Laboratory Behaviour of Rio de Janeiro Soft Clays. Part 1: Index and Compression Properties

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Abstract. This paper describes the Index and compression properties of Rio de Janeiro sedimentary clays properties and behaviour of ten deposits of soft to medium clays, situated in industrialized and residential areas of Rio de Janeiro City and Rio de Janeiro State. The data reported in this paper is a summary of the geotechnical properties obtained from laboratory and in situ tests carried out under well-defined contour and drainage conditions. The deposits are described in terms of its index properties, stress history, compressibility, consolidation and strength properties.

Key words: index properties, compression, stress history, sedimentary clays, laboratory tests.

1. Introduction

The geology of the Rio de Janeiro State consists primarily of granites and gneissic rocks formed in the Precambrian Age. The sedimentary depositions found in the coastal plains consist mostly of alluvia and marine depositions of the Quaternary Age. Kaolinite is the main clay mineral present in the soft clay deposits, but illite and/or smectite can also be found in a smaller proportion (Antunes, 1978). The presence of organic matter in this reduced environment gives the dark grey color observed in Rio de Janeiro soft clays.

Pacheco Silva (1953) carried out a pioneer and important study on the geotechnical properties of Rio de Janeiro clays. However, the most comprehensive study was carried out on Sarapuí soft clay by researchers of the Federal University of Rio de Janeiro (UFRJ) and Catholic University (PUC-RIO), in the seventies and eighties. Lacerda *et al.* (1977) and Werneck *et al.* (1977) presented the first results of these studies and Almeida & Marques (2002) made a comprehensive update.

A number of other soft clays deposits have been studied in the last 30 years in the City of Rio de Janeiro and vicinity, in association with some engineering works. Some examples of these works are the construction of highways around Guanabara Bay, the construction of the Rio de Janeiro subway, besides other projects such as dams, industrial fills, landfills and others.

In some of these deposits it was possible to perform research projects, by means of master or doctoral studies. Botafogo and Uruguaiana (subway: Vilela, 1976, Lins & Lacerda, 1980), Barra da Tijuca (industrial fill), Caju (sanitary fill: Cunha & Lacerda, 1991) and St. Cruz (industrial fill) sites are located in Rio de Janeiro City. Fluminense Plains, Sarapuí (experimental fills, Ortigão *et al.*, 1983), North Coast, Itaipu (experimental excavation: Sandroni *et al.*, 1984) and Juturnaíba dam (Coutinho & Lacerda, 1994) sites are located in Rio de Janeiro State.

This paper summarizes the geotechnical data of these clay deposits (Futai, 1999), which include: index properties, compressibility and stress history, and undrained and drained strengths. The role of the clay structure on both compressibility and undrained strength is also illustrated. A companion paper (Futai *et al.*, 2008) discusses strength and yield behaviour of the Rio de Janeiro soft clays.

2. Soil Characterization

Schematic geotechnical profiles of the Rio de Janeiro clay deposits studied here are shown in Fig. 1. