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The influence of wetting and drying paths on the shear strength of a silty clayey compacted soil

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Abstract. The vast majority of geotechnical projects are designed in saturated condition, aiming safety. However, when some conditions might be achieved, designing in unsaturated conditions may end up being economically interesting, while still safe. Therefore, this study aims at evaluating the shear strength behaviour of a silty clayey soil, with optimum moisture content of 16% and dry unit weight of 16,5 kN/m³ from south Brazil. From direct shear tests, performed in saturate and unsaturated conditions, with three different starting moisture conditions – 14%, 16% and 18%, and the same unit weight, this paper shows the influence of the wetting and drying paths on this material and its contribution to evaluate shear strength. The results showed that a variation of ±2% around the optimum, in drying and wetting paths, can significantly influence the behaviour of the studied material. The wetting process caused a small variation in comparison with the optimum, while the drying process resulted in increased shear resistance for all the analyzed samples. With this study, it was possible to obtain a better understanding of the behaviour of an unsaturated soil from south Brazil, when evaluating tradeoffs in project's safety and economics.

1 Introduction

The layers that form a pavement structure are compacted at optimum moisture content (ω), therefore in unsaturated conditions. These layers' moisture content (and of the subgrade) may vary during the construction of a pavement, due to poor technical control or even deliberate not following standardization. It's known that the characteristics of the soil where the pavement is settled directly influence its lifetime; following Brazilian standardization DNIT 137/2010 [1], there is a tolerance of ±2% around optimum moisture content (ω_0). Even though the moisture content may be altered during construction and also after the structure is opened to traffic, seasonal weather conditions may also influence the saturation level, compromising the pavement's performance.

Considering the importance of saturation conditions of the soils when building these structures, the evaluation of the shear strength – tied up to the moisture content at time of compaction, and also to wetting and drying paths, induced by climate conditions – may influence significantly pavements analysis and design. Several papers highlight the importance of evaluating pavements' mechanical behaviour and the relevance of knowing the materials' properties, such as Rodrigues (1997, [2]), Zaman and Khoury (2007, [3]), Chittoori et al. (2012, [4]), Weber (2013, [5]) and Matuella et al. (2014, [6]). By this mean, the present study aims at evaluating the shear strength of a soil against variations in the moisture content after its compaction.

2 Material and methods

The experimental program consisted in two main steps: the first was to choose the soil to be analyzed, based on its applicability as a pavement material; the second was to arrange test procedures that would make possible to evaluate moisture content variations during and after compaction and its influence in the soil shear strength. It is assumed that those variations might be related to climate changes and to possible construction problems, which could be reproduced in laboratory by wetting and drying paths.

2.1 Material of study

The studied soil was collected in the Brazilian highway BR-116, near the city of Porto Alegre, located in the state of Rio Grande do Sul. Figure 1 shows the location where the studied soil has been collected from. This soil was

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chosen because it was part of a quarry that would be used in the highway's duplication. Some characteristics of the studied soil are presented in Table 1. Figure 2 shows the compaction curve obtained for the studied soil while Figure 3 presents its grain size distribution curve. The soil specimens were compacted using standard Proctor effort and then shaped in order to carry out direct shear tests and suction tests.

Figure 1. Location where the soil was collected from.

Table 1. Soil physical properties.

	Size	Sand	Silt	Clay
Grain size distribution	With dispersant	36%	19%	45%
	Without dispersant	31%	65%	4%
Compaction test results (Standard Proctor)	ω_0	16%		
	γ_d	16,5 kN/m³		
Atterberg Limits	Liquid limit	36%		
	Plastic limit	27%		
	Plasticity index	9%		

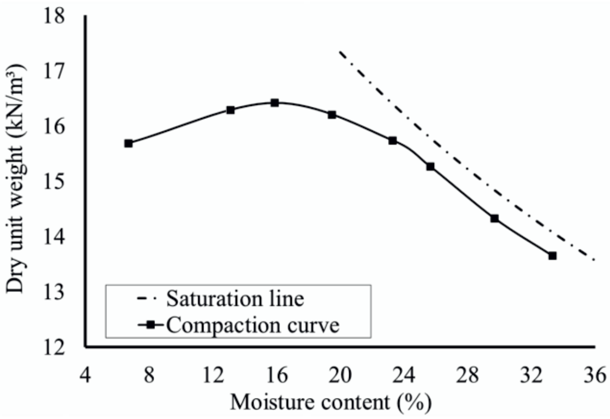

Figure 2. Compaction curve.

