The Influence of Laboratory Compaction Methods on Soil Structure: Mechanical and Micromorphological Analyses

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Abstract. This paper addresses the influence of the static and dynamic laboratory compaction procedures in the compaction curves and mechanical strength of two residual soils from the Zona da Mata Norte, in the state of Minas Gerais, Brazil. The laboratory testing program was directed to: (i) two gneissic residual soils, respectively, with silty-sandy clay and clayey-silty sand textures; (ii) compaction of specimens at the standard Proctor compaction effort and at the optimum water content (w_{ot}), as well as at w_{ot} - 3% and w_{ot} + 2%; (iii) determination of the unconfined compressive strength of the compacted specimens; (iv) micromorphological analysis of thin sections of the compacted specimens using optical microscopy; (v) statistical analysis of the laboratory testing program data. Conclusions are, as follows: (i) there was statistically significant influence of the compaction procedures on the optimum compaction parameters; (ii) for both soils, significant structural changes represented by variations in the unconfined compression strength were observed evidencing the importance of the soils formation processes in their mechanical responses when compacted; and (iii) differences in the soils structures produced by the static and dynamic compaction procedures were identified through incorporation of the micromorphological analysis.

Keywords: tropical soils, static and dynamic laboratory compaction curves, unconfined compressive strength, statistical and micromorphological analyses.

1. Introduction

Compaction can be understood as a procedure that causes reduction of soil volume without variation in its water or mass content; therefore, it is a process that essentially alters soil structure. In the 30's, Ralph R. Proctor brought an important contribution for the development of the soil compaction technique, showing the relationship between dry apparent specific mass, water content and compaction energy.

Internationally, the most common compaction test is the Proctor, which in Brazil has been regulated by the Brazilian Association of Technical Standards (ABNT, 1986) and by the former Brazilian National Roads Department (DNER, 1994), nowadays the Brazilian National Department of Transportation Infrastructure (DNIT). However, in geotechnical laboratories, different compaction methods have been used in an attempt to come as close as possible to real field situations, and to reduce specimen compaction time.

Since compaction is a process that basically modifies soil structure, it is important to analyze the effects of applying different compaction procedures on the soil compaction curve, as well as it should be emphasized that some aspects of the mechanical response of compacted soils are still poorly understood, mainly regarding tropical soils, because morphological and microstructural features related to geotechnical behavior are rarely quantified or even observed (Schaefer, 2001; Viana *et al.*, 2004). For instance, the optical microscopy technique is a process that has rarely been used for such purpose, even though it allows the examination of soil composition in microscopic detail, such as size, arrangement and particle orientation, and the observation of soil mass pores and shear zones.

Particularly, in studies of soil morphology, the optical microscope allows images over 1,000 times bigger, although it is common to resize them from 10 to 100 (Resende *et al.*, 2002). These authors assert that image studies through optical microscopy starting from thin sections (of approximately 25 μm thick) allow for identification of the

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organization (form) of soil particles that are over 20 µm, as well as it is harder to identify smaller particles, and almost impossible to visualize those smaller than 5 µm.

The evaluation of the influence of different compaction methods in the soil compaction curve and, consequently, in its mechanical behavior (shear strength, compressibility and permeability) is indeed a difficult task, once there is a great number of factors involved and related to the interaction and stress distribution in the solid, liquid and gas phases, capillarity phenomena and osmotic pressures. In order to advance studies on this matter, this paper addresses the influence of the static and dynamic soil compaction procedures using as elements of analysis basic soil compaction parameters, and data from unconfined compression tests and micromorphological analysis.

