0	23.5	14.04	19.0	14.17

PROCEDURE TO EVALUATE COMPACTION CURVES WITH GYRATORY EQUIPMENT

Samples of 2300 g of air-dried soil were mixed with a selection of molding water in the range of water contents where standard and modified compaction curves were measured. After water was mixed thoroughly with the soil, it was stored in a plastic bag for at least 16 hours. Following the storage, the compaction mold of the gyratory compactor was prepared by placing several vertical plastic strips around its interior to prevent the soil from sticking and to facilitate the removal of the sample without causing damage. The loose soil (2300 g) was placed into the mold (Figure 1a) and it was lightly tampered to accommodate the entire amount. The mold was then placed inside the gyratory compactor (Figure 1b) and the material was compacted in accordance with the selected combination of variables shown in Table 2.

After compaction, the specimen was extruded from the mold (Figure 1c) and dimensions and mass were recorded. The compacted specimen was then broken up to obtain three representative samples for water content measurement. The water content together with mass and dimensions of the specimen were utilized to determine the dry unit weight of the compacted sample.

EVALUATION OF RESILIENT MODULUS AND UNCONFINED COMPRESSION

Regarding the results of resilient modulus and unconfined compression, all soils were evaluated at optimum water content and maximum dry density (using the Proctor standard test). Only the results of CH1, CH2, and the ML soils are shown in this document due to limited space.

Compaction of Specimens in the Gyratory Compactor

The first step to compact the specimens was to select the variables to be set in the gyratory compactor in order to obtain the required density. The soil specimens were compacted using the following variables:ML and CH2 soils: 20 gyrations/minute, 1.25 degrees of gyration angle, 200 gyrations and 200 kPa of vertical pressure. Soil CH1: 30 gyrations/minute, 1.25 degrees of gyration angle, 100 gyrations and 200 kPa of vertical pressure.

After compaction in the gyratory compactor,the specimen has a height of 10 cm diameter and 20 cm height. It was the next ruded and trimmed to achieve 71 mm diameter and 144 mm height. These are the dimensions of test specimens (Figure 2a, 2b and 2c).The specimens were then measured and weighed before performing the testing.

(a)

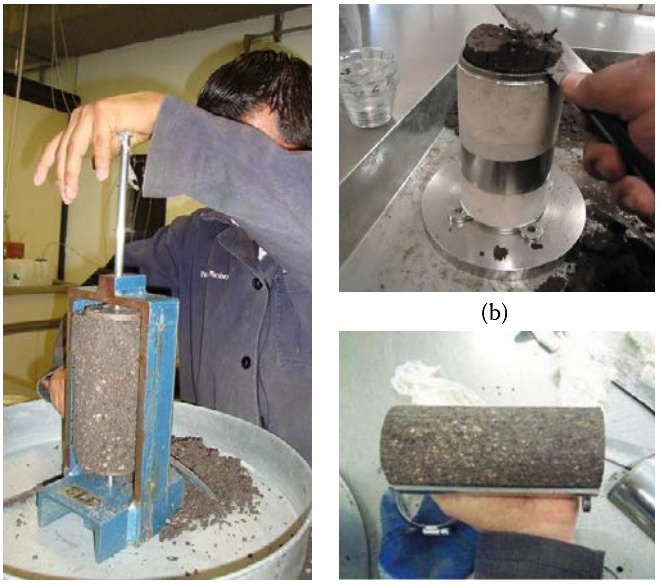
(b)

(c)

Figure 1. (a) Placing the loose soil into the mold; (b) Placing the mold inside the gyratory compactor; and (c) Sample after compaction

Table 2. *Variables studied during the compaction*

Soil Type	Gyration rate, gyrations/minute	Angle of gyration, degrees	Vertical pressure, kPa	No. of gyrations	Replicates for each point
ML	10, 20, 30	1.25	200, 300, 400, 500, 600	500	3
SM	10, 20, 30	1.25	200, 300, 400, 500, 600	500	3
CH1	10, 20, 30	1, 1.25	200, 300, 400, 500, 600	500	3
CH2	10, 20, 30	1, 1.25	200, 300, 400, 500, 600	500	3
CH3	30	1.25	200, 300, 400, 500, 600, 800	500	3