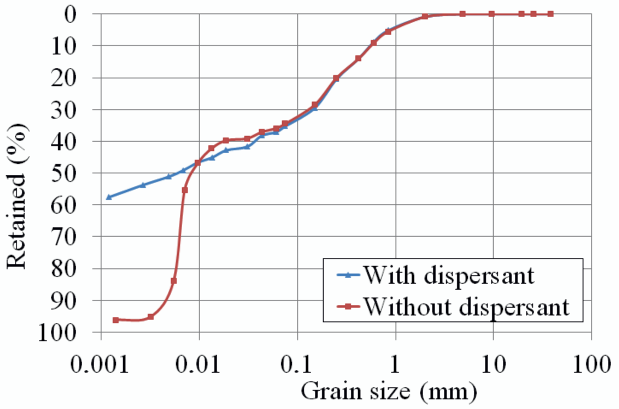

Figure 3. Grain size distribution curve.

2.2 Direct Shear Test

The direct shear test was adopted because of two main reasons: relatively fast results and simple testing procedures, following ASTM D3080 [7].

Cylindrical specimens with 6 cm in diameter and 2 cm in height were compacted with moisture contents equal to 14%, 16% and 18% (within the allowable limits established by DNIT 137/2010). Some samples were then wet, some of them dried and some of them remained at the same moisture content. The specimens in the drying path were air dried and water was added to the specimens in the wetting path. In both cases, the moisture content was controlled by mass variation; after achieving the correct content, the specimens were wrapped in plastic film and stored in order to provide homogeneity in moisture. Table 2 synthesizes the moisture content at compaction and while the tests were run.

Table 2. Variations of the friction angle as function of the moisture content at compaction and wetting/drying paths.

Path	**ω at compaction**	**ω at testing**
No path	14	saturated
	16	saturated
	18	saturated
	14	14
	16	16
	18	18
Wetting	14	16
	16	18
	18	20
Drying	14	12
	16	14
	18	16

When tested under saturated conditions, the soil specimens were compacted at desired moisture content, placed at the Wykeham Farrance equipment for direct shear test, shown in figure 4, where they were flooded, thickened up to stabilization, and then tested.

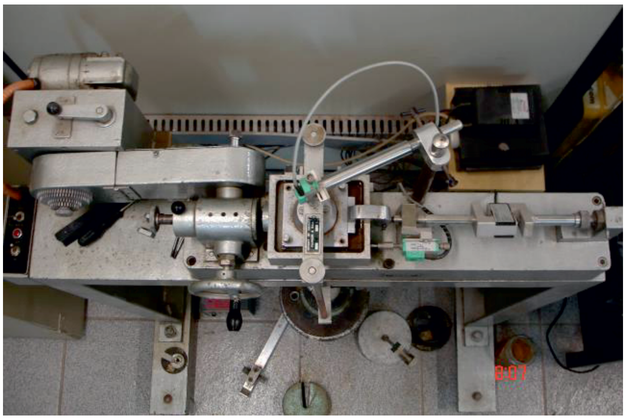

Figure 4. Wykeham Farrance equipment for direct shear test.

During the test, it was observed that the moisture content was constant in the unsaturated condition. On the other hand, the saturated condition tests were carried out after keeping the specimens in water during a predefined period of time in order to achieve complete saturation. The applied normal stresses were 25 kPa, 50 kPa and 100 kPa and two hypotheses were assumed as rupture criteria: the shear stress stabilization or a horizontal displacement of 10% the specimen diameter.

3 Results and analysis

From the stress x strain curves obtained at the direct shear test to the set of conditions studied, the following shear stress (T) x normal stress (σ) graphics, shown in Figures 5 to 8, were plotted.

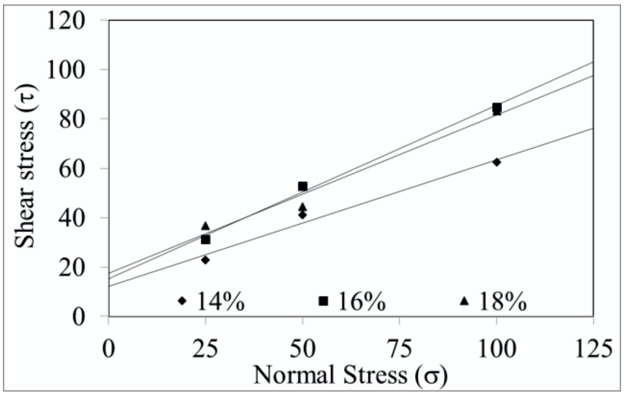

Figure 5. . T *x* σ diagram for saturated samples.