2. Materials and Methods

The study was carried out in the Laboratory of Civil Engineering at the Universidade Federal de Viçosa – UFV, located in the city of Viçosa, Minas Gerais state, Brazil, using two gneissic residual soils, as follows: (i) soil 1 - the soil sample was collected in the B horizon of a cut slope in the Campus of the UFV at the geographical coordinates 20°45'35” S and 42°52'28” W. It is a mature residual soil, pedologically classified as red yellow latosol (EMBRAPA, 2006), and according to Trindade (2006) in its clay fraction there is predominance of kaolinite and goethite, and traces of gibbsite, as well as after compaction there is a micro-aggregate coalescence tendency, resulting in a highly cohesive and compact structure; (ii) soil 2 - the soil sample was collected in the C horizon of a cut slope in the Secundino Village located in the Campus of the UFV at the geographical coordinates 20°45'38” S and 42°52'25” W. It is a young residual soil, and following Trindade (2006) description its sand and silt fractions are constituted, basically, by quartz, mica and feldspars, and its clay fraction is predominantly composed by kaolinite with traces of goethite. Structurally, this soil shows a bridge structure (argillaceous bridges connecting the grains) involved in scarce plasma.

The geotechnical characterization of soils 1 and 2 followed the ABNT technical standards including grain size distribution (ABNT, 1984a), liquid limit (ABNT, 1984b), plastic limit (ABNT, 1984c), and specific gravity of soil solids (ABNT, 1984d).

In an attempt to reproduce the compaction effort and water content commonly used in the field compaction of landfills and sub-grade soil layers, all specimens were compacted at the standard Proctor compaction effort (ABNT, 1986) adopting nine repetitions of the compaction curve at the following water contents: optimum (w_{ot}); optimum minus 3% (w_{ot} -3%); and optimum plus 2% (w_{ot} + 2%). All specimens were compacted 24 h after mixing in order to reach equilibrium water content in the soil mass. The compaction tests were carried out through dynamic and static compaction laboratory procedures, as follows: (i) dynamic compaction (ABNT, 1986) using the standard Proctor compaction cylinder to produce three-layer compacted specimens 0.100 m in diameter and 0.127 m in height and determining the dry unit weight (γ_d) at each selected water content; (ii) static compaction using a hydraulic press to impose the required force to each layer of three layer specimens in order to produce the desired γ_d determined via dynamic compaction at the selected water contents. It should be emphasized that in the static compaction procedure there was no control of the applied force to the specimen; therefore, only the mass and height layers were controlled. The acceptance criteria adopted for specimen preparation was water content maximum deviation of ± 0.3%.

The unconfined compression strength (UCS) of the compacted specimens was determined following the ABNT (1992) at the deformation rate of 1.25 x 10^{-5} m/s. The statistic tests t and F were applied to the UCS data in order to evaluate the influence of the compaction procedures in the soils structures, considering the 5% probability level in all analyses.

As illustrated in Fig. 1, the micromorphological study was directed to the analysis of thin sections cut from the medium section of four specimens of each soil compacted statically and dynamically at the water contents w_{ot} -3% and w_{ot}.

The micromorphological analysis was carried out using an optical microscope according to the following procedure:

• The compacted specimens were placed and kept in a 35 °C stove during two days. Subsequently, they were impregnated with the resin Revopal T-208 with Bayer blue colorant in a mixture 1:1 with styrene monomer, adding 6 drops of catalyzer for each 200 mL of mixture;

• After impregnation, 0.025 m x 0.047 m polished thin sections were taken from the direction of the specimen cylinder axis and analyzed using the optical microscope OLYMPUS DX-40 equipped with digital camera (NIKON Coopix);

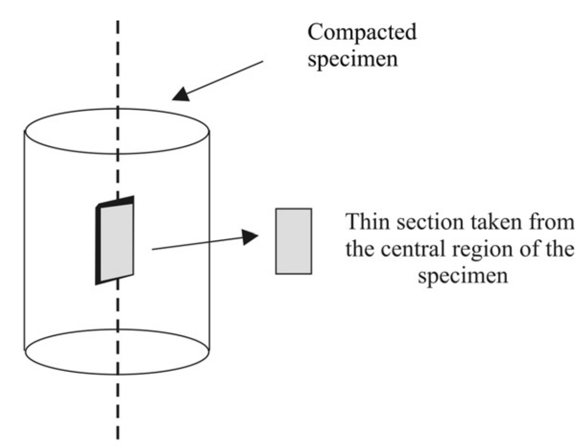

Figure 1 - Position of a thin section in the compacted specimen.

• Descriptions of microstructure and porosity followed the recommendations of Fitzpatrick (1993), and emphasizing the micromorphological and mineralogical aspects of geotechnical relevance;

• The QUANTIPORO software (Fernandes Filho & Viana, 2001) was used to measure porosity, plasma and grains adopting the average means of data from 5 to 8 photomicrographs taken from different regions of each thin section.

Figure 2 summarizes all activities developed in the research program.

3. Results and Discussions

Table 1 shows the geotechnical characterization data of soils 1 and 2, and Fig. 3 presents theirs grain size distributions according to ABNT (1995).

0 summarizes compaction data at the standard Proctor energy and water contents of w_{ot} - 3%, w_{ot} and w_{ot} + 2%, and Fig. 4 shows the compaction curves and unconfined compression data from laboratory tests performed in specimens of soils 1 and 2.

From Fig. 4, it was observed that the static compaction mode produced soil specimens with higher and lower shear strength, respectively for soils 1 and 2, emphasizing the influence of soils formation processes in their mechanical strength.

Figure 5 shows relative differences between the mean values of the parameters γ_d and UCS of soils 1 and 2, adopting the dynamic compaction data as reference. For practical engineering applications, the relative differences between the γ_d mean values are not significant, not over 1% for soil 1 and 3% for soil 2; on the other hand, regarding the UCS mean values, the relative differences are higher, reaching approximately 37% for soil 1 and 20% for soil 2, which emphasizes the significant influence of the compaction procedure on soil mechanical strength.

Table 1 - Geotechnical characterization and classifications of soils 1 and 2.

Properties	Soil 1	Soil 2
Grain size distribution (%)		
Clay ($\Phi \leq 0.002$ mm)	66	7
Silt ($0.002 < \Phi \leq 0.06$ mm)	4	25
Sand ($0.06 < \Phi \leq 2$ mm)	30	68
Gravel ($\Phi > 2$ mm)	0	0
Atterberg limits (%)		
Liquid limit (LL)	74	27
Plasticity index (PI)	48	12
Specific weight of grains (kN/m^3)		
γ_s	27.17	24.91
Soil classification		
TRB	A-7-5(20)	A-2-6(0)
USC	CH	SC
MCT (Trindade, 2006)	LG'	NA'

Table 3 introduces the results of the statistical analyses applied to γ_d and UCS data from soils 1 and 2 at the 5% significance level. Regarding the parameter $\gamma_{d,}$ there are significant statistical differences between the data from the static and the dynamic compaction procedures, except for specimens of soil 1 compacted at the water content w_{ot} + 2%; on the other hand, considering the UCS parame-

