Oven-drying effects on the characterization of marine and lacustrine soils

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Abstract. Considering the extensive use of plasticity-based correlations in geotechnical practice to estimate soil parameters, the paper explores the influence of oven drying on the plasticity of two natural soft soil deposits: (i) Ballina clay, a marine structured soft clay from Australia and (ii) Bogotá clay, a lacustrine soft clay from Colombia. These two soils display extremely high plasticity when Atterberg limits are estimated using the natural soil. However, a strong reduction in liquid limit (up to 85%) is measured when the soil is oven dried before testing. The fact that the plastic limit seems insensitive to oven drying leads to a reduction in plasticity index close to 30% in Ballina clay and around 85% in the case of Bogotá clay. This behaviour is attributed to irreversible changes in soil fabric triggered by the oven drying process. The paper evaluates the consequences of neglecting oven drying effects in practice when adopting well-established relationships between mechanical parameters and soil plasticity. Plasticity-based estimates of index properties, compressibility and friction parameters are compared against values obtained from index tests as well as one-dimensional consolidation tests and ring shear tests.

1 Introduction

Natural soft soils are commonly used as foundation material for civil and transport infrastructure worldwide. Typical examples are the marine soft soils encountered along Australian [1-3] and Indian [e.g., 4-6] coastlines, as well as the lacustrine soils found in heavily populated areas like Mexico City (Mexico) [e.g., 7] and Bogotá City (Colombia) [8]. The complex mineralogical and geochemical composition of those deposits put forward important challenges for the characterization of their index and mechanical properties which are used in geotechnical design.

Although the influence of oven drying on the characterization of natural soft soils has not received important attention over the past decades, available studies have reported a decrease in soil plasticity in oven dried soft soils which leads to misleading soil's classification. This phenomenon seems to be strongly soil-dependent and attributed to several factors like the presence of organic matter [9], the presence of halloysite minerals [10-12] but also due to irreversible changes in soil microstructure [13, 14].

This paper examines the influence of oven drying on the plasticity of two natural soft soil deposits: (i) Ballina clay, a marine structured soft clay from Australia and (ii) Bogotá clay, a lacustrine soft soil from Colombia. Plasticity and mechanical tests, carried out on natural and oven dried specimens, are reported below. Those tests are complemented with microstructural analyses aimed at evaluating changes in soil fabric. Laboratory results are compared against available plasticity-based correlations commonly used in geotechnical design to discuss possible practical implications.

2 Soils tested

2.1 Ballina clay

Ballina clay represents the marine soft deposits found along the eastern and southern coastlines in Australia. Ballina clay is enountetered at the National Soft Soil Testing Facility NFTF [3, 15] in northern New South Wales. The soil profile at the NFTF is composed by four soil layers as shown in Fig. 1. Layer 1 is a silty-sand alluvial crust. Layers 2 and 3 comprises the upper and lower estuarine silty clay (hereafter Ballina clay). Layer 4 is the silty-sand transition layer which overlies a sand layer and a deeper stiff clay layer. The natural water content increases with depth from 20% ($z \approx 1$ m) up to 120% ($z > 7$ m). The liquid limit LL is typically 10-15% higher than the natural water content whereas the plastic limit PL ranges between 20-53%. Natural dry density reduces from 1.50 Mg/m^3 at ground surface to 0.70 Mg/m^3 at 4.5 m depth. However, minor changes are noticed between 3 m and 11 m. Despite the large sand content observed above 2m depth, the clay fraction is predominant up to 11 m depth, with maximum values around 82%.

Soils at the NFTF are composed of amorphous minerals, kaolinite, illite, quartz, interstratified illite/smectite, plagioclase, pyrite, K-feldspar, mica and calcite. Sodium (0.93–8.23 g/L) and chloride (2.5–15.4

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g/L) are the most abundant cations and anions in the pore fluid. The bulk electrical conductivity EC_{bulk} increases with depth from 4 to 15 mS/cm whereas the pore fluid conductivity EC_{fluid} increases from 7 up to 36 mS/cm (average value below 5 m). This corresponds to salt concentrations between 4–23.5 g/L. The presence of salts during soil deposition promoted a porous fabric composed by aggregates separated by large voids. A detailed characterization is presented in [2].

Laboratory tests presented below were carried out on high-quality block samples retrieved in 2024 between 5.3 – 6.2 m depth using the mini Sherbrooke block sampler [16]. At this depth, the electrical conductivity of the pore fluid is EC_{fluid}≈35 mS/cm. To minimize changes in soil behaviour due to modifications in the pore fluid chemistry of Ballina clay specimens, laboratory tests reported in this paper were carried out using a synthetic solution prepared at similar salt concentration as the in situ pore fluid (NaCl≈23 g/L). Values of gravimetric water content for Ballina clay were corrected for the concentration of salts dissolved in the pore fluid following the approach described in [17].