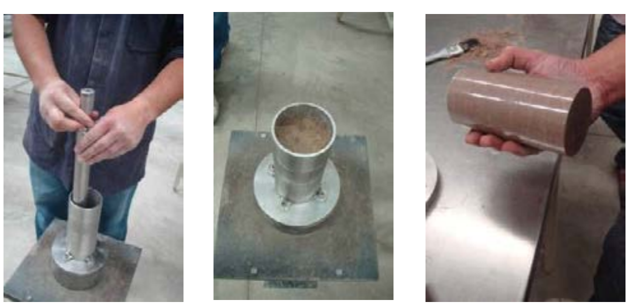


(a) (b) (c)

Figure 2. (a) Trimming the sample (dimensions after compaction: 100 mm diameter and 200 mm height); (b) The trimmed sample is placed inside a mold that has144 mm height; the excess material was trimmed off; and (c) Sample of 71 mm diameter and 144 mm height.

Samples Dynamically Compacted

The soil was mixed with a specified amount of water in order toachieve the desired water content (optimum water content condition, 2% below optimum, or 2% above optimum). The material was then allowed to cure overnight in a sealed plastic bag. The mass of the soil required to attain the specified dry unit weight was weighed and compacted into the split mold (71 mm diameter and 144 mm height) in eight layers with a rammer of 1 kg mass and dropped from a height of 30 cm (Figure 3a and 3b). The number of drops was calculated such that the maximum dry unit weight was achieved for each compacted layer of soil. After the final lift was compacted, the specimen was trimmed to give a uniform surface.The sample was separated from the mold (Figure 3c), weighed and measured.



(a) (b) (c)

Figure 3. (a) Compaction with a rammer of 1 kg mass; (b) Specimen after the last layer was compacted; and (c) Specimen of 71 mm diameter and 144 mm height.

RESILIENT MODULUS TESTING

The resilient modulus tests were conducted in accordance with the NCHRP 1-28A test protocol for subgrade materials. The tests consist of applying a cyclic-haversine shaped load with duration of 0.2 seconds and a rest period of 0.8 seconds. During the test, 16 sequences involving different states of stress were applied. In each sequence, 100 load cycles were applied at a frequency of 5 Hz; the last five cycles of each sequence were recorded and used to determine the resilient modulus, with the exception of sequence zero which is used as precondition of the soil sample.

UNCONFINED COMPRESSION TEST

The unconfined compression tests were performed in accordance with the ASTM D 2166-98a standard. The specimens were placed in a load frame and loaded at a rate of 1.2%/min. After the maximum load was reached, the soil specimen was broken up to give representative samples for water content measurements. The maximum value of compressive stress was reported as the unconfined compression strength.

DISCUSSION OF RESULTS

Unit Weight of Compacted Samples in the Gyratory Compactor

Five or six molding water contents were used at each vertical pressure for evaluation of the gyratory compaction curves. At least three replicate specimens were compacted at each molding water content. It should be noted that the gyratory compaction equipment does not directly report the dry unit weight of the soil, it was calculated by taking into account the height of the specimen (which was reported for every gyration), the diameter and mass of the specimen, and the water content which was determined at the end of the compaction test.

Figure 4 shows an example of the densification curves of three replicate specimens.This figure indicates that there are just small differences in the replicate specimens at the beginning of the compaction process. After 50 gyrations, all specimens tend to the same dry unit weight.The dry density at gyration 500 and the mean value of the three water contents were used to draw the compaction curves.