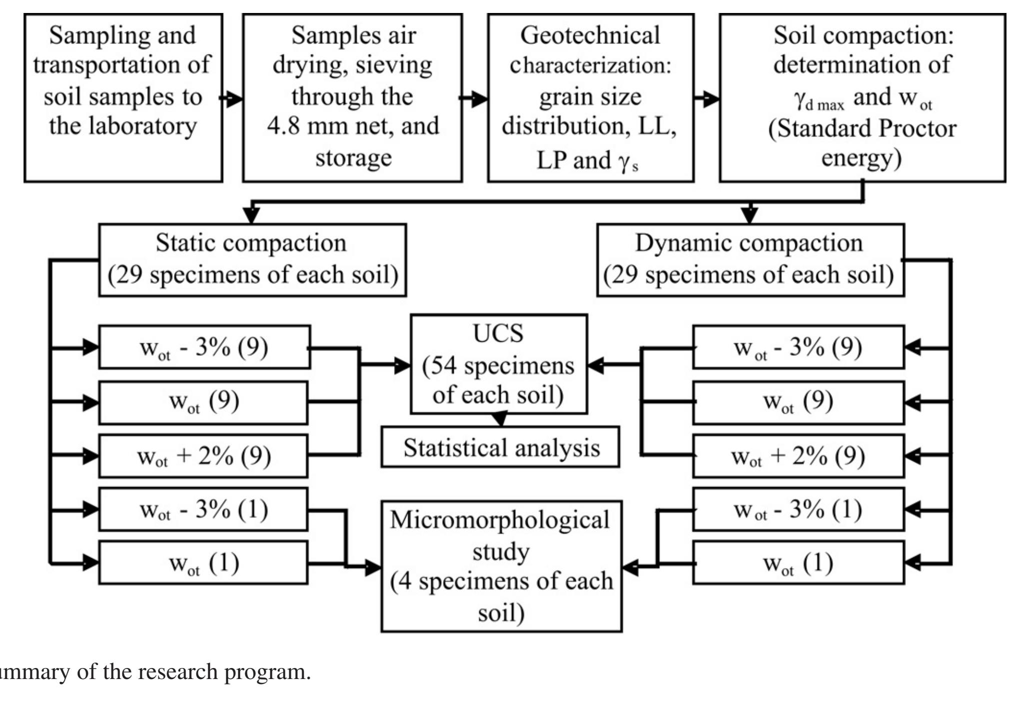

Figure 2 - Summary of the research program.

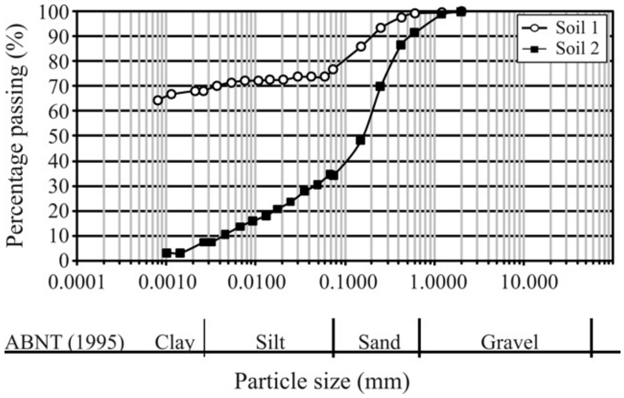

Figure 3 - Grain size distribution curves of soils 1 and 2.

ter, the results of the statistical analysis confirm that the compaction procedure affects the soils mechanical strength, except for specimens of soil 1 compacted at the water content w_{ot} + 2%.

Figures 6 and 7 present photomicrographs taken from thin section of specimens from soils 1 and 2 statically and dynamically compacted at the water contents w_{ot} - 3% and w_{ot}, and Fig. 8 introduces the respective porosity data determined using the QUANTIPORO software (Fernandes Filho & Viana, 2001).

At the water content w_{ot}, Fig. 6a shows that the statically compacted specimens of soil 1 present features of original microagreggation, noticing original nodules, for-

Table 2 - Compaction data of specimens from soils 1 and 2.

Soil	w_{ot} - 3% (%)	γ_d (kN/m^3)	w_{ot} (%)	$\gamma_{d\,max}$ (kN/m^3)	w_{ot} + 2% (%)	γ_d (kN/m^3)
1	27.50	13.62	30.50	14.18	32.50	13.78
2	11.90	17.15	14.90	17.42	16.90	17.15

