Effect of stress level on permanent deformation for fine-grained compacted soils and the re-evaluation of the natural proportionality model

Effet du niveau de contrainte sur la déformation permanente des sols fins compactés et réévaluation du modèle de proportionnalité naturelle.

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ABSTRACT

One of the frequent distresses on the roads is rutting or permanent deformation cumulated on the pavement surface. Once the permanent deformation reaches certain level, the quality of the ride will decrease greatly and the operation costs will increase. The authors have presented some researche relative to permanent deformation and resilient modulus mainly for clayey soils. This paper presents results on permanent deformation obtained from compacted samples of a silty soil (ML).The results show how the accumulation of permanent deformation is influenced if the load is applied in steps or if the maximum stress level is applied. It is discussed the practical implications in pavement construction. Finally, some curves of permanent deformation of the same soil are used to demonstrate the suitability of the natural law model to fit experimental data. It is suggested that permanent deformation in subgrade soils can be limited if the stress level is controlled during compaction.

RÉSUMÉ

Il est connu qu'un des endommagements les plus fréquents des chaussées est l'orniérage ou déformation permanente cumulée à la surface de roulement. Une fois que cette déformation dépasse un certain seuil, la qualité de roulement se voit fortement affectée et induit une augmentation des coûts opération de la voie. Les auteurs ont déjà présentés des résultats des recherches sur la déformation permanente et le module de résilience des sols fins. Dans ce travail on présent les résultats des essais de déformation permanente sur des sols limoneux (ML). Les résultats montrent que la cumulation de la déformation permanente est largement dépendent de la amplitude et la séquence du chargement répété. On discute les implications pratiques dans la construction des chaussées. Finalement, il montre comment quelques courbes de l'évolution de la déformation permanente peuvent servir à la calibration d'un modèle de proportionnalité naturelle qui peut s'avérer très puissante. Il est avancé que la déformation permanente des sols compactés peut être fortement limitée par le contrôle du niveau de contrainte appliquée par le matériel de compactage.

Keywords : rutting, permanent deformation, stress level, natural law model, distress

1 INTRODUCTION

It is well known that one of the main distresses that appears on the surface of the pavement is rutting. This distress together with fatigue cracking are the ones which control pavement design. As a matter of fact, to calculate the thickness of the layers that constitute the structure, it is necessary control rutting, fatigue cracking, thermal cracking, etc., at certain values that can be tolerated, that is to say, the user can ride in a confortable way.

It is frequent that once a new pavement is opened to traffic, the surface starts to show some types of distresses. The question is ¿Was the pavement designed for the real conditions or not? The answer involves the analysis of many factors, for example, it could be a bad quality control of the compaction process, the quality of materials was innapropiate, the traffic level of design was underestimated, and so on.

The above issues have lead the researchers into finding new ways to avoid the appearance of rutting, cracks and other distresses on the pavement surface at least during the design life. Needless to say that rutting is the cumulative deformation of all the layers (hot asphalt mix, base, subbase and roadbase), however, depending on the mechanical behavior of the materials that constitute each layer, some of them will deform more than the others.

Some of the ways that have been used to solve the problem are the stabilization of the materials with lime, fly ash, polymers, and so forth. In spite of making use of all these techniques, the engineer needs to face the appearance of distresses on the surface and sometimes this needs to be soon after the new pavement has opened to traffic as stated before.

On the other hand, there is one issue that sometimes is left aside during the construction of any highway. This is the quality control during the construction, more specifically, the compaction process. The control usually involves making a sand cone test on the surface of a material that has already been compacted at some specified dry density and water content. This means that the only factor which controls the percent compaction can be the dry density even if water content is shown to be more important. Once the contractor has reached the specified value of density he is allowed to continue placing the next layer. One can ask ¿is dry density the right property for quality control? If not, then, ¿which is a better way to carry out the quality control?

An overview of the pavement performance shows that as soon as traffic passes over the structure, the deformation starts to appear on the wheel path. The authors of this paper think that if layers of material are compacted with a stress level larger than the applied for the traffic, it is likely that the deformation remain on specified ranges that can be tolerated at least during the design period.