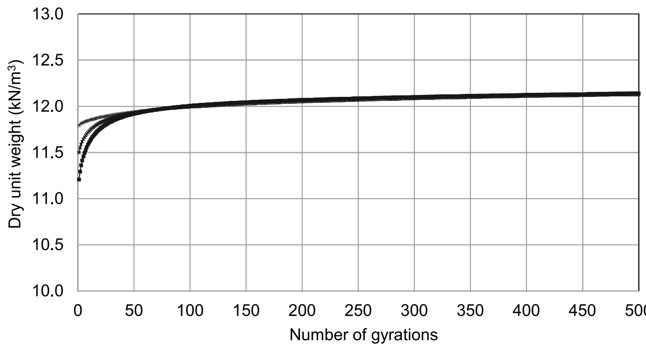


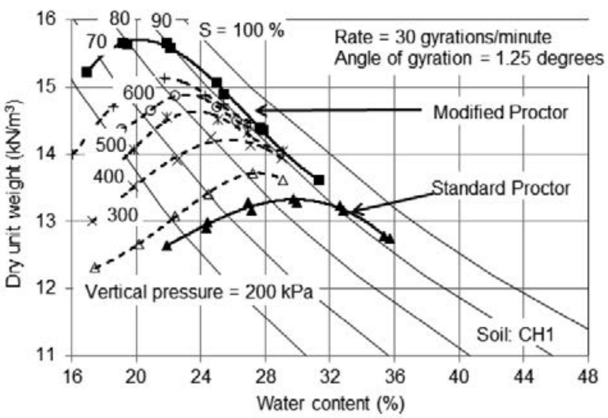
Figure 4.Evolution of dry unit weight during the compaction process

Proctor and Gyratory Compaction Curves

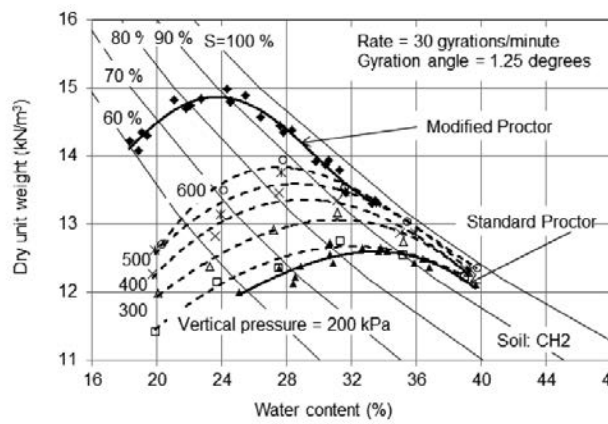
Figure 5 shows examples of the results of compaction curves obtained utilizing a rate of 30 gyrations/minute and a gyration angle of 1.25 degrees. The Proctor standard and modified compaction curves are shown for comparison purposes. From this figure it is observed that the standard compaction curve can be obtained with a particular combination of variables (e.g., 30 gyrations/minute, 1.25 degrees of angle of rotation and approximately 200 kPa of vertical pressure), for the case of CH and ML soils (Figure 5b, 5c and 5d). However, for the SM soil, the compaction curves do not show the typical trend once the water content came close to the optimum water content (Figure 5e). The dry unit weights continued to increase even when the compaction water content was increased. This is likely due to the loss of water during the compaction process (Figure 5f). Figure 5 also indicates that in most cases the modified compaction curve was never reached. The exception was soil CH3 where a vertical pressure of 800 kPa provided a compaction curve close to that of the modified compaction energy (Figure 5c).

Variables that Influence the Evaluation of Compaction Curves with Gyratory Compaction

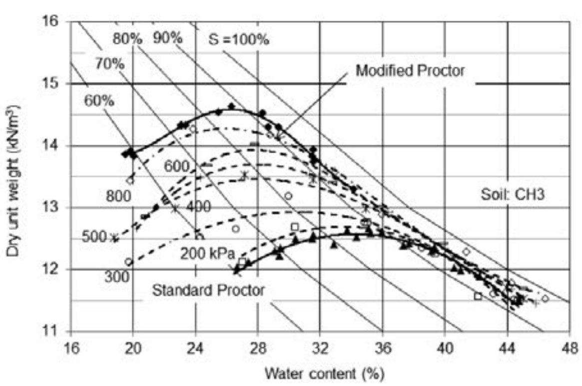
Numerous variables can be varied to compact soil when using the gyratory compaction equipment. The following sections illustrate the effect of vertical pressure, angle of gyration, rate of compaction, and the number of gyrations.