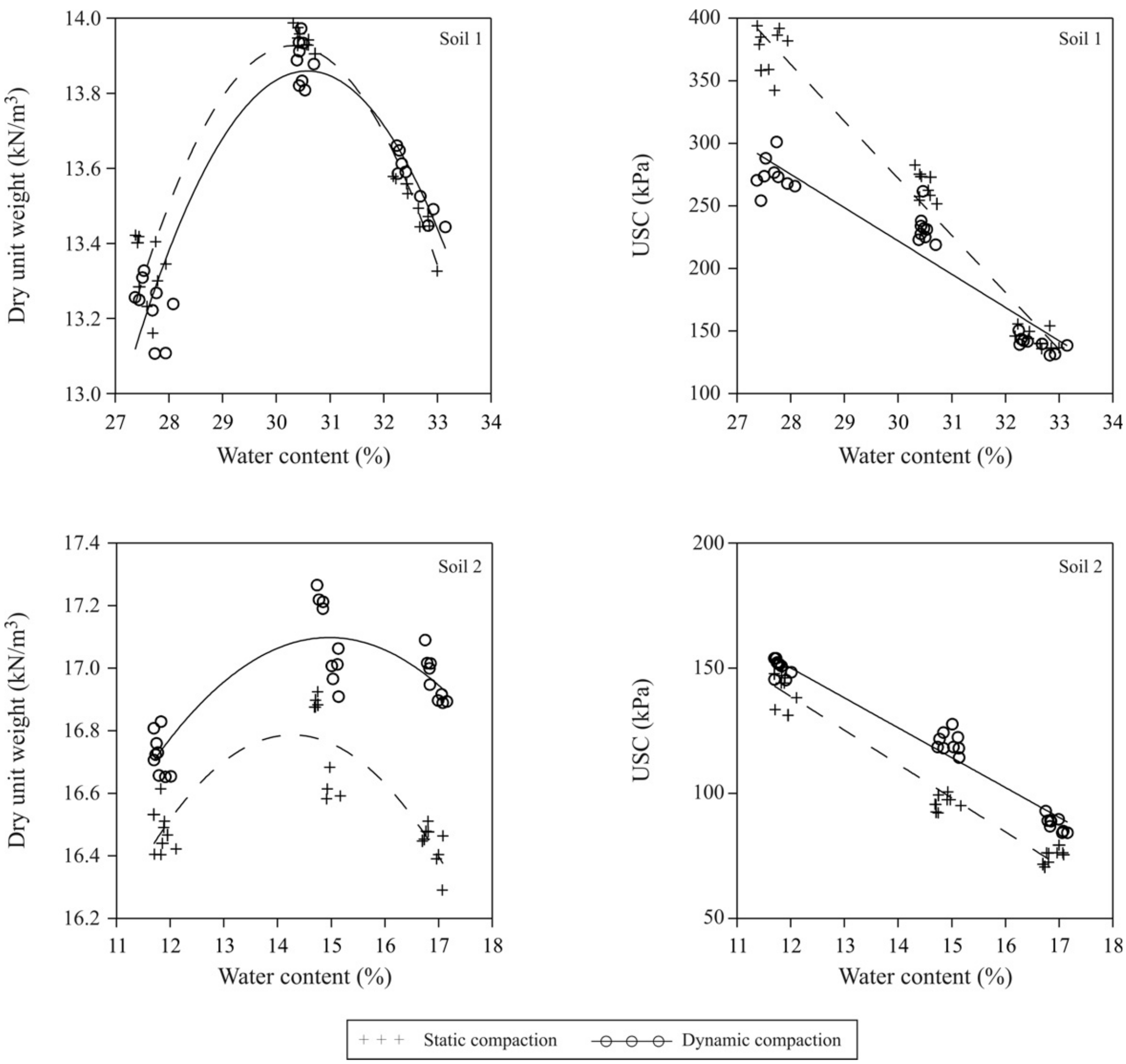

Figure 4 - Compaction curves and unconfined compressive strength (UCS) of soils 1 and 2.

Table 3 - Results from statistical analysis applied to data from soils 1 and 2 at 5% probability level.

Evaluated parameter	w_{ot} - 3%	w_{ot}	w_{ot} + 2%	w_{ot} - 3%	w_{ot}	w_{ot} + 2%
		Soil 1			Soil 2	
γ_d	*	*	Ns	*	*	*
RCNC	*	*	Ns	*	*	*

(*) indicates the occurrence of significant differences, and (Ns) that there are no significant statistical differences at 5% probability level.