This paper presents a series of deformation tests that show how this parameter is affected when different levels of stress are applied. Most of the test points are located very closely to the standard compaction curve.

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2 TEST SOIL

When building any engineering structure, it is likely that the engineer will face problems with soils that need to be used as a construction material or because the structure needs to be placed on it. Fine-grained soils (high compressibility) pose real problems because of theirs degree of expansion, its collapsibility, etc., so that, this is the kind of soil that is chosen in many research projects.

The soil test for this study is a low compressibility silt sampled at the bus station in Queretaro city (Mexico). The index propeties of the soil are shown in Table 1.

Table 1. Index properties of the test soil

USCS class	Atterberg limits			Compaction characteristics (Proctor Standard)		Pass 200 sieve	Gs
	LL (%)	PL (%)	PI (%)	w_{opt} (%)	γ_{dmax} (kN/m^3)	(%)	
ML	46.5	36.0	10.5	36.5	12.32	92.4	2.66

As a matter of fact, some oedometer tests showed that this soil is collapsible.

3 EQUIPMENT

The equipment used to perform the deformation tests is a GCTS triaxial equipment. The system is capable of developing different tests, for example, consolidation, resilient modulus, unconfined compression, cyclic loading, all of triaxial test types, etc. It is also equipped with the CATS program that allows the user to open several windows during the test process, thus, he can observe the behavior of the ongoing test.

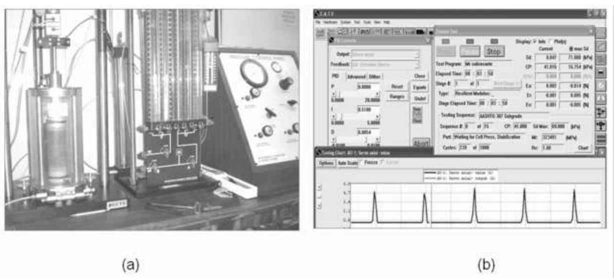

Figure 1. (a) Triaxial equipment; (b) Screen of the CATS program for an ongoing test.

4 SPECIMEN PREPARATION

After the soil was sampled, it was thoroughly mixed and split to obtain representative samples. Then, it was stored in plastic bags for water content to homogenize.

The determination of the initial water content followed the procedure. Based on this value, it was calculated the amount of water to be added to the amount of soil needed for the specimen. Afterwards, the water was sprayed on the surface of the soil, mixed thoroughly and then stored for 24 hours. Finally, the sample was compacted in a split mold in eight layers. The dimensions of the mold are 7.1 cm diameter and 14.4 cm height.

For a certain condition, two similar samples were compacted, because in one the load was applied in one phase (97 kPa of vertical stress and 14 kPa of confining pressure) and the other one was tested at three different levels of load (28, 48 y 97 kPa of vertical stress and 14 kPa of confining pressure).

5 TESTING PROGRAM

The testing program consisted in performing several cyclic tests at different water contents and dry density. Figure 2 shows the location of the test points. As can be seen, most of the test points are located along the standard compaction curve.

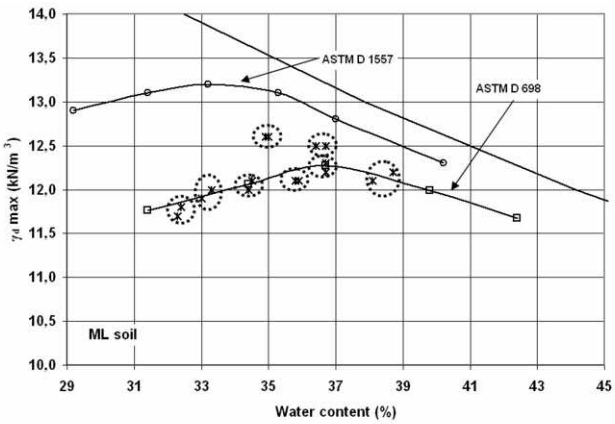

Figure 2. Location of test points.