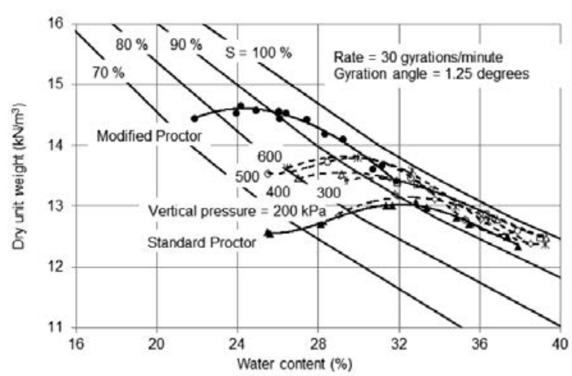
(a) Soil CH1



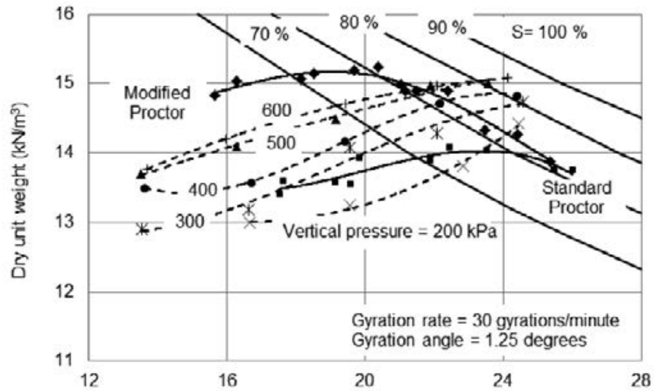
(b) Soil CH2



(c) Soil CH3



(d) Soil ML



(e) Soil SM

(f) Compacted sample at high molding water content

Figure 5. Compaction curves of tested soils and flow of water from sandy soil

Number of gyrations

The rate of change of the dry unit weight of the specimen is important during the first 50 or 100 cycles, however, eventually there is number of gyrations after which dry unit weight does not increase further. Thus, it can be concluded that compaction time can be reduced if samples are compacted with 100 gyrations (Figure 4).

Rate of gyration

The rates of gyration investigated in this research study were 10, 20, and 30 gyrations/minute. Figure 6 (corresponding to the CH2 soil) showsthat the velocity of compaction has a slight effect on the dry unit weight when compaction is on the dry side on the compaction curve. The velocity of compaction does not appear to have an influence on the wet side of optimum; this result is also observed in a plot of dry unit weight obtained for two different rates. The R^2 values are close to 1, which indicates that both rates of compaction provide similar results (Figure 7). The curves presented correspond to soil CH2, however, analogous behavior was observed for other soils (CH1, ML, and SM).It can be concluded that the soil can be compacted with 30 gyrations/minute(i.e., the largest rate studied) which will speed up the process.

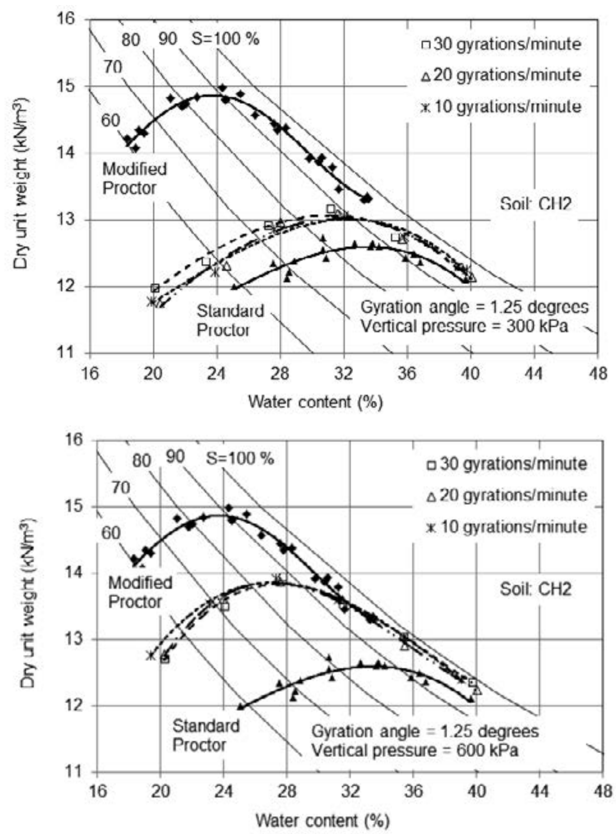


Figure 6. Effect of gyration rate on compaction curves

Angle of gyration

The effect of the angle of gyration was studied for 1 and 1.25 degrees. For this variable, even when the change was not large, it is observed that an increase in this parameter produced slight differences in the compaction curve at 200 kPa of vertical pressure (Figure 8a). However, for larger vertical pressures, the angle of gyration seems to have a more pronounced effect. The results indicate that the compaction energy can also be augmented by increasing the gyration angle (see Figure 8b, c, and d).

