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Thixotropic behaviour study of clayey soils from the lacustrine deposits of Bogotá high plateau

J C Ruge[1]**, F Molina-Gómez**[2]**, and J P Rojas**[3]

[1] Universidad Militar Nueva Granada, Bogotá, Colombia
[2] Universidade do Porto, Porto, Portugal
[3] Universidad Francisco de Paula Santander, San José de Cúcuta, Colombia

E-mail: `juan.ruge@unimilitar.edu.co`

Abstract. Thixotropy is a distinctively rheological (time-dependent) phenomenon, which is found in many complex materials, especially colloidal systems as fine-grained soils. Clays are materials that can recover their initial strength after remoulding. The estimation of such recovering allows optimising the designs of geotechnical structures and then reducing the construction costs. This paper presents the results of a study that evaluates the thixotropy phenomenon of clayey soils. The work methodology involved an experimental plan composed of five phases: (i) extraction of samples; (ii) physical and mechanical characterisation of the undisturbed samples; (iii) remoulding of samples after testing; (iv) storage of remoulded samples; and (v) evaluation of undrained shear strength recovering for 0, 15, 30, and 60 days after remoulding. Undisturbed samples were collected using Shelby tube from the municipality of Madrid, near Bogotá, in Colombia. Results were analysed in terms of sensitivity degree because this parameter allows estimating the shear strength recovering. Findings show that clayey soils from lacustrine deposits of Bogotá high plateau do not loss completely all of their original mechanical properties after remoulding and exhibit a medium sensitive behaviour. Conclusions indicate there is a recovering of undrained shear strength along the time, in which the samples will recover their original state about one year after remoulding.

1. Introduction

Thixotropy is a softening process caused by remoulding, followed by a time-dependent return to the original harder state. Seng [1] defined thixotropy as the phenomenon in which soil has hardening, over time, under constant humidity or volume conditions after a remoulding process. This phenomenon is related to the recovering of strength or stiffness, and it may depend totally or partially on the properties of the material. Some comprehensive reviews about thixotropy of different materials are in [2–4]. Detailed studies about thixotropy phenomenon in clayey soils can be found in [5,6]. Rinaldi [7] explain that the main concepts involved in thixotropy phenomenon include: (i) the change of the microstructure in time, after the shearing stage and during rest, and (ii) the reversible and isothermal variation in rheological properties of the suspensions such as elastic modulus, yielding stress and viscosity after remoulding.

The studies about thixotropic soils (*e.g.* clays) are relevant because of the use of remoulded samples for experimental investigations in the laboratory. Such investigations can be related to the characterisation of soil behaviour on the field after the construction of geotechnical structures.

This paper aims the assessment of the thixotropic behaviour of natural clayey soils at different times. Such assessment allows providing an approach to evaluate the rheological properties of clayey soils. To estimate the shear strength recovering, undisturbed and remoulded samples were tested in the laboratory. The measuring of the tixotropic behaviour was carried out thought unconfined and lab vane tests. Soil samples were collected Bogotá high plateau, specifically at the municipality of Madrid (Colombia). Remoulded samples were prepared after performing unconfined compression in undisturbed conditions. Besides, these were stored during 0, 15, 30 and 60 days. The main contribution of this research is the proposal of a model, using the regression method, which estimates the undrained shear strength evolution after the remoulding process in this soil type.

2. Materials and methods

2.1. Thixotropy and its measuring

Soil thixotropy is quantified through the sensitivity degree (S_t). Sensitivity is the ratio between the shear strength in undisturbed conditions against the shear strength, of the same soil, in remoulded conditions [8]. The sensitivity rate is an dimensionless parameter. Equation (1) refers to the S_t in terms of undrained shear strength (Su) for both conditions undisturbed and remoulded. Su was adopted since S_t particularly refers to clayey soils.