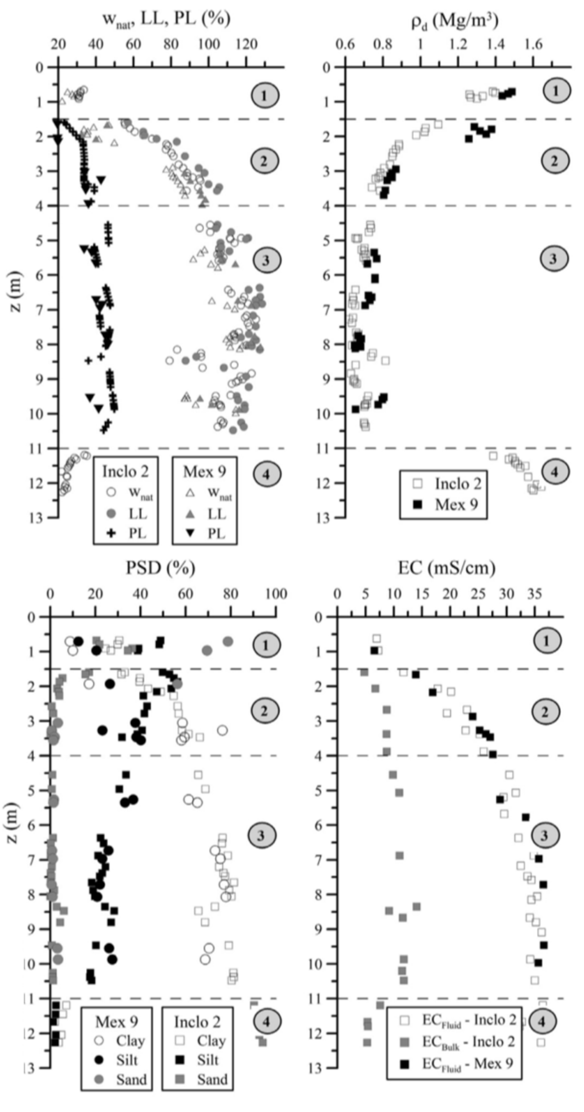


Fig. 1. Index properties of soil deposits at the National soft soil Field Testing Facility in Ballina (NSW) [2]

2.2 Bogotá clay

Bogotá clay refers to the lacustrine soft soil deposits encountered on a high plateau of The Andes Mountains, at 2550m above the sea level, which serves as foundation soil for most of the civil infrastructure of Bogotá City (population of about 9 million) in Colombia. These deposits, with a maximum thickness of about 586 m, are the result of three main deposition mechanisms that took place over the past 3.2 million years [18]: (i) sedimentation of predominant fine-grained materials in a low energy regime under deep water conditions, (ii) sedimentation of silts and sands in a high energy regime in low water tables, and (iii) swamp and fluvio-lacustrine sediments with large proportion of organic matter deposited in shallow water tables. The mineralogical composition includes quartz (~50%), feldspars (15-42%) and clay (15-30%). The predominant clay mineral is smectite.

Fig. 2 presents profiles of index and mechanical properties reported in Caicedo et al. [8] using tube specimens retrieved from seven boreholes drilled to a maximum depth of 240 m. The natural water content is consistently lower than the liquid limit along the entire profile. The liquid limit reaches values up to 200% between 5 – 50 m depth. Plastic limit ranges around 40 – 60 % which leads to plasticity indexes around 150%. The natural profile includes thin layers with values of plasticity index up to 300% which are explained by their large proportion of organic matter. Atterberg limits and the natural water content decrease drastically between 50 - 100 m depth, reaching relatively constant values below this depth. This is reflected by an average plasticity index around 30%.

The organic matter content, estimated using the loss of ignition method [19], increases from 6 -10% (z<5m) up to 30% at z=35m. It decreases to values lower than 10% below 70 m depth. The proportion of clay particles (<2μm) reaches a maximum about 50 % at depths lower than 30m. It then decreases to less than 10%. The unit weight shows large variability with depth, with an average value around 16 kN/m³. This variability is attributed to different degrees of disturbance experienced by the soil during sampling. Similarly, the profile of undrained shear strength, estimated from unconfined compressive strength according to [20], shown in Fig. 2 display large scatter also explained in terms of sample disturbance effects.

Another important feature of the lacustrine soft soils in Bogotá City is the presence of diatoms (fossils) which are composed mainly by silica (~90%) as well as iron and aluminium oxides (~10%). Their low density, open structure and large specific surface area implies that, depending on their proportion within the soil mass, diatoms may play an important role on the water absorption and mechanical properties of the soft sediments.

Laboratory tests presented below were carried out on tube specimens retrieved in 2024 using a 75mm in diameter open (Shelby) sampler between 26 – 27 m depth.