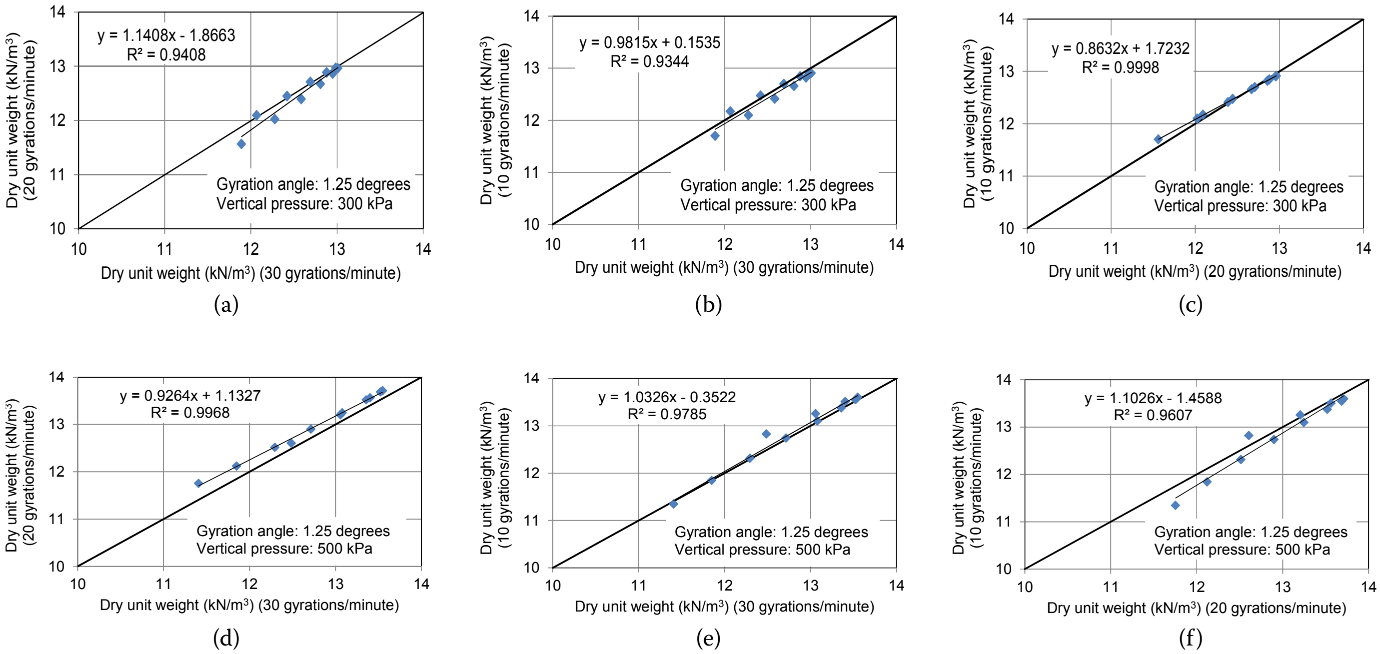


Figure 7. Comparison of dry unit weights evaluated at three different rates of gyration