$$S_t = \frac{Su_{un}}{Su_{re}} \tag{1}$$

A sensitive soil tends to lose its shear strength more easily rather a non-sensitive soil [9]. For many clayey soils naturally deposited, the simple compressive strength is much less when the soils are tested after being remoulded without any change in moisture content. Figure 1 shows the two types thixotropic behaviour most common in soils.
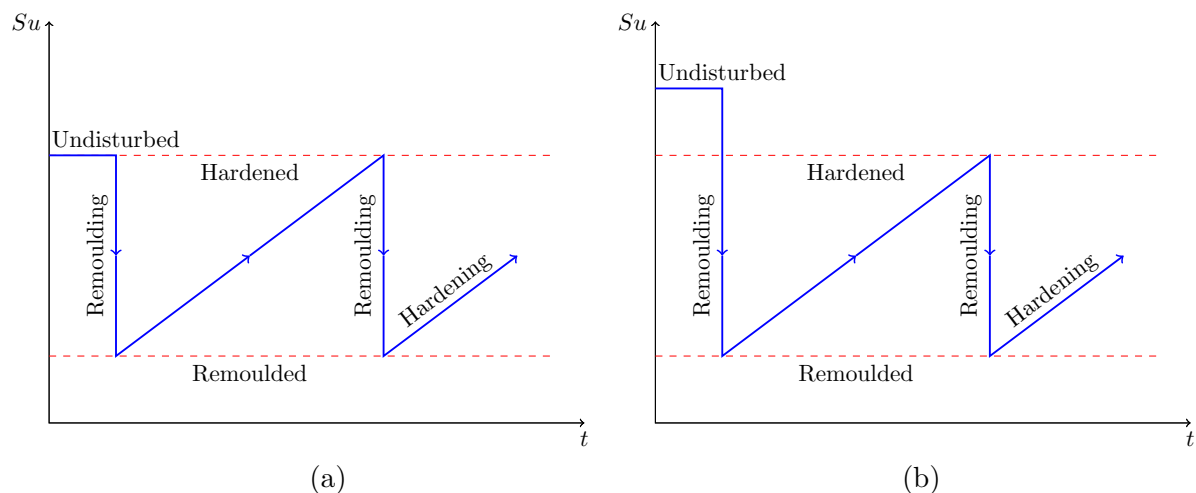
Figure 1. Behaviour of thixotropic soils: (a) thixotropic soil; (b) partially thixotropic soil.

Table 1 presents the classification of the soil sensitivity based on the S_T range. For of most clays, S_T ranges between 1 and 8. However, highly flocculent marine deposits can reach values between 10 and 80. Such materials are named quick clay, because of the rapid loss of their shear strength [5]. The loss of strength of the clayey is mainly caused by the destruction of the clay particle structure that was formed in the original sedimentation process [10].

Table 1. Typical values of sensitivity [10].

Condition	Range
Low sensitivity	2-4
Medium sensitivity	4-8
High sensitivity	8-16
Quick sensitivity	16-24
Extra quick sensitivity	>24

2.2. Materials

The clayey soils of this study were collected in two adjacent boreholes using the Shelby tube technique. Such boreholes are located at the municipality of Madrid (Colombia). Madrid is in the Department of Cundinamarca at 29 km from Colombia's capital, Bogotá. Besides, it is part of the west sector of the Bogotá high plateau, which is at the Eastern of the Colombian Andes. The municipality covers 120.5 km^2 area 2550 m above sea level and is watered by the Bojacá and Subachoque rivers. The topography of the sector is flat to slightly undulating.

The soils of are mainly made up of terrace plains and floodplains of the Quaternary. Hence, lacustrine deposits cover a large part of the municipality area. Since its formation origin, the soils of this zone are clays weakly structured [11]. Shallow deposits of soil from 2 m to 5 m deep are overconsolidated [12]. At some sites of the plateau, the depth of the lacustrine deposit can reach 586 m. Further details about the behaviour of the Bogotá high plateau soils can be found in Caicedo, *et al.* [13].

2.3. Experimental procedures

Four different boreholes were drilled to collect undisturbed samples of clayey soils. Boreholes were positioned in two locations, which are separated 2 m distance. Eight different samples (two per borehole) were retrieved, between 1.0 m and 1.5 m depth, using the Shelby tube method. This sampling method uses a thin-walled tube, which minimises the soil disturbance during the collecting. Due to all samples were retrieved from adjacent points non-spatial variability was assumed.