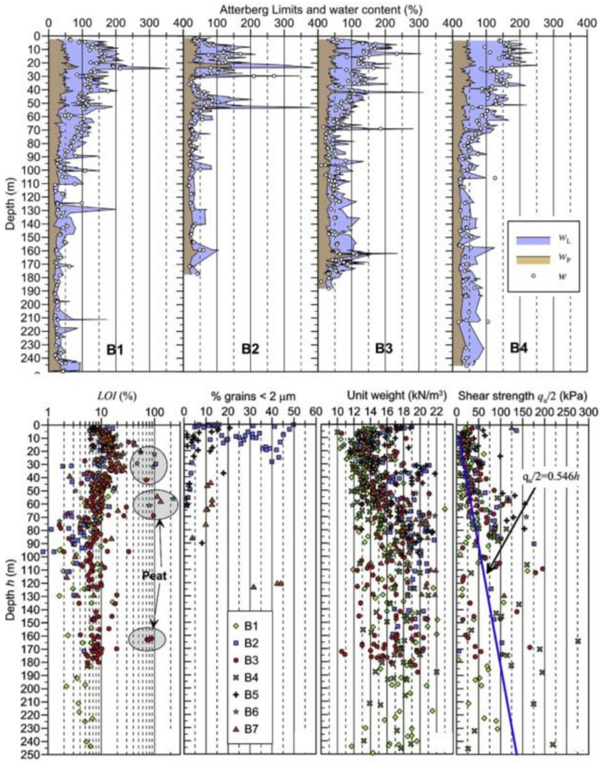


Fig. 2. Index and mechanical properties of the lacustrine soil deposits in Bogotá City [8].

3 Experimental program

The experimental program combined Atterberg limit tests with mechanical tests aimed at estimating shear strength and compressibility parameters. A brief description of the testing protocols is given below.

3.1 Atterberg limits tests

The liquid limit LL was evaluated using the fall cone method following the experimental procedure described in [21]. A standard 80 g cone with an apex angle of 30° with a smooth surface was employed. The penetration of the cone measured after 5 seconds was used in the estimation of the LL. Liquid limit tests were carried out on natural soil but also on material oven dried at 60°C before testing. Each point in the LL test included an equalization/resting period of 24h where the soil mass was placed inside a sealed container to ensure an homogeneous moisture content within the sample. The plastic limit PL was estimated using the thread rolling method.

In the case of Ballina clay, either the natural clay or the clay powder was mixed with a synthetic solution prepared at the in situ electrical conductivity (EC_{fluid}=35 mS/cm). On the other hand, tap water was employed in liquid limit and plastic limit tests carried out on natural and oven dried Bogotá clay.

3.2 Ring shear tests

Drained ring shear tests were carried out on remoulded specimens (natural and oven dried) to estimate the residual friction angle of Ballina clay and Bogotá clay. Saturated ring shear tests were performed in a Bromhead ring shear apparatus following the recommendations given in [22]. Tests on natural specimens (i.e. without previous oven drying) were carried out at the soil's natural water content. The oven-dried material was mixed with fluid (either synthetic saline solution or tap water) to reach a moisture content around 60% (~15% higher than the plastic limit) before ring shear testing. Specimens were consolidated to vertical effective stresses between 25 – 200 kPa. A shearing rate of 0.053 mm/min was adopted to ensure drained conditions.

3.3 Constant rate of strain (CRS) consolidation tests

CRS oedometer tests were performed on natural specimens of Ballina clay and Bogotá clay, following the procedure described in [23]. Specimens of 50 mm in diameter and 20 mm in height were used in the CRS tests. Each test consisted of 3 stages: saturation, loading and unloading. Ballina clay specimens were percolated with a synthetic saline solution (EC_{fluid} = 35 mS/cm) whereas tap water was used for the saturation of Bogotá clay samples. Specimens were loaded monotonically using a displacement rate of 0.004 mm/min. The excess pore water pressure caused by loading was monitored at the base whereas free drainage was allowed from the top of the samples. Table 1 summarizes the initial state of specimens employed in the CRS tests.

Table 1. Initial conditions of natural specimens used in CRS tests.

Specimen	Gs (-)	w/c (%)	e (-)	σ'_{v0} (kPa)
Ballina clay	2.66	134.7	3.51	26.5
Bogotá clay	2.66	174.2	4.55	155

Gs: specific gravity ; w/c: gravimetric water content ; e: void ratio ; σ'_{v0}: estimated in situ vertical effective stress

3.4 Scanning electron microscopy (SEM) analysis

SEM analysis was carried out to evaluate the influence of oven drying on soil fabric. SEM microphotographs for natural soil as well as oven-dried and re-wetted material were compared.

Microphotographs on natural soil were obtained at the soil's natural water content whose moisture content is slightly lower than that at liquid limit. In the case of oven-dried and re-wetted soil, microphotographs were taken on specimens with a moisture content closer to the liquid limit, i.e. the material for which the penetration measured in the fall cone test ranged around 19 - 21 mm. SEM analysis was carried out using a field emission microscope (Zeiss Sigma VP FESEM). Specimens were gold-coated to increase electrical conductivity before SEM photography.

