Behavior of fine-grained soils compacted with high shear stresses

Comportement des sols fins compactés avec des niveaux de cisaillement élevés

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ABSTRACT: One of the parameters used to carry out the quality control of unbound compacted fine-grained materials is the maximum dry unit weight obtained from a Proctor standard or modified test. However, these tests are far from simulating the field compaction mechanism produced by the sheep foot roller equipment. Lately, the gyratory compactor has been put forward as a new laboratory equipment to determine the compaction curves. This paper shows results of Proctor and modified compaction curves as well as the ones obtained from the gyratory compactor. The new method of compaction was evaluated for three soils classified as CH, ML and SM. The controlled variables in the gyratory compactor were the gyration angle, the vertical pressure, and the number of gyrations. The results showed that the optimum water content is reduced as the vertical pressure increases and the opposite happens with the dry unit weight. In addition, it was observed that the Proctor compaction curve is obtained with a vertical pressure of 200 kPa and around 200 gyrations regardless the soil type. On the other hand, it seems that the compaction curves are similar disregarding the rate of gyration and gyration angle.

RÉSUMÉ : Un des paramètres classiques utilisés pour le contrôle de qualité des sols fins compactés non traités est le poids volumique sec obtenu dans l'essai Proctor, standard ou modifié. Cet essai est cependant loin de simuler les mécanismes de compactage in situ produits par des équipements tels que les rouleaux à pieds dameurs. Récemment, le dispositif de compactage giratoire a été mis en avant, en tant que nouveau dispositif de laboratoire pour la détermination des courbes de compactage. Cette communication présente une comparaison des courbes de compactage obtenues aussi bien avec les essais Proctor qu'avec le dispositif giratoire, pour lequel les influences de paramètres tels que la pression verticale, l'angle de giration et le nombre de girations ont été évaluées pour des sols de classe CH, ML et SM. Une discussion est ensuite proposée, montrant que la teneur en eau optimale diminue avec l'augmentation de la pression verticale, une tendance opposée apparaissant pour le poids volumique sec. On a aussi observé que la courbe Proctor classique est obtenue pour une pression verticale de 200 kPa et environ 200 girations, quel que soit le type de sol. Les courbes de compactage obtenues ne semblent cependant pas dépendre de la vitesse ni de l'angle de giration.

KEYWORDS: gyratory compactor, soil compaction, quality control, Proctor test, compaction curves, pavements, unbound materials.

MOTS-CLÉS : compacteur giratoire, compactage des sols, contrôle de qualité, essai Proctor, courbes de compactage, revêtement routier, matériau non traité

1 INTRODUCTION

Soil compaction is a process which is often used in the construction of almost every single engineering structure. Examples such structures are dams, the approaches of bridges, mats for buildings, airports, pavements, etc.

To carry out the quality control of the compacted materials it is necessary to count with two parameters, that is to say, the field dry unit weight and the maximum dry unit weight obtained in a laboratory test which can be Proctor standard or modified (this paper is focused in the evaluation of lab maximum dry unit weight).

To evaluate laboratory properties (i.e. the dry unit weight, resilient modulus, unconfined compression, etc), it is paramount that the test specimens possess as far as possible the same structure that the soil will have in field. The evaluation of the maximum dry unit weight and optimum water content of fine-grained soils with test as the Proctor standard and modified test is an example of an inconsistency between field and lab structure. The field equipment for these cases are the sheepfoot roller which compacts the soil from bottom to top while in the Proctor standard test the soil is compacted by impacts, thus, it is expected to obtain different soil structures. On the other hand, Ping et al. (2003) have found that the field and laboratory compaction curves are completely different. Thus, as a consequence, some researchers (Ping et al., 2003;Milberger y Dunlap, 1996; Mokwa et al., 2008, etc.) have put forward the gyratory compactor as a new equipment to determine the laboratory compaction curves.

In this paper, the compaction curves were obtained with the gyratory compactor and then they were compared with the standard and modified compaction curves. In addition, it was studied the effect on the compaction curve of variables as the vertical pressure, the angle of gyration and the number of gyrations. The procedures, equipments and results are described in the following paragraphs.

2 GYRATORY COMPACTOR

Compaction in this equipment is achieved by the application of vertical stress to a known mass within a mold of 100 or 150 mm internal diameter. The longitudinal axis of the mould is rorated (gyrated) at a fixed angle to the vertical while the platens are kept parallel and horizontal. During the compaction the height of the sample is automatically measured and the mixture density is calculated. The operator can choose whether to compact to a certain number of gyrations, a certain height or until a target density(http://www.cooper.co.uk).It is important to mention that even this equipment was designed to compact specimens of asphalt mix, lately it has been utilized to compact fine-grained and granular soils.