In the laboratory, the experimental plan was divided in two phases: (i) physical characterisation; and (ii) Su estimation by unconfined compression and laboratory vane tests. Physical characterisation included specific gravity of solid particles (Gs), liquid limit (LL) and plastic limit (PL), as well as the soil classification according to the unified system of classification of soils (USCS). Table 2 presents the physical properties of the soil.

Table 2. Physical properties of the soil.

Parameter	Test procedure	Units	Value
Gs	ASTM D854 [14]	-	2.68
LL	ASTM D4318 [15]	%	82
PL	ASTM D4318 [15]	%	30
PI	ASTM D4318 [15]	%	52
SUCS	ASTM D2487 [16]	-	CH

During the second phase of the experimental plan, samples in the same borehole were named using the numbers 1 and 2. Such classification allowed facilitating the comparison of results between undisturbed against remoulded conditions. Based on such comparisons, the S_t values were estimated for each sample. Figure 2 shows the stress-strain curves obtained from the unconfined compression tests for the undisturbed sample.
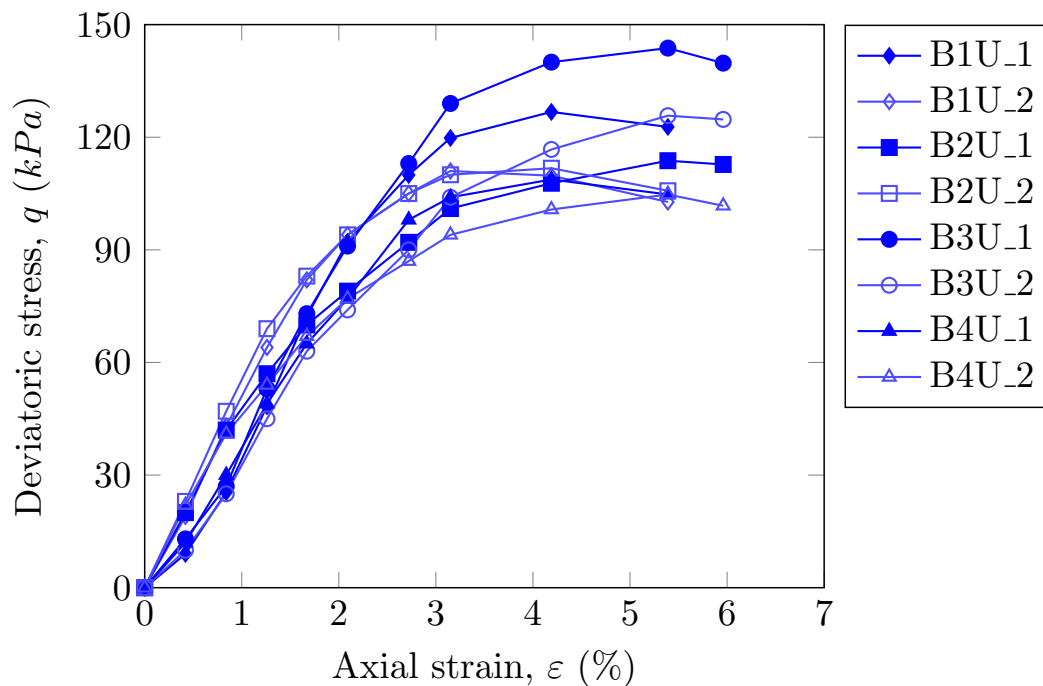

Figure 2. Unconfined compression test results.

The Su of the samples was measured through unconfined compression and lab vane tests. After unconfined compression tests, samples were remoulding according to the following procedure. The scraping of samples, to obtain small pieces that could easily adhere to one another, and to generate the remoulded sample. The material poured into a mould, which has the same internal diameter of the Shelby tube (70 mm). The sampling compaction in four layers with 35 mm height. The compaction was done through a hammer 1585 g weight and 17.17 cm fall height. By this procedure, samples with a height/diameter ratio equal to 2:1 were obtained. After compaction, the samples were extruded from the mould in a vertical position. The samples were covered with plastic wrap and aluminium foil, to avoid water content changes. Furthermore, the samples were sealed and putted into a box and stored during 15, 30 and 60 days into a curing room laboratory able to control the temperature and humidity. Figure 3 summarises the remoulding procedure.