4 Results

4.1 Soil plasticity

Table 2 summarizes the results of the Atterberg limits estimated for natural and oven dried Ballina clay and Bogotá clay. Both soils show a strong influence of oven drying on the liquid limit which reduces from 120% to 93.5% and 170% to 82% for Ballina clay and Bogotá clay, respectively. Interestingly, the plastic limit is insensitive to oven drying, in agreement with previous studies for non-active clays [9].

Table 2. Atterberg limits for natural and oven dried soils.

Soil	Natural			Oven dried		
	LL (%)	PL (%)	PI (%)	LL (%)	PL (%)	PI (%)
Ballina clay	120	46	74	93.5	45	48.5
Bogotá clay	170	46	124	82	43	39

Fig. 3 shows the Atterberg's tests results plotted in the plasticity chart. At natural state, both soils classify as clays of extremely high plasticity (CE). Oven drying reduces the plasticity index of Ballina clay by 30% changing the soil's classification to silt of very high to extremely high plasticity (MV-ME). A more contrasting result is observed in Bogotá clay which, after a reduction in plasticity index of 85%, classifies as silt of very high plasticity (MV).

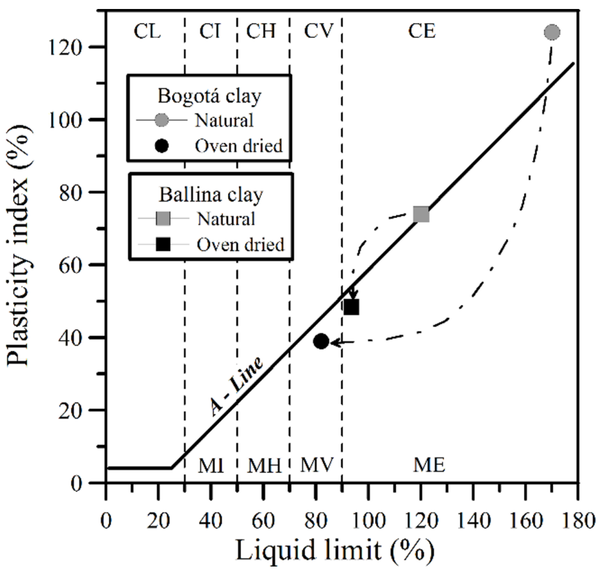


Fig. 3. Plasticity chart

Fig. 4 shows the variation of liquid limit with depth for the materials that compose the soil profile at the NFTF in Ballina, Australia. Values for the natural clay (without oven drying) are replotted here from those reported in the characterization study by Pineda et al. [2]. Additional liquid limit tests (fall cone method) were carried out in this study using leftover samples from the tube specimens tested by Pineda et al. [2]. Those samples where oven dried at 60°C, stored in sealed containers for 9 years, and finally crushed and sieved for liquid limit testing in 2024. The soil powder was mixed with a synthetic solution prepared at the required in situ EC_{fluid} according to the procedure described in [2]. Fall cone tests for oven dried and re-wetted specimens show a lower liquid limit irrespective of the sample depth (see grey symbols in Fig. 4). This effect is more pronounced for the soil below 4m depth where the maximum difference between natural and oven dried LL ranges between 30 – 40%. The results for the block specimen reported in Table 2, are consistent with the trend shown in Fig. 4 and remarks the importance of oven drying on the characterization of this marine soft clay.

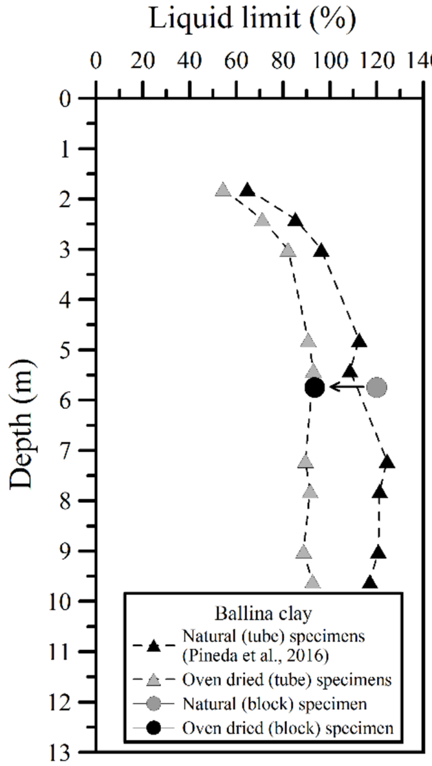
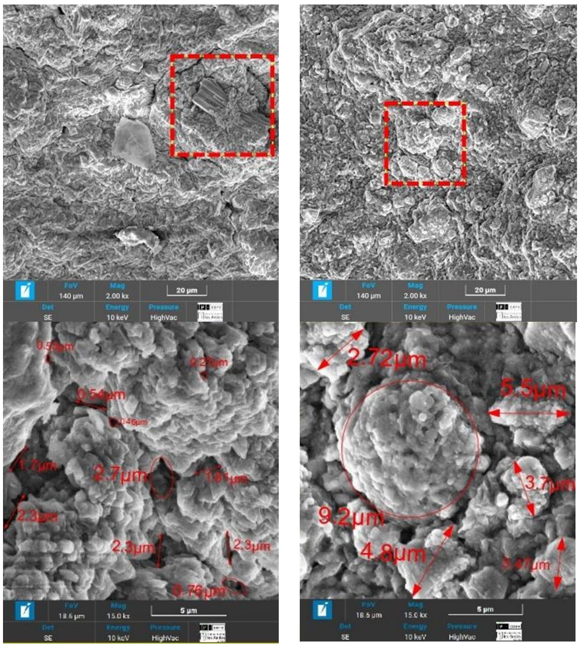