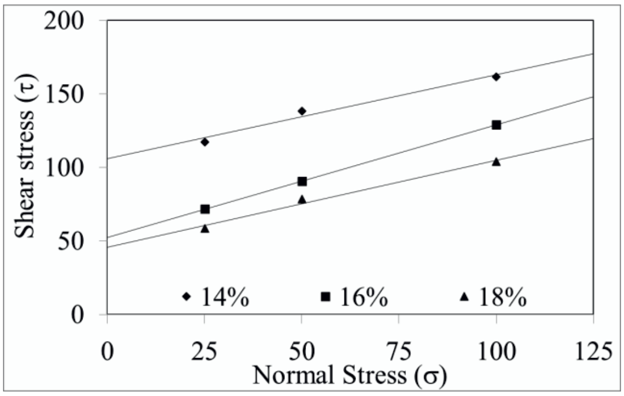

Figure 6. . T *x* σ diagram for unsaturated samples.

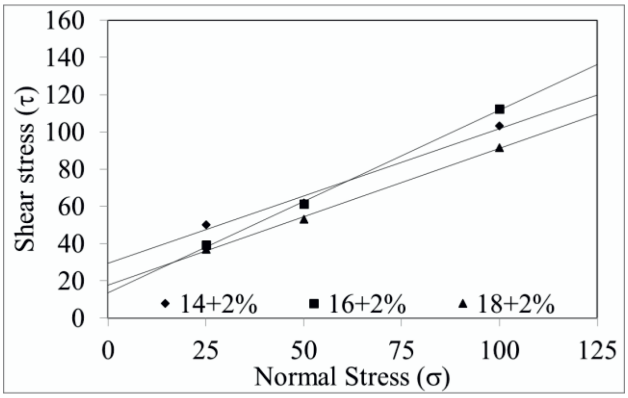

Figure 7. . T *x* σ diagram for unsaturated samples under a wetting path.

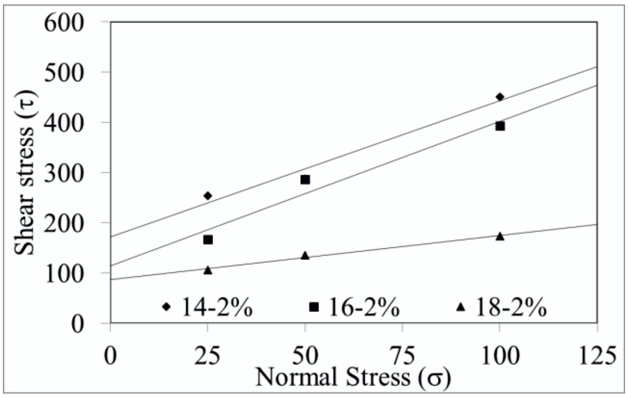

Figure 8. . T *x* σ diagram for unsaturated samples under a drying path.

The results were then summarized; table 3 shows the variation of the friction angle, while table 4 expresses the variations in the cohesion, both related to moisture content of the samples at the moment they were tested.

Table 3. Variations of the friction angle, related to the moisture content at compaction and wetting/drying paths.

ω at compact-tion	**friction angle – ϕ (º)**			
	Satu-rated	Unsa-turated	Wet (+2%)	Dried (-2%)
14%	27,1	29,7	35,8	69,8
16%	35,1	37,4	44,5	70,9
18%	32,6	30,5	36,3	41,4

Table 4. Variations of the cohesion as function of the moisture content at compaction and wetting/drying paths.

ω at compact-tion	**Cohesion (kPa)**			
	Satu-rated	Unsa-turated	Wet (+2%)	Dried (-2%)
14%	12,2	105,8	29,6	172,0
16%	15,3	52,5	13,8	113,7
18%	17,5	45,8	17,8	86,8

After obtained, these values were plotted in order to help in the analysis of the soil's mechanical behaviour. In figure 9, the variation of the cohesion is presented, related to the variations of moisture contents, while figure 10 shows the friction angle as function of the moisture content.