To verify that the reconstituted samples were as similar as possible to the undisturbed samples, unit weight (γ) values of both conditions were compared. The γ computation included the results of water content (ω) of samples. Table 3 shows such comparison. From this preliminary analysis, it can be observed that the difference of γ between undisturbed and reconstituted samples is 0.32% average with a coefficient of variation (COV) equal to 9%. Hence, similar physical properties of the sample was found for undisturbed and remoulded conditions before testing.
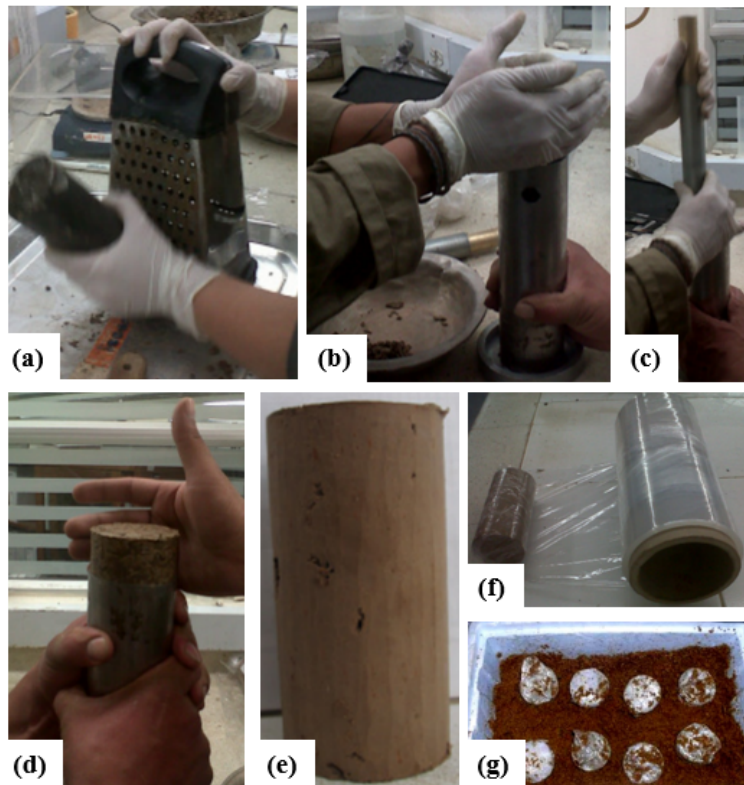
Figure 3. Remoulding procedure: (a) scraping of samples; (b) pouring of material into the mould (c) sample compaction; (d) extrusion from the mould; (e) aspect of the remoulding sample; (f) sample sealing; (g) remoulding samples into the store box.

Table 3. Comparison between undisturbed against remoulded state of samples.

Sample	ω_{un} (%)	ω_{re} (%)	γ_{un} (kN/m^3)	γ_{re} (kN/m^3)
B1U_1	48.9	48.4	17.26	17.20
B1U_2	48.7	48.8	16.76	16.70
B2U_1	53.3	53.0	16.77	17.72
B2U_2	52.9	53.2	16.76	16.70
B3U_1	45.2	47.8	16.33	16.28
B3U_2	46.8	48.4	17.26	17.21
B4U_1	45.2	47.8	16.33	16.28
B4U_2	46.8	48.4	17.26	17.21

3. Analysis of results

The Su values were estimated for under undisturbed and remoulded conditions. Samples were stored and tested 0, 15, 30 and 60 days after sample remoulding. Such values were measured through unconfined compression tests and vane shear apparatus. Vane shear tests were performed after the unconfined compression test and Su values were measured at three different points (top, base and centre) in each sample. From these results, it can be recognised that all samples presented similar values of S_T for each ageing period, as well as a reduction in the time of such estimator. Therefore, it is evident a thixotropic behaviour in the clayey soils from lacustrine deposits of Bogotá high plateau in Colombia.

Table 4 presents the mean values of Su obtained in the laboratory. In addition, Table 4 includes the Su variability of the test results. By comparing the data presented in Table 4,

similitude between Su values, as well as S_T was found for all samples. However, slightly higher values were obtained in the shear vane test. Furthermore, shear vane test results provided reliable data since the Su was measured in three different points in each sample.