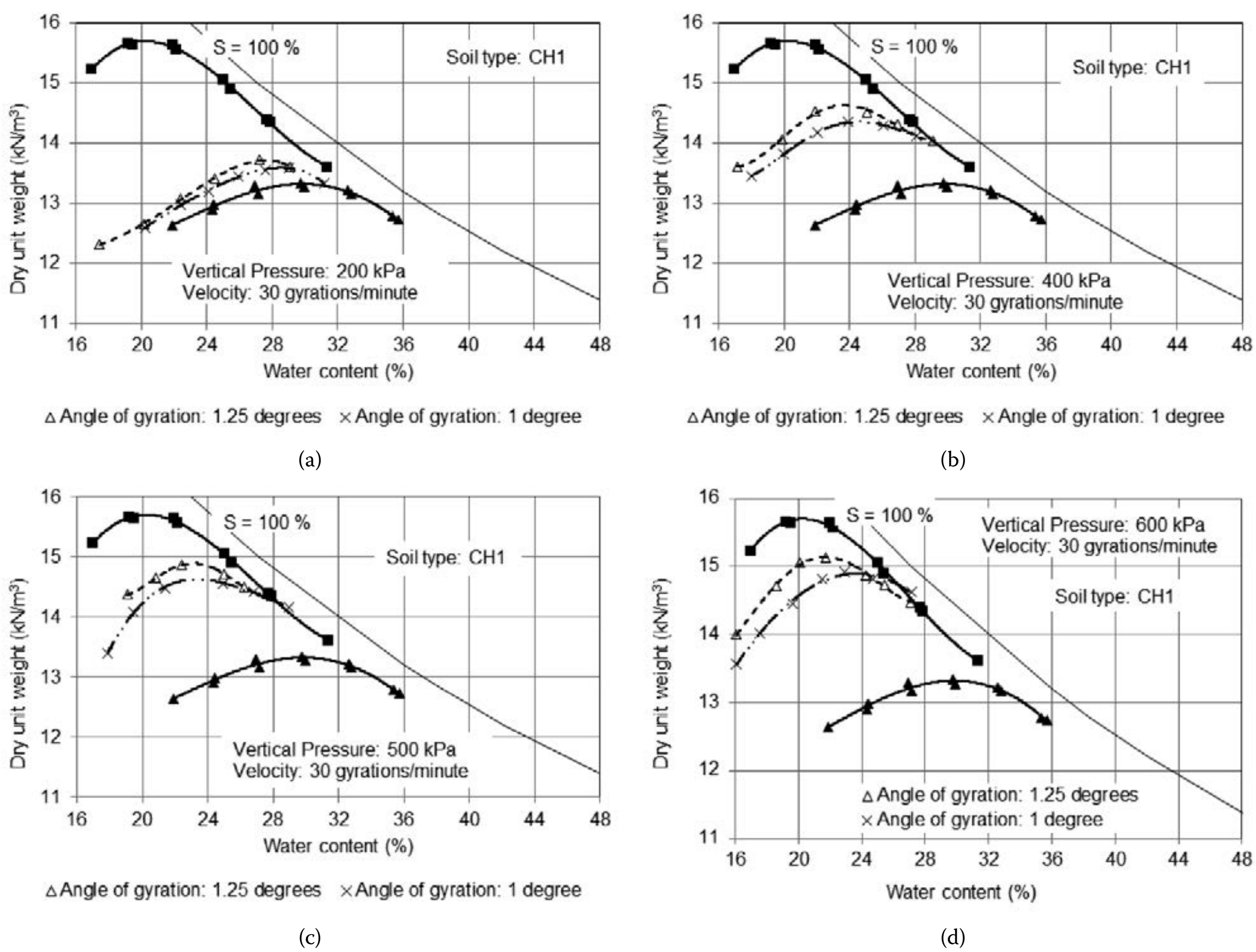


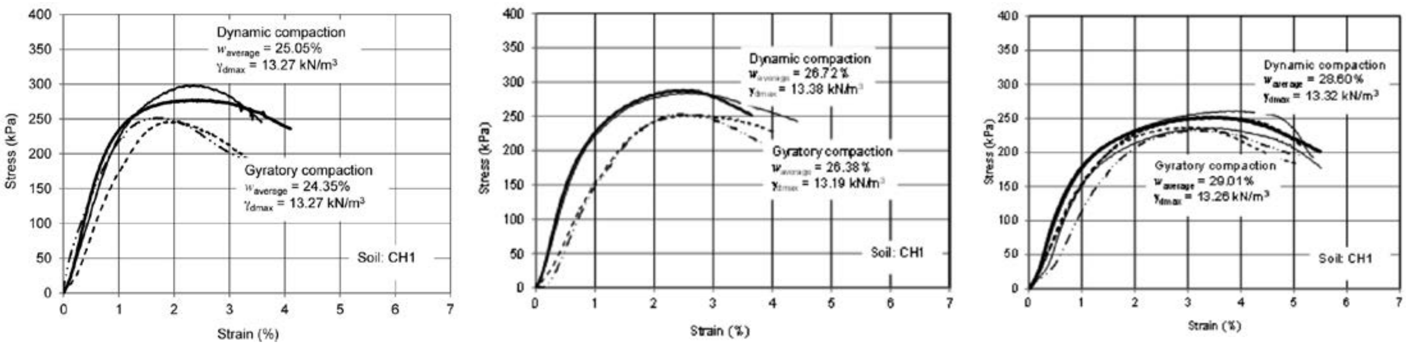
Figure 8. Effect of angle of gyration on compaction curves

Comparison of Mechanical Properties

Unconfined Compression

Results from unconfined compression tests reveal that stress-strain curves of specimens compacted in the gyratory compactor for optimum water content and dry of optimum were always below to those compacted using dynamic compaction (Figure 9a and b). This may indicate that the gyratory compactor produces a loose structure which contributes to a lower strength. To verify this hypothesis, some compacted samples in the gyratory compactor were broken up and some subsamples were taken at the top, medium and bottom to measure the respective unit weights (Figure 10a). The results indicated that indeed, unit weight in the middle of the sample is lower than that obtained at bottom and top section of the sample (Figure 10b). It is likely that samples of considerable length (20 cm length) may not be uniformly compacted when the material is densified in one layer.

Figure 9c indicates that samples prepared above optimum water content have similar strengths regardless of the compaction method. Similar results were obtained for ML and CH2 soils.



(a) 2% dry of optimum (b) At optimum water content (c) 2% wet of optimum

Figure 9. Unconfined compression tests for CH1 soil

(a)

Sample No.	Mass, g	d_{prom}(cm)	h_{prom}(cm)	γ_m(kN/m³)	Subsample No.	γ_m(kN/m³)	$\gamma_{m\ average}$(kN/m³)	SD (kN/m³)	Position of subsamples
3	2291	10.14	19.85	14.02	1	14.38	14.27	0.11	Top
					2	14.26			
					4	14.16			
					1	13.06	12.97	0.17	Medium
					2	12.77			
					4	13.07			
					2	13.78	14.18	0.51	Bottom
					3	14.75			
					4	13.99			
4	2289.5	10.14	19.92	13.96	1	13.54	13.55	0.02	Top
					2	13.58			
					3	13.53			
					1	12.34	12.34	0.05	Medium
					2	12.39			
					3	12.29			
					1	13.10	13.42	0.67	Bottom
					2	14.34			
					3	12.79			
					4	13.45			

(b)

Figure 10. Measurement of volume to determine unit weight; (b) Measurements of unit weight of compacted sample and subsamples

Resilient modulus

Figures 11a through 11c show the resilient modulus results for the ML soil. These plots reveal that the resilient modulus values of dynamically compacted and gyratory compacted specimens vary some what when compacted below optimum. However, when they are prepared at optimum or above this value, the resilient modulus values are more similar for both methods of compaction.

Results for CH2 soil also indicate that this parameter depends on compaction type (Figure 11d and e). The values of this soil agree with the suggested behavior obtained in unconfined compression which indicates a looser structure for samples from the gyratory compactor.