3 TEST SOILS

During this research it was collected a series of samples classified as clay (CH), silt (ML) and sand (SM) (Figure 1).

(a) (b) (c)

Figure 1. Places from where the soils were sampled. (a) Silt (ML); (b) Sand (SM); and (c) Clay, CH.

The index properties of the soils are listed in Table 1 and the compaction characteristics obtained from Proctor and modified tests are summarized in Table 2 (Figure 2 a 4).

Table 1.Index properties of the test soils.

Soil Type	Atterberg limits			% passing 200 sieve (%)	G_s
	LL (%)	PL (%)	PI (%)		
CH	66	25	41	85.7	2.61
ML	44	33	11	87.0	2.56
SM	NP	NP	NP	37.0	2.52

Table 2.Compaction characteristics.

Soil type	Standard effort (ASTM D698)		Modified effort (ASTM D 1557)	
	w_{opt} (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	γ_{dmax} (kN/m^3)
CH	30.0	13.32	---	---
ML	30.5	13.33	24.5	14.59
SM	23.54	14.04	19.0	15.17

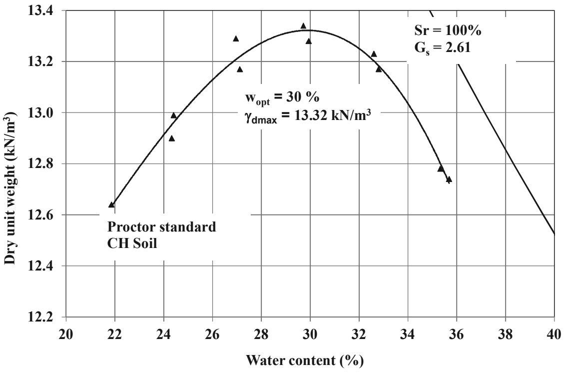


Figure 2.Compaction curve of the CH soil.

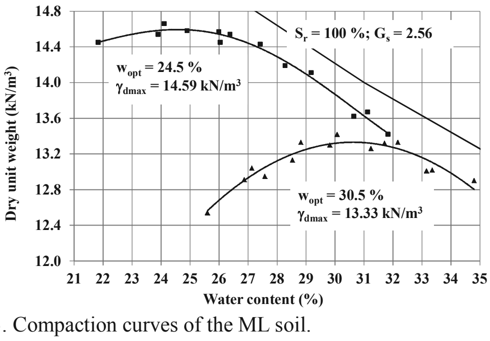


Figure 3. Compaction curves of the ML soil.

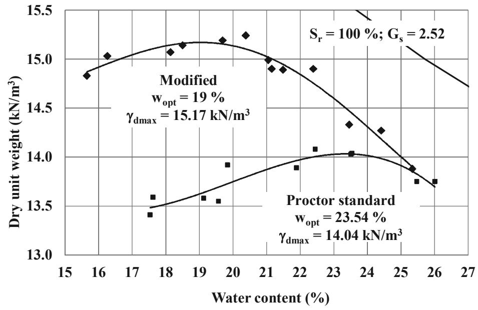


Figure 4. Compaction curves of the SM soil.

4 TEST PROCEDURES.

4.1 Compaction curves. Proctor standard and modified (ASTM D698 and ASTM D 1557)

To obtain the standard and modified compaction curves, the ASTM procedures were followed (ASTM D698 and ASTM D1557). From these procecdures, the method A was utilized in both cases since all material tested passed sieve number 4.

4.2 Compaction curves. Gyratory compactor

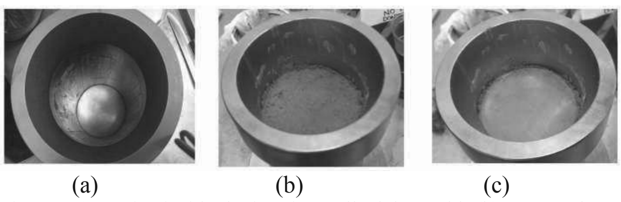
As was mentioned in previous paragraphs, in this equipment the operator can control variables such as: vertical pressure, angle of gyration, height of specimen, density, etc. In this study, the controlled variables were as follows:

- Vertical pressure: 200, 300, 400, 500, and 600 kPa.
- Angle of gyration: 1 and 1.25 degrees
- Number of gyrations: 500
- Rate of gyrations: 10, 20 and 30 gyrations/min
- Soil type: 3
- Mass of compacted soil: 2300 g

Once the soils were gathered, the material larger than No. 4 sieve was discarded. The material passing was allowed to dry at environmental conditions and subsequently itwas mixed throughly and then stored in sacks.