TEST PROCEDURE

The first step in researching the permanent deformation behavior was to compact the specimens at the desired water content and dry density. Once they were compacted, the diameter and height were taken in order to compute the dry density.

The specimen was then placed in the triaxial chamber and then subjected to 20 000 of a haversine cyclic load, with a 1 hz frequency and a rest period of 0.9 s. The deviator stress and confining pressure were 97 kPa and 14 kPa or 28, 48, 97 kPa of vertical stress and 14 kPa of confining pressure. When the test was done, the specimen is taken out of the triaxial chamber and broken up to take samples for determining the final water content which is the one reported herein.

The confining pressure and deviator stress applied during the cyclic load correspond to the minimum confining pressure and maximum deviator stresses applied in the resilient modulus test, which are thought to be the stress level at subgrade level.

6 PERMANENT DEFORMATION RESULTS

Figure 3 corresponds to the comparison of two samples compacted approximately at the same water content and dry unit weight (w = 36.4 % y 36.7 %; γ_d = 12 kN/m^3). This point is located just up to the optimum water content and maximum dry density, as shown in the inset (see Figure 3).

Analyzing this comparison, it is noted that most of the permanent deformation is developed at the first few cycles and then the acumulation is slowy and stays steady in the last cycles for the sample tested at 97 kPa (load applied in one phase);

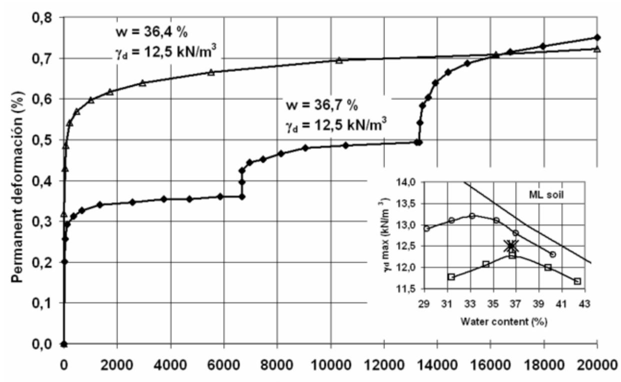

Figure 3. Permanent deformation of two samples compacted under same conditions.

regarding the sample loaded in three phases (28, 48 y 97 kPa), the deformation is still increasing after reaching the 20 000 cycles. In addition, it shows that the final permanent deformation differs slightly respect to the one loaded in one stage.

Another plot with two samples compacted at optimum condition shows that the behavior shown in Figure 3 is repeated, however, the permanent deformation when applying three levels of load is larger and keeps on increasing in the last phase of load application (Figure 4). Thus, it is clear that when the maximum stress is applied since the beginning, the permanent deformation reaches a constant value faster compared to the specimen loaded in three phases.

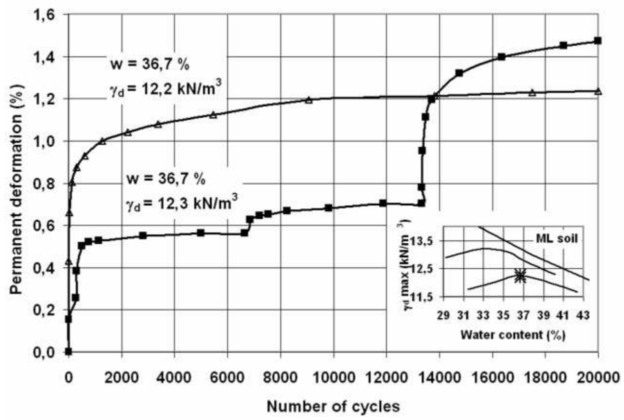

Figure 4. Permanent deformation of two samples compacted at optimum conditions.

On the other hand, two samples compacted in the dry side of the Proctor Standard compaction curve show that the difference in both curves is large (Figure 5). Note that for this case, the permanent deformation curve obtained when the sample is loaded in three steps is below the one loaded with the maximum level of stress, implying that the position of both curves will depend not only in the stress level, but also on the compaction characteristics.