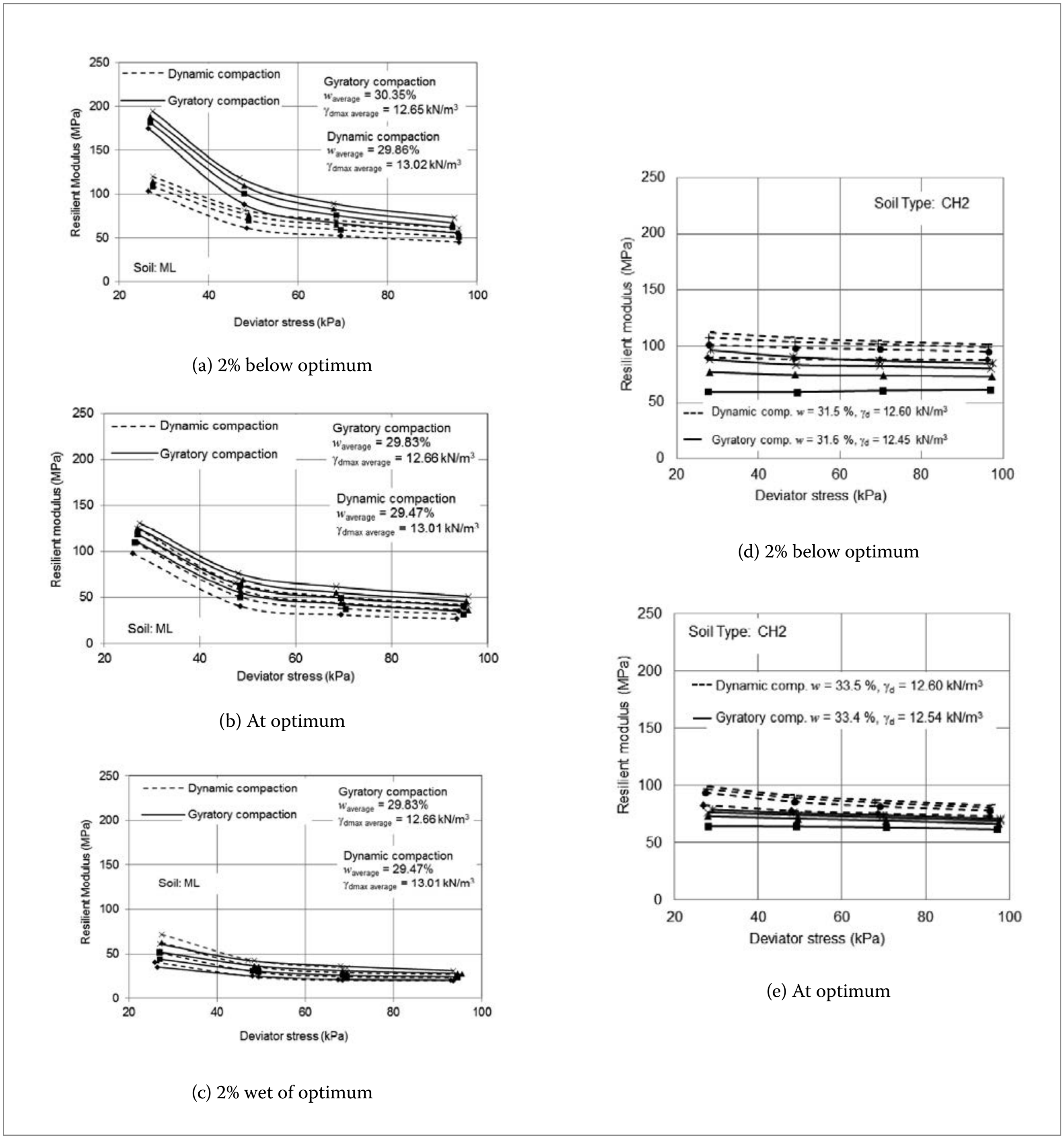


Figure 11. Resilient modulus test results for ML and CH2 soil

CONCLUSIONS

The laboratory research study shows that the gyratory compactor shows promise as a device that can be used to measure compaction curves. However, it is important to assess the proper combination of variables that correspond to required compaction conditions. One of the advantages of the gyratory compactor is that the specimens produced can be directly used to determine stress-strain relationships. The specimens obtained from the gyratory compactor canhave a height/diameter ratio of 2, butif this is not the case, it is possible to trim the specimens to the proper dimensions; however, care should be taken to ensure consistent unit weights along the length of the specimen. The gyratory compactor is an automated machine, thus the operator can preset each of the variables on the compactor and this can lead to specimens with less variation. The dynamic compaction procedure is manual and can result in human errors. It was found that unconfined compression strength measurements were lower for specimens compacted using the gyratory machine when the water contents were at optimum and 2% below optimum. When the compaction water content was 2% above optimum, the unconfined compression strengths were similar. The resilient modulus values are affected by the compaction method when the material was compacted below optimum water content while the values are similar when the samples are compacted above optimum. It was noted that the CH2 resilient modulus values for samples compacted in the gyratory machine were lower, which indicates a more deformable soil. This behavior agrees with the response observed in the unconfined compression tests.

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