Fig. 4. Variation of the liquid limit at the NFTF. Natural and oven dried measurements

4.2 Soil fabric

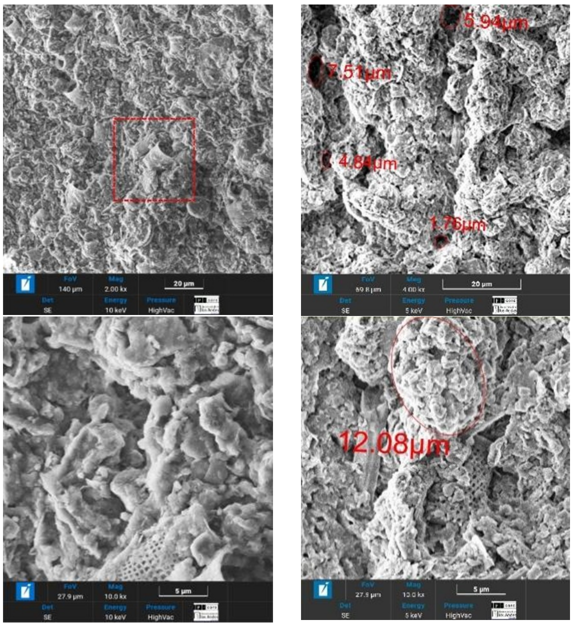
Suwal et al. [24] reported an increase in the proportion of particles lower than 0.1μm when Ballina clay was oven dried prior to liquid limit testing. Although SEM analysis was not reported, Suwal et al., hypothesized that soil aggregation was the reason for this increase.

Figs. 5 and 6 show SEM microphotographs for natural and oven dried Ballina clay and Bogotá clay, respectively. Natural and oven dried samples used in the SEM analysis represent a moisture state close to its liquid limit. Soil aggregation is observed in the clays previously subjected to oven drying. Nevertheless, this feature is more evident in the case of Bogotá clay (Fig. 6). In this case, aggregation of clay minerals creates macro pores not observed in the natural clay. Diatoms are also detected in Bogotá clay specimens. Although diatoms may be sensitive to heating, SEM images indicate that aggregation of soil minerals is the dominant fabric change observed in Ballina and Bogotá clays. The change in the structural arrangement (aggregation) observed in both clays after oven drying is plausible to explain the decrease in the water retention capacity of the clay, i.e. their lower liquid limit. Consequences on mechanical properties are evaluated in following sections.



Natural soil Oven dried soil

Fig. 5. SEM microphotographs of Ballina clay. (left) Natural soil. (right) oven dried soil.



Natural soil Oven dried soil

Fig. 6. SEM microphotographs of Bogotá clay. (left) Natural soil. (right) oven dried soil.

4.3 Residual shear strength

Figs. 7 and 8 shows the evolution of the stress ratio τ/σ' = tan (ϕ'_{res}) with angular displacement for Ballina clay and Bogotá clay, respectively. Natural Ballina clay shows peak stress ratios between 0.33 – 0.47. At large displacements, the stress ratio reduces to 0.25 – 0.35. Oven drying causes an increase in both peak and post-peak τ/σ'. The stress ratio at peak ranges around 0.40 – 0.80 but then it decreases to 0.30 – 0.55 at large displacements. A similar behaviour is observed in Bogotá clay where values of τ/σ' at peak ranges around 0.44 – 0.52 for the natural clay. It reduces to an average value around 0.36 at large displacements. Oven drying also increases the stress ratio of Bogotá clay. Peak values increase up to 0.51 – 0.60 whereas post peak values tend towards 0.37 – 0.43.

The increase in τ/σ' in oven dried clay may be explained by the aggregation observed in SEM images. This effect is clearer at low normal stresses where the aggregated structure is preserved, and the soil seems to behave as a 'granular-like' fabric upon shearing. Another feature of soil oven drying is the increase in soil brittleness observed in the stress-displacement curves which, again, may be explained by the progressive shearing of soil aggregates created during the oven drying and re-wetting process.