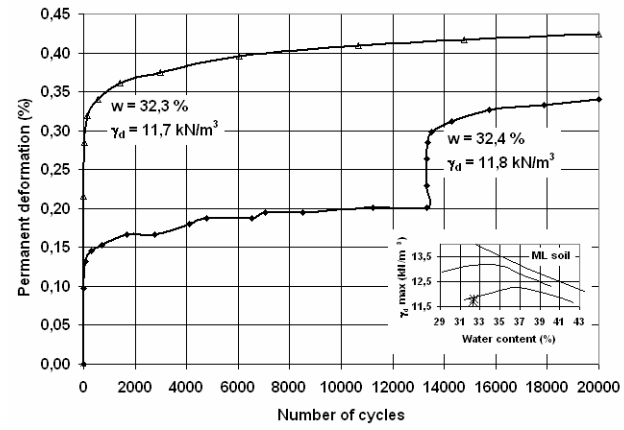

Figure 5. Behavior of two samples compacted in the dry side of the Proctor Standard compaction curve.

The results presented before were samples loaded in one step (97 and 14 kPa) or three steps (28, 48, 97 kPa and 14 kPa). Now, if the sample is loaded in three steps, but starting with the largest level and finishing with the lowest, it can be noted that the deformation obtained once the maximum stress level has been applied does not increase any longer (Figure 6). Thus, the practical implication is: "When constructing a pavement structure, if a stress level larger than that expected in field conditions can be applied with the compaction equipment, such that the permanent deformation is induced in this step of the compaction process, then, after the pavement is opened to traffic, it is likely that the permanent deformation will keep a small value.

In addition to the aforementioned comments, it is important to observe that the curves obtained for the samples loaded with 97 kPa in the first step are very close to each other, implying that the samples are much alike, which is desirable when studying behavior of soils on samples that should be equal.

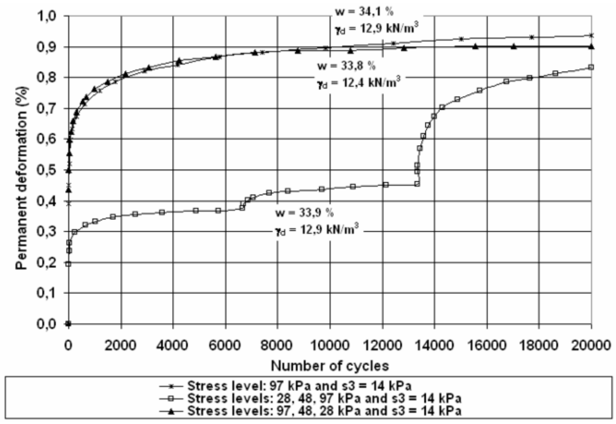

Figure 6. Behavior of permanent deformation on specimens loaded in three fashions.

Figure 6 shows three curves, however, to clarify the effect of loading the specimen beginning with 97, 48 and 28 kPa, it is presented Figure 7 which shows not only permanent deformation, but also the total and recoverable for each step.

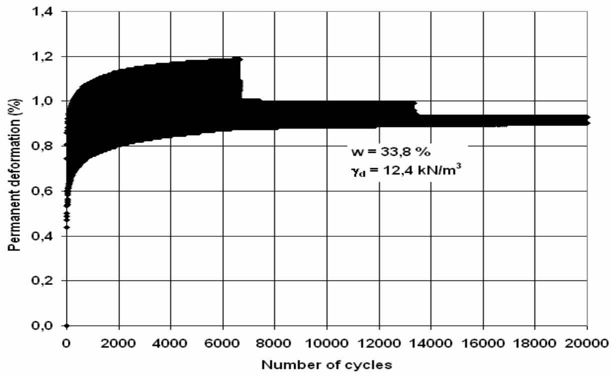

Figure 7. Specimen loaded at 97, 48 and 28 kPa of vertical stress and 14 kPa of confining pressure.