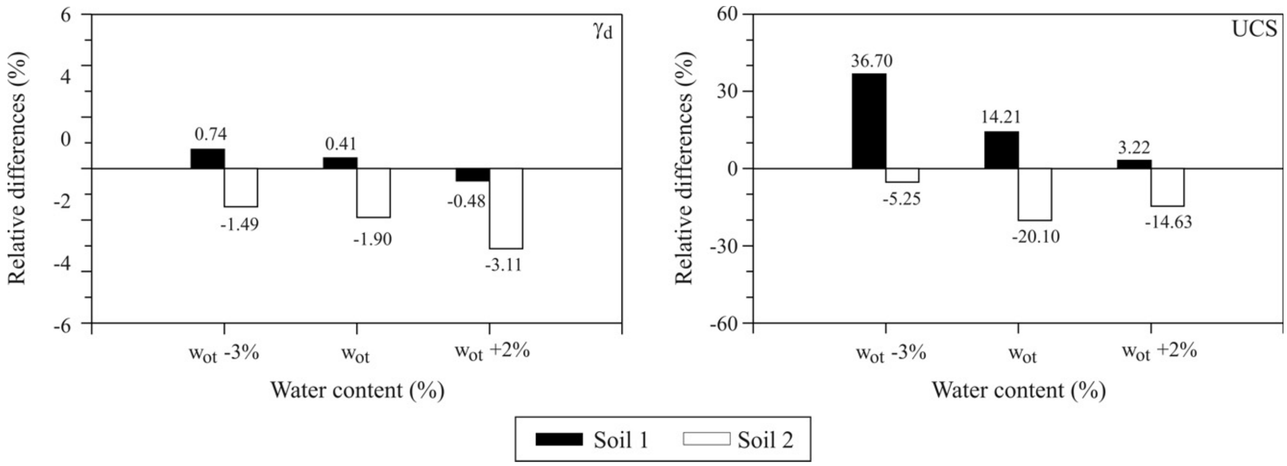

Figure 5 - Relative differences between mean values of the parameters γ_d and RCNC of soils 1 and 2, adopting the dynamic compaction data as reference.

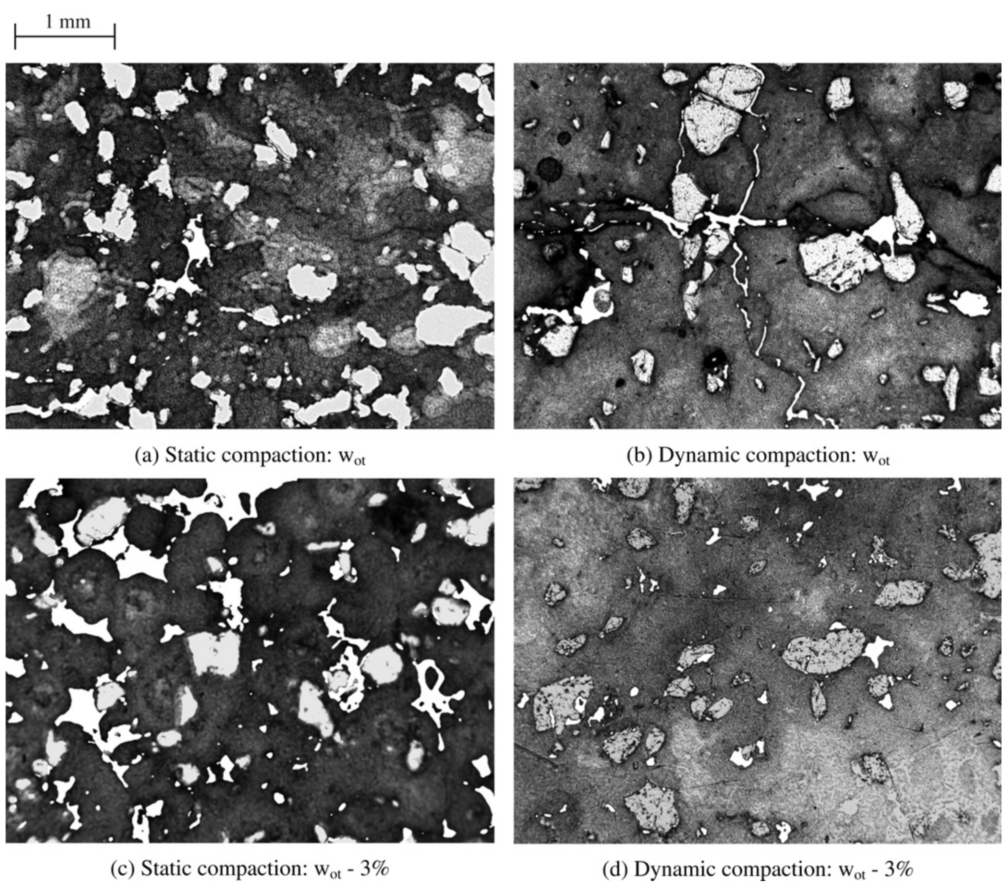

Figure 6 - Photomicrographs taken from thin section obtained from specimens of soils 1 and 2 statically and dynamically compacted at the water contents w_{ot} and w_{ot} - 3%.