For all three soils, the procedure followed to evaluate the compaction curves was as follows:

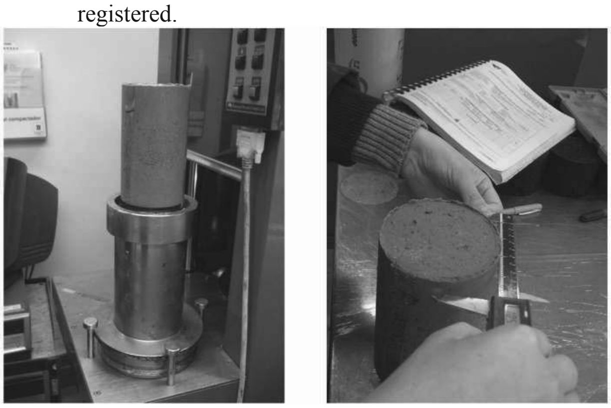
1. 180 soil samples of 2300 g of dry soil (of each soil type) were weighted so that to cover all the combinations of the variables to be controlled (5 vertical pressures x 2 angles of gyration x 3 rates of gyration x 1 sample at each point x 6 points on the compaction curve).
2. Different amounts of water were added to each sample so that to cover the range in which the modified and standard tests were found (to develop each curve, six points were considered).
3. The soil samples were stored during 24 hours.
4. An amount of 2300 g of wet soil was placed inside the compaction mold (Figure 5b and 5c), but previously some plastic strips were placed on the interior wall of the mold so that the soil did not stick and the sample could be extracted (Figura 5a). In addition, another plastic circle was placed on top of the soil so that it did not stick against the top compaction platen.



(a) (b) (c)

Figure 5.(a) Strips inside the interior wall of the mold; (b) 2300g of wet soil were placed in the mold, and, (c) A plasticcirclewas placed on top of the mold for the soil not to stick to the compaction platen.

5. The mold was placed inside the machine (SERVOPAC). It was programmed to compact the soil at a required angle of gyration, vertical pressure and 500 gyrations.This step was repeated for the 180 samples of each soil type.
6. After the sample was compacted at 500 gyrations, it was extracted. The dimensions and weight were taken and registered.



(a) (b)

Figure 6.(a) Ejection of the compacted sample; (b) the dimensions of the sample were taken.

7. In the final step the sample was taken apart to obtain samples to determine el water content.
8. With data of water conent, height of the specimen and dimensions, the dry unit weight was calculated at every gyration. A typical plot obtained for every single sample is ilustrated in Figure 7.

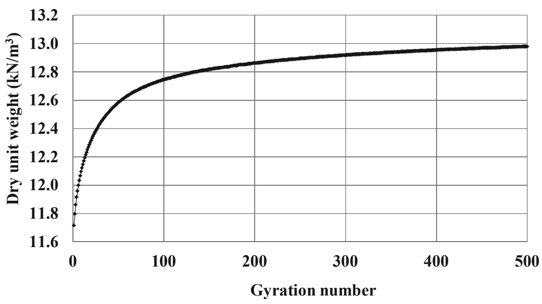


Figure 7.Typical plot of dry unit weight versus gyration number

From Figure 7 data at 100, 200, 300, 400, and 500 gyrations were taken to plot the compaction curves.

5 DISCUSION OF RESULTS

5.1 Compaction curves from gyratory compactor

Figure 8, 9 and 10 illustrates the compaction curves obtained at different vertical pressures, 1.25 angle of gyration, 10 gyrations per minute and for each soil type. The dry unit weight plotted in these figures was taken at gyration number 500.

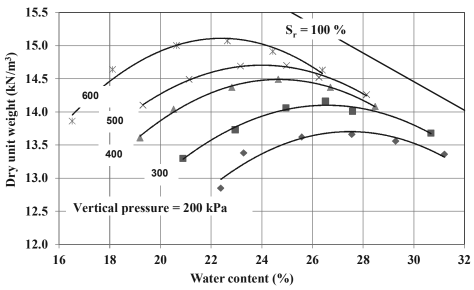


Figure 8. Compaction curves for CH soil.