7 NATURAL PROPORTIONALITY MODEL

The authors of this paper have shown that the proportionality law model proposed by Juarez-Badillo (Juarez-Badillo, 1989; Juarez-Badillo, 1995; Juarez-Badillo, 1999) fits very well the behavior of permanent deformation.

Garnica et al., (2000) derived such model for permanent deformation. The equation was as follows:

$$e_a = \frac{e_{af}}{1 + \left(\frac{e_{af}}{e_{a1}} - 1 \right) \left(\frac{N}{N_1} \right)^{-\delta}} \quad (1)$$

Where:
e_a = value of permanent deformation at point in question
e_{af} = final value of the permanent deformation
N = number of cycle at point in question
N_1 = 10 000 cycles for this case
e_{a1} = permanent deformation at 10 000 cycles
δ = Fitting parameter

The verification of the model showed that the equation fitted very well the experimental data obtained for a high compressibility clay classified as CH (Garnica et al., 2000).

Analyzing the same model for the results obtained in this study, it can be observed that the model agrees very closely to the experimental data (Figure 8 and 9). These are only two examples, however, it is important to note that the fitting parameter is similar in both cases, even though the water content and dry unit weight of the samples are different. It is likely that the δ parameter could be the same for one soil type.

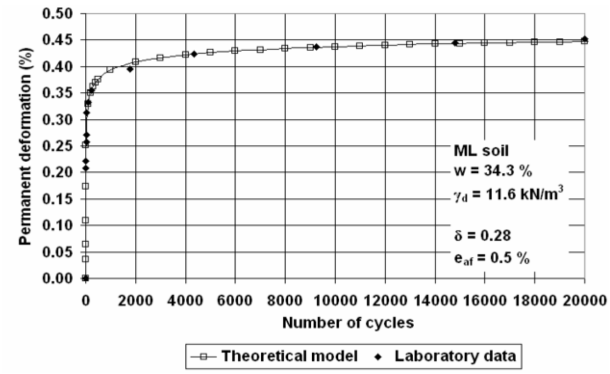

Figure 8. Verification of the proportionality model for a sample compacted at w = 34.3 % and γ_d = 11.6 kN/m^3.

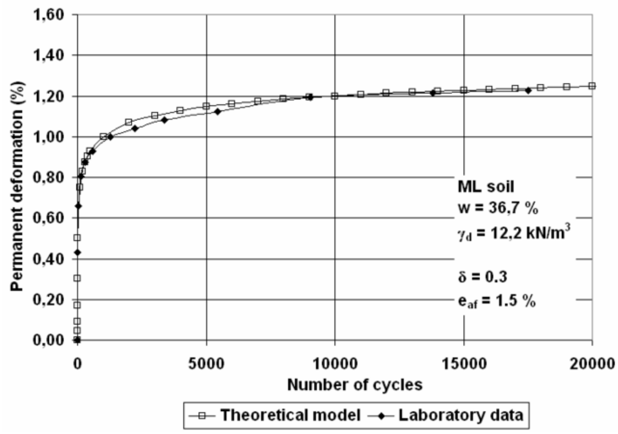

Figure 9. Verification of the proportionality model for a sample compacted at w = 36.7 % and γ_d = 12.2 kN/m^3.

8 CONCLUSIONS

The results presented in this paper show that the behavior of the permanent deformation obtained from a cyclic load test will depend on many factors. Here, it was studied the level of load applied and the compaction condition of the specimen (water content and dry density). On one side, the final value of permanent deformation can be very close if the sample is loaded in steps or in one step with the maximum stress (optimum conditions). But, two specimens compacted in the dry side show different behavior. The curve of permanent deformation when load is applied in three steps is below the curve obtained with a specimen loaded in one phase.

It is suggested that permanent deformation in subgrade soils can be limited if stress level is controlled during the compaction process. Actual technology of the so-called intelligent compaction equipments seem to be suitable to achieve this goal.

Finally, the natural law model was verified for two curves of permanent deformation. Again, the model shows a very good agreement with experimental data. The equations presented provide a valuable alternative for establishing the rutting models into the new mechanistic pavement procedures for design.

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