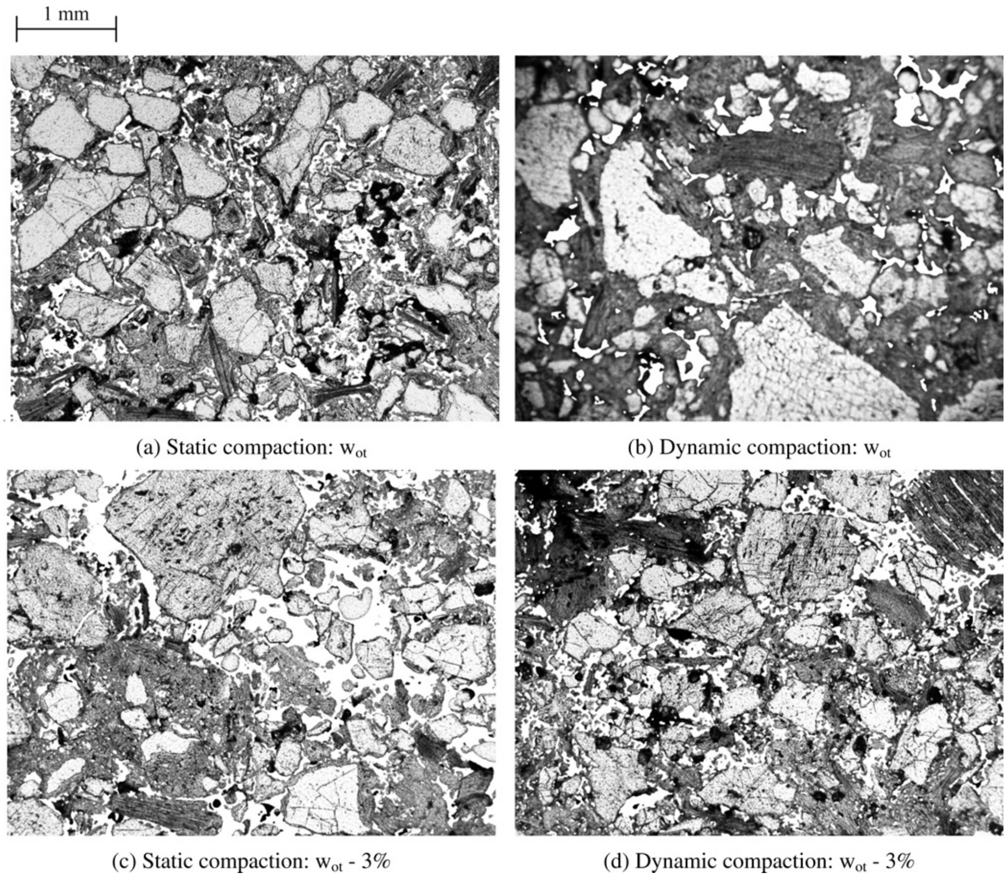

Figure 7 - Photomicrographs taken from thin section obtained from specimens of soils 1 and 2 statically and dynamically compacted at the water contents w_{ot} and w_{ot} - 3%.

mation of isolated gaps and fissured and oriented porosity, and low porosity, around 3%, as depicted in Fig. 8. On the other hand, at this same water content, Fig. 6b supports that the dynamically compacted specimens present a few original microaggregation features, with porosity almost all lost, around 2%, as presented in Fig. 8. At the water content w_{ot} - 3%, as showed in Fig. 6c and Fig. 6d, the static compaction applied to soil 1 produced structure with strong features of original microaggregation and gaps, and porosity