4.4 Compressibility

Compressibility curves ε_v vs σ'_v obtained from CRS tests on natural specimens of Ballina clay and Bogotá clay are shown in Fig. 9. Despite the differences in depth and index properties between both soils, Fig. 9 highlights sample quality effects. The compressibility curve of the Ballina clay specimen shows an almost horizontal recompression branch where small volumetric deformation is recorded before the yield stress is exceeded. The behaviour post-yield is non-linear due to the destructuration of the natural fabric. Those features are commonly observed in high quality block specimens [e.g. 25]. On the other hand, the compressibility curve of the specimen of Bogotá clay shows large volumetric deformation (~20%) before reaching the in situ stress ($\sigma'_{v0} \approx 155$ kPa). This suggests severe sample disturbance commonly observed in specimens retrieved with the Shelby sampler.

A direct consequence of sample disturbance is reflected in the compressibility index C_c, a key parameter for settlement calculations. Fig. 10 shows the variation of the compressibility index C_c with the vertical effective stress for natural Ballina clay and Bogotá clay. Values of C_c were estimated from the CRS tests as the derivative of the compressibility curve $C_c = -\partial e/\partial \log(\sigma_v')$. The nonlinearity of the compressibility curve observed for Ballina clay produces a peak in $C_c \approx 1.76$ which takes place at stresses close to σ'_{yield}. C_c reduces with the increase in the stress level, reaching a value around $C_c \approx 0.95$ at large stresses. The poor quality of the natural specimen of Bogotá clay led to similar peak and post peak values of C_c which range around 1.60 and 1.55, respectively. The effect of oven drying on C_c is discussed in following sections.

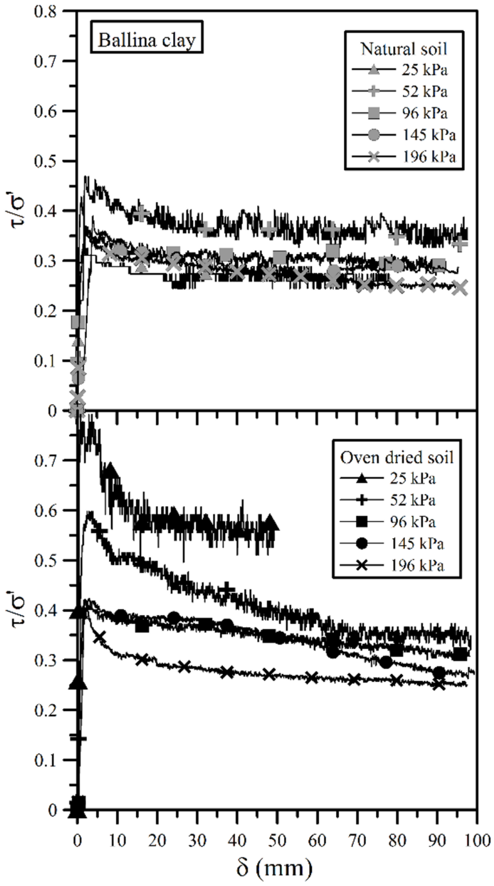


Fig. 7. Results of drained ring shear tests on Ballina clay.

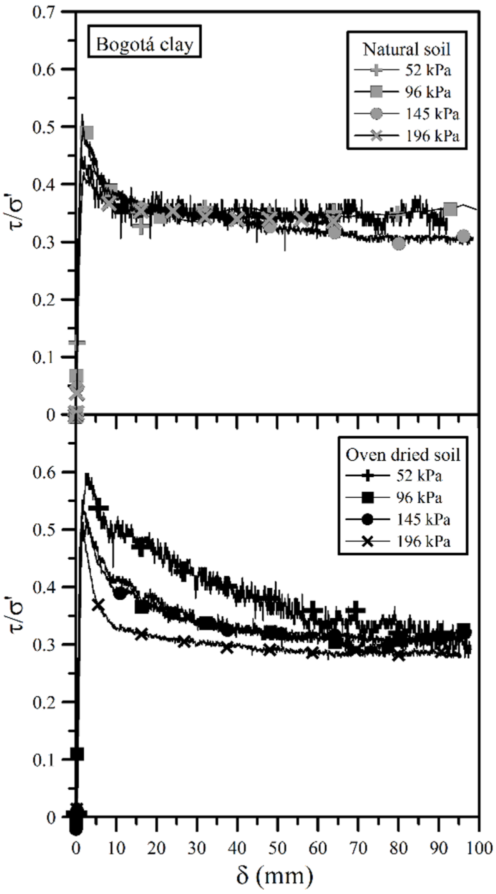


Fig. 8. Results of drained ring shear tests on Bogotá clay.