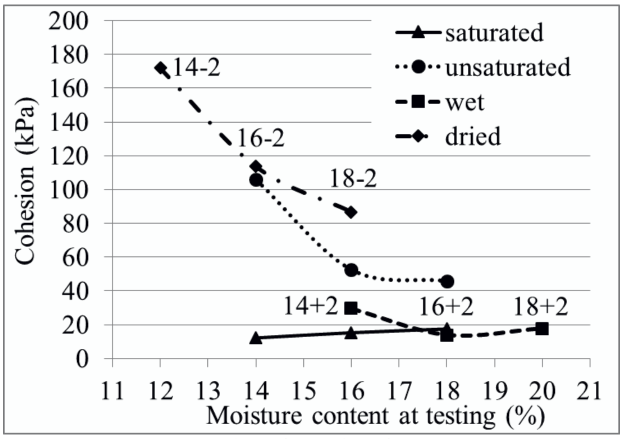

Figure 9. Cohesion as function of moisture content.

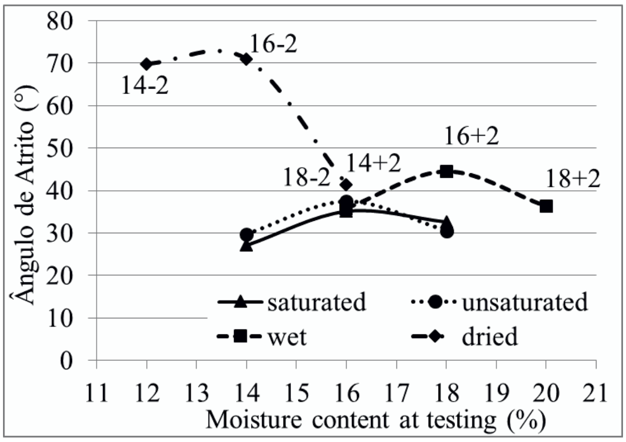

Figure 10. Friction angle as function of moisture content.

About the mechanical behaviour of this soil, as most relevant, it was observed that:

- Under saturated and under unsaturated conditions, the friction angle tends to have a maximum value, related to optimum moisture content at compaction. When under wetting paths, the samples compacted at optimum moisture content presented higher friction angle, compared to those which did not have its moisture changed. When not compacted at ω_0, values of the same order of magnitude were obtained, as the ones resulted when the samples were tested at ω_0, with no moisture variations. When analysing the samples that underwent the drying process, all the three cases showed an increase in the friction angle. In this case, the ones compacted at 14% and 16% presented exceedingly high values for this parameter. There is still lack of results to evaluate the behaviour of the drying paths, at lower moisture contents, to determine if the friction angles will stabilize, decrease or still show a peak value.
- The soil's cohesion, under saturated condition, presents a slight increment, as the moisture content at compaction increases, but this increment is not as notable as the cohesion obtained in unsaturated conditions. When compared directly, for every value of moisture content at compaction, cohesion under unsaturated conditions are roughly at least 3 times higher. As expected, the wetting path proved to be a worse condition when compared to all unsaturated samples. It was observed that the drying paths may endow the soil substantial improvements, in terms of cohesion (46 kPa to 87 kPa, for samples compacted at 18%, 52 kPa to 114 kPa, for the samples compacted at 16% and 105 kPa to 172 kPa, for those compacted at 14% of moisture content).

4 Conclusion

The experiments developed in this work allowed the evaluation of the behaviour of the shear strength of a compacted soil at different moisture contents, which were conducted through wetting and drying paths.

It was noticed that when this soil is compacted near optimum moisture content and, after compaction, it suffer loss of moisture, we can achieve considerable increases in shear strength. When the effect is the opposite and the moisture content of the material increases after compaction, there may be great resistance loss, particularly when the material is compacted below optimum moisture content.

These observations are of great relevance to the practical applications of geotechnical engineering. With proper control of soil moisture, we might save financial resources and get benefits in terms of security.

We can, for example, in long-term construction work, plan a certain excavation or cutting a slope, which should be done in a drier season when the soil is possibly less humid and hence support higher shear stresses and remain stable on steeper slopes. Another example to be taken into account is the construction of a highway: if we manage to control the moisture of the pavement support layers by installing devices which lead the water out of the pavement structure, or by using layers which allow the percolation of the water in a way that it wouldn't accumulate within the structure, we prevent these layers from loosing strength due to high humidity.

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