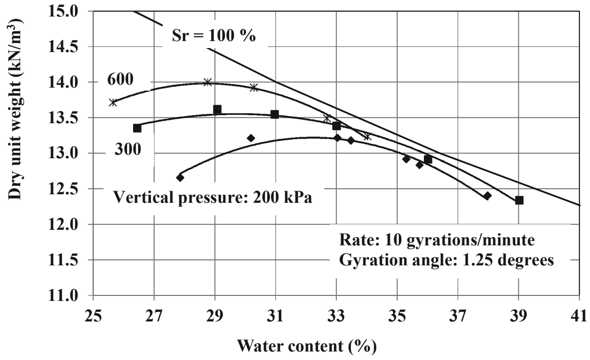


Figure 9. Compaction curves for ML soil.

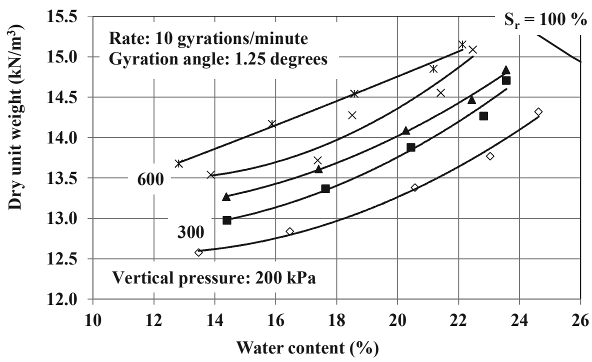


Figure 10. Compaction curves for SM soil.

As can be noted from Figures 8, 9 and 10, the dry unit weight increases and the optimum water content is reduced as the vertical pressure increases, however, this trend is clear for the CH and ML soil. On the other hand, for the SM soil, the dry unit weight increases, but for water contents larger than the optimum of the Proctor standard test, the material cannot be compacted because water starts to flow out of the mold. For this reason, the compaction curves do not show the maximum dry unit weight that can be observed in the standard compaction curve obtained by impacts.

5.2 Effect of different variables on the compaction curve

5.2.1 Gyration number

In Figures 8 to 10 the value of dry unit weight that was plotted was calculated at gyration number 500, however, for each compacted sample, it was obtained a curve of gyration number versus dry unit weight. Thus, to detect the effect of the number of gyrations, some of the compaction curves were plotted on the compaction space together with the standard and modified curves (Figure 11). As seen from this figure and also from Figure 7, the mayor change in the dry unit weight is noted in the first 100 or 200 cycles. For further gyrations, there is only a slow change in dry unit weight. Thus, it can be concluded that the soil can be compacted with 100 or 200 gyrations.

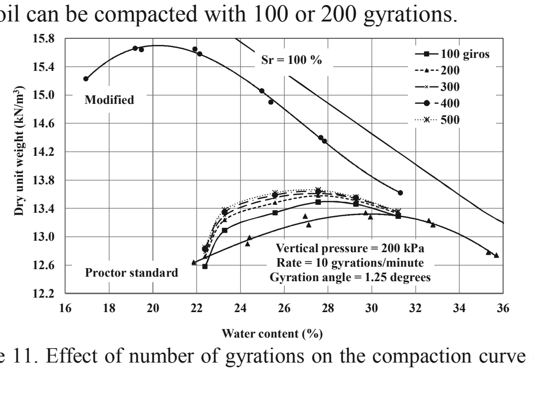


Figure 11. Effect of number of gyrations on the compaction curve (CH soil).

From Figures 8 and 11 it is also clear that to compact material in field, a heavy equipment is more effective than to apply many passes of a light one.

5.2.2 *Gyration angle*

The data obtained in this study indicates that the compaction curve is independent of the gyration angles, at least for the two gyration angles studied (Figure 12).

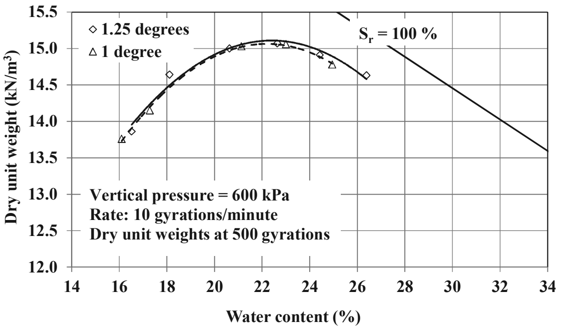


Figure 12.Effect of gyration angle (CH soil).