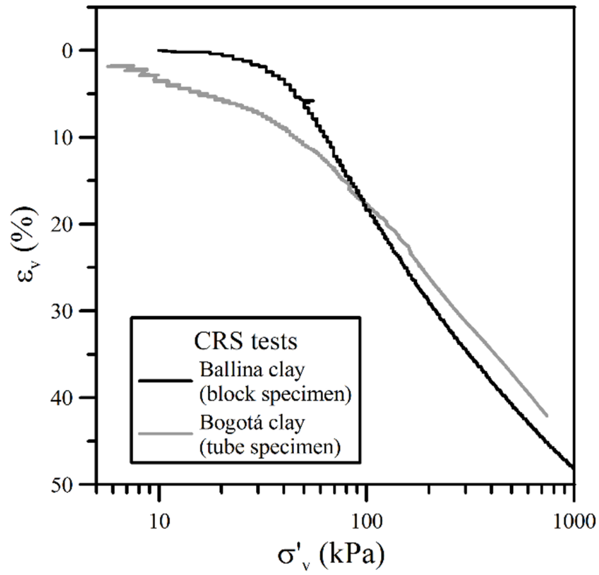


Fig. 9. Compressibility curves for natural specimens of Ballina clay and Bogotá clay.

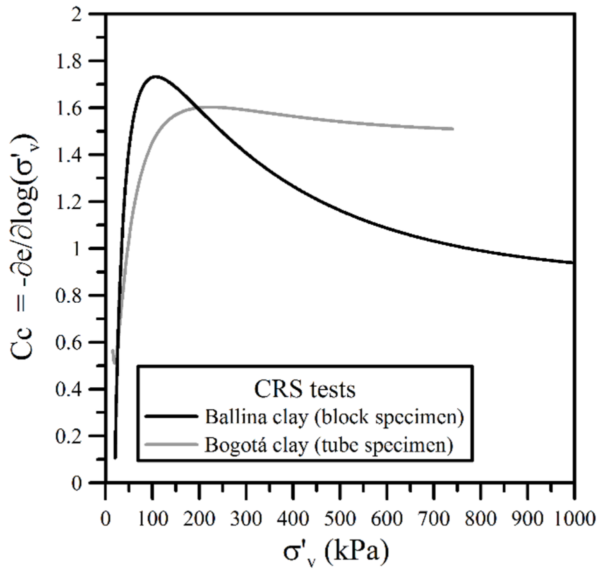


Fig. 10. Variation of the compressibility index C_c for natural specimens of Ballina clay and Bogotá clay.

5 Practical implications

Experimental results presented above have remarked the strong impact of soil oven drying on the plasticity and mechanical properties of a marine (Ballina clay) and a lacustrine (Bogotá clay) soil. This indicates that misleading prediction of soil behaviour may be obtained when empirical correlations are used to estimate soil parameters if oven drying effects are not properly considered. Two empirical correlations available in geotechnical practice are used here to highlight this statement.

Fig. 11 shows the variation of the residual friction angle ($\phi'_{res} = \tan^{-1}(\tau/\sigma')$) with the plasticity index PI. Values of ϕ'_{res} plotted in this figure correspond to those estimated in Figs. 7 and 8 at large displacements ($80 < \delta < 100$ mm). Vertical black lines represent the range of variation of ϕ'_{res} for different normal stress. Grey and black symbols represent mean values. The empirical correlation for the friction angle at critical state ϕ'_{cs} and PI reported in [26] is also included in this figure. Although ϕ'_{res} and ϕ'_{cs} represent different states of shear, they both depend on soil plasticity which makes this comparison acceptable.

Natural Ballina clay shows values around 13° < ϕ'_{res} < 19° (mean ≈ 16°). Oven drying increases the residual friction angle of Ballina clay to values between 16.5° < ϕ'_{res} < 28.5° (mean ≈ 21°). In the case of natural Bogotá clay, ϕ'_{res} shows minimum variation with the stress level, with a mean value of 19°. Oven dried Bogotá clay has a mean residual friction angle of ϕ'_{res} ≈ 22°, three degrees higher than that for natural soil. Ring shear tests indicate that, despite the smaller reduction in soil plasticity measured in Ballina clay, oven drying has a larger effect on ϕ'_{res} in the marine clay than the lacustrine clay.

The empirical correlation included in Fig. 11 suggests a larger increase in ϕ'_{cs} for Bogotá clay after oven drying ($\Delta\phi'_{cs}$≈ 7°) compared with Ballina clay ($\Delta\phi'_{cs}$≈ 3°). Nevertheless, the use of oven dried parameters would lead to unsafe stability calculations (e.g. reactivated landslides) due to the over-prediction of ϕ'_{res} and/or ϕ'_{cs}.