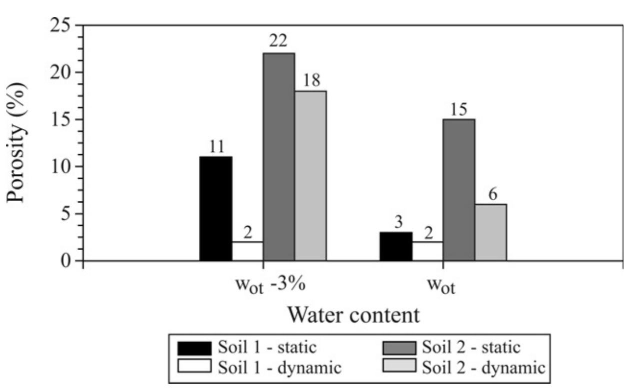

Figure 8 - Porosity data obtained from photomicrographs taken from thin sections of specimens of soils 1 and 2 statically and dynamically compacted at the water contents w_{ot} and w_{ot} - 3%.

around 11% as indicated in Fig. 8. From another standpoint, the dynamic compaction produced partially bonded microstructured argillaceous plasma (coalited), with the original microaggregation destroyed, and porosity reaching around 2%, which is much lower than the one imposed by the static compaction.

It should be emphasized that soil 1 was collected in the B horizon from the profile and exhibits silty-sandy clay texture, with significant clay fraction of 66%, accordingly to Table 1. Geotechnically, it is classified as mature residual soil, and pedologically, as red-yellow latosol, indicating occurrence of advanced pedogenetic formation processes. It also presents granular structure, with well individualized granules and highly porous aspect that can present potential collapse according to Azevedo (1999). Therefore, in soil 1 specimens there can be predominance of interparticle forces that were affected or destroyed by the dynamic compaction, producing structures with lower shear strength. This kind of behavior is compatible with the one described by Bueno *et al.* (1992) when analyzing the effect of dynamic compaction in a red-yellow latosol in comparison with its mechanical response under undisturbed field condition.

On the other hand, Soil 2 specimens compacted statically at the water content w_{ot} presented porosity close to those compacted dynamically, respectively 22% and 18% as presented in Fig. 8. However, the statically compacted specimens showed a fairly uniform distribution of porosity, and those dynamically compacted specimens presented isolated pores, as revealed in Fig. 7a and 7b. This behavior may be related to the higher mechanical strength of the specimens compacted dynamically, as presented in Fig. 4, because once the pores are isolated the soil structure (plasma and grains) can resist better to the shear effort than that permeated by an uniform pore distribution. From another standpoint, at the water content w_{ot} - 3% the static compaction produced porosity around 15%, and the dynamic compaction less than half of that, 6%, as illustrated in Fig. 8; in this case, certainly it is possible to associate the higher mechanical strength of the dynamically compacted specimens to their lower porosity.

It should be also stressed that the sample of soil 2 was collected in the C horizon from the profile and presents clayey-silty sand texture, with considerable sand fraction accordingly to Table 1 (around 68%). From the results presented in Fig. 7, it is possible to explain the higher efficiency of dynamic compaction of the specimens mainly due to the significant influence of vibration on the gradual sand particles arrangement and, consequently, on the efficiency of the compaction procedure as asserted by Rico & Del Castillo (1976), Guedes de Melo (1985) and Hilf (1991).

4. Conclusions

This research brought up the influence of the compaction mode (static and dynamic) in the compaction parameters and in the structure of two residual soils. The conclusions from this study are the following:

• Compared to the dynamic compaction, the static procedure produced specimens with higher UCS for the clayey soil (soil 1), and lower UCS for the granular soil (soil 2), bringing up the importance of soils formation processes in their mechanical responses;

• Considering the applied compaction methods, statistically significant differences were identified in the parameters γ_d and UCS of both soils, except for specimens of soil 1 compacted 2% above the optimum. Therefore, the use of the static compaction procedure in laboratory to obtain compaction and mechanical strength parameters of soils for field applications requires careful study;

• Incorporation of the micromorphological analysis to the present study allowed to identifying differences in the structures produced by the static and dynamic compaction procedures.

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List of Symbols

$\gamma_{d\ max}$: maximum dry unit weight
γ_d: dry unit weight
γ_s: specific weight of grains
LL: liquid limit
PI: plasticity index
w_{ot}: optimum water content
w_{ot} - 3%: optimum water content minus 3%
w_{ot} + 2%: optimum water content plus 2%
MCT: Miniatura, compactado, tropical
TRB: Transportation Research Board
UCS: Unconfined compression strength
USC: Unified Soil Classification