5.2.3 *Gyration angle*

The data obtained in this study indicates that the compaction curve is independent of the gyration rate, at least for the three gyration rates studied (Figures 13, 14 and 15). Thus, for practical purposes it is convenient to carry out the tests at the highest velocity tested in this study.

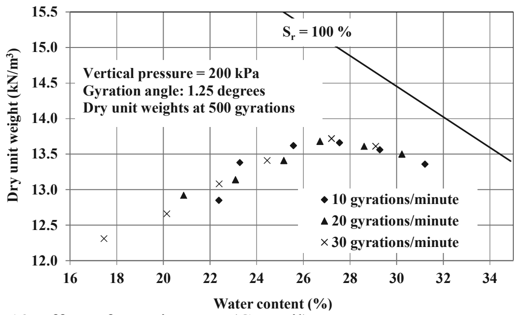


Figure 13.Effect of gyration rate (CH soil).

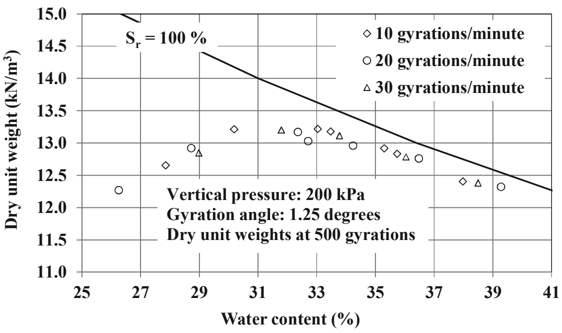


Figure 14.Effect of gyration rate (ML soil).

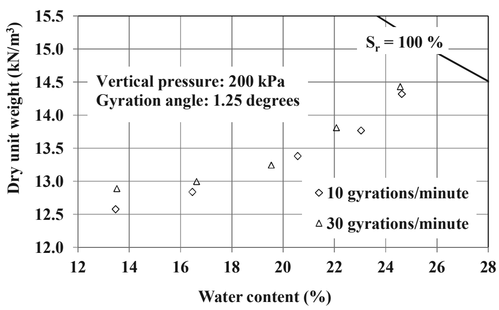


Figure 15.Effect of gyration rate (SM soil).

5.3 *Shear stresses from gyratory compaction*

The data registered during the compaction in the gyratory compactor not only includes the height of the specimen, the vertical pressure and the gyration angle, it also contains the shear stress developed during the whole process of compaction. Figure 16 shows an example of the magnitude of the shear stresses that can be developed during the process of compaction of a claywith 600 kPa of vertical pressure.

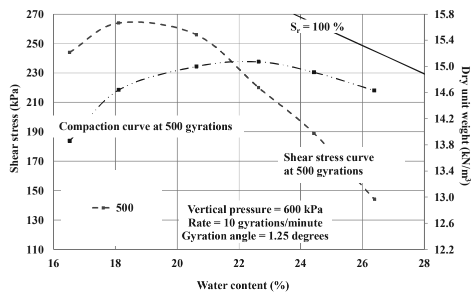


Figure 16.Shear stress curve for CH soil (600 kPa of vertical pressure).

From Figure 16 it can be observed that the shear stress tends to increase when the compacted soil is on the dry side of the compaction curve, however, close to the optimum, the shear stresses are reduced. It was expected because as the water content increases the contacts between grains are reduced and as a consequence the shear stresses are reduced.

6 CONCLUSIONS

The study of the behavior of compacted soils is of paramount importance becuase this kind of material is involved in the construction of almost all civil engineering structures. Its quality control has been determined by the evaluation of two parameters, that is to say, the field and laboratory density. To evaluate the second one, the standard or modified Proctor tests have been in use long time ago, however, these test are far from developing the same soil structure provided for example for a sheepsfoot roller which are utilized to compact fine-grained soils. For this reason, the gyratory compactor has been put forward as a new lab equipment to determine the standard and modified compaction curves. This paper presented a series of compaction curves developed in this equipment. It was observed that there are a series of combinations of variables that can be controlled in the gyratory compactor to obtain the standard compaction curve. On the other hand, the compaction curves seems to be independent of variables as the gyration angle and the gyration rate, at least for the two gyration angles studied and the three velocities. In addition, it is clear that to increase the dry density of a soil, it is more effective to utilize heavy equipment that many passes of a light one.

7 REFERENCES

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