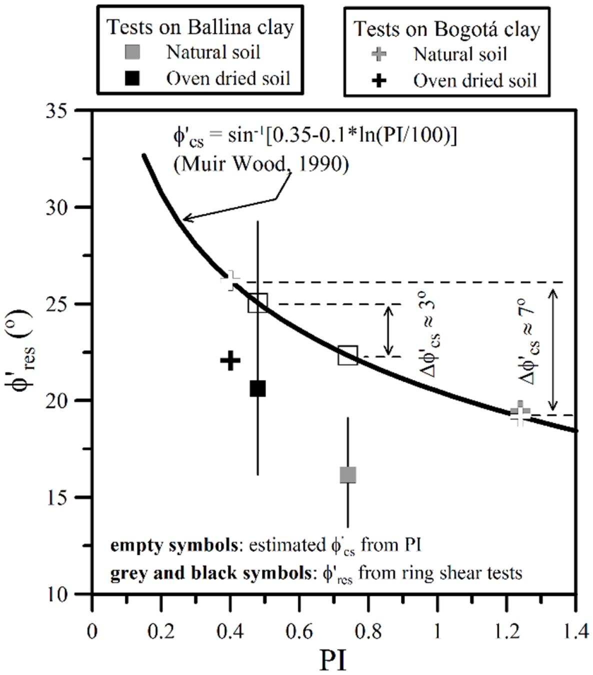


Fig. 11. Variation of the residual friction angle ϕ'_{res} with PI.

Fig. 12 shows the relationship between the compression index C_c, a key parameter in settlement calculations, and plasticity index PI. The relationship reported in [24], $C_c = 1.35*PI$ is plotted in this figure. Grey and black symbols represent values calculated from CRS tests whereas empty symbols refer to estimates for oven dried soil based on PI. The value of C_c calculated for natural Ballina clay at large stresses in Fig. 10 (grey square) plots close to the empirical equation. A similar agreement is observed for values of C_c calculated for Bogotá clay (grey and black crosses). It is important to note that the peak C_c calculated from Fig. 10 for Ballina clay (black square) locates above the linear trend. This empirical correlation does not consider the higher C_c displayed by natural (structured) soft soils which, as in the case of the Shelby specimen of Bogotá clay, may be easily erased during sampling.

The comparison between natural and oven dried values shows a reduction in C_c from 0.95 to 0.65 in the case of Ballina clay (ΔC_c ≈0.30) and from 1.55 to 0.53 (ΔC_c ≈1) for Bogotá clay. Other parameters being equal, this reduction in C_c would lead to large underprediction of the total consolidation settlement [e.g. 27] in these soft soil deposits. A similar behaviour has been recently described in [24] for Cochin Clay, a marine soft clay from India studied by Rao and Sridharan [28].

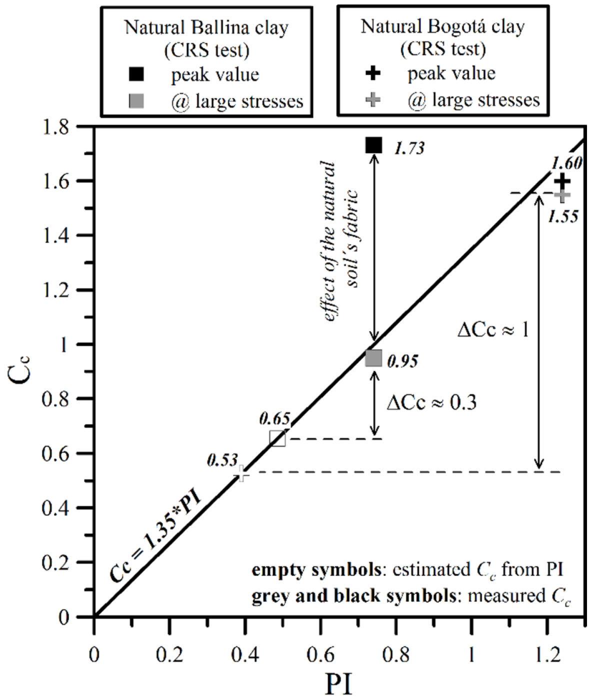


Fig. 12. Variation of the compressibility index C_c with PI.

6 Concluding remarks

This paper has presented experimental evidence of the effects of oven drying on index and mechanical properties of a marine soft clay from Australia (Ballina clay) and a lacustrine soft clay from Colombia (Bogotá clay). Despite their different mineralogical and geochemical compositions, these two soft soils display similar responses after drying:

- The plasticity of both soils reduced post oven drying. A reduction in PI of 30% and 85% was measured in Ballina clay and Bogotá clay, respectively. This decrease in PI is controlled by the reduction in liquid limit.
- SEM analysis indicated that soil aggregation took place after both clays were subjected to oven drying and re-wetting. Soil aggregation seems to decrease the capacity of individual clay minerals to absorb water thus reducing the moisture content at liquid limit. Although diatoms were observed in specimens of Bogotá clay, their proportion is less than that for specimens reported in [8]. SEM images

showed no influence of the diatoms on the mechanism of clay aggregation.

- The residual friction angle increased in specimens previously subjected to oven drying. An increase of 3° and 7° was measured in Ballina clay and Bogotá clay, respectively. Soil aggregation may be responsible for the increase in the friction coefficient of both soils. However, this effect is clearer at low normal stresses where the aggregated structure is preserved, and the soil behaves as a ‘granular-like’ fabric upon shearing.

The practical implications of neglecting the effects of oven drying have been highlighted using two correlations available in the literature. It has been demonstrated that misleading interpretation of soil’s behaviour may be obtained when oven drying effects are not properly considered.

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