Table 4. Su and S_T results of undisturbed and remoulded samples.

Sample	Aging	Su_{un} (kPa)	COV_{un}	Su_{re} (kPa)	COV_{re}	S_T (-)
B3_1	0	79.2	7.6	28.1	4.4	2.8
B3_2	0	65.5	5.8	23.9	6.5	2.7
B1_2	15	64.4	7.1	20.3	9.9	3.2
B1_2	15	57.4	4.0	18.3	3.2	3.1
B2_1	30	58.5	9.4	19.8	8.4	2.9
B2_2	30	57.2	7.6	19.4	6.7	2.9
B4_1	60	55.5	8.4	22.0	8.2	2.5
B4_2	60	54.6	3.9	21.3	1.8	2.6

The thixotropic strength recovery is evaluated in terms of thixotropic strength ratio (Υ). Mitchell and Soga [17] defined Υ as the ratio of strength gained above the initial strength (strength corresponding to zero aging time or immediately after remoulding). Figure 4 shows the Υ results.
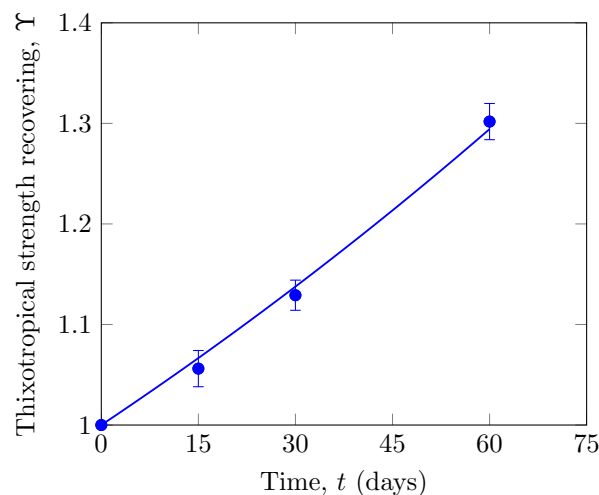

Figure 4. Thixotropical strength recovering.

From reliable data of laboratory tests, a regression model was computed. Experimental results provided the Equation (2), which allows estimating the time (t) to recover the Su in undisturbed conditions of each sample. This model established that the time for 100% recovering of Su in all samples is between 210-255 days.

$$\Upsilon = \exp^{0.0045t} \tag{2}$$

Based on the classification proposed by [10], the thixotropic behaviour of the clayey soils from lacustrine deposits of Bogotá high plateau (Colombia) was categorised as low sensitivity. The category of behaviour remained constant throughout all evaluation times, indicating that the remoulding process in this material does not induce a total loss of its shear strength. Such behaviour indicates that this Colombian soil does not collapse and can support the geotechnical structures after the disturbances induced by the construction process.

4. Conclusions

This paper explores the phenomenon of thixotropy in clayey soils from lacustrine deposits of Bogotá high plateau (Colombia). *Su* strength attained during different ageing periods was determined by performing the unconfined compression and vane shear tests. Results of undisturbed and remoulded samples of this material allowed obtaining a model to estimate total recuperation of the Su by means of the thixotropical strength recovering parameter.

The clayey soils studied have S_T in a range of 2 to 3, classified as moderately sensitive, which indicates that even breaking the structure of this material reconstituted its mechanical properties do not fall to zero.

The remoulding procedure implemented in this work allowed obtaining γ close to the values of undisturbed samples. This process guaranteed the conservation of the remoulded samples. To achieve such condition samples were weighed constantly during the reconstitution process of the sample and its volume was controlled by a mould with dimensions equal to the Shelby tube. Besides, control of water content of the soil.

The recovery of resistance, measured by Υ, exhibited an exponential tendency along the aging periods. It was evidenced a thixotropic behaviour in clayey soils from lacustrine deposits of Bogota high plateau. Based on the findings, we suggest to include Υ parameter within the designs, in order to optimise the cost of geotechnical structures builds on this type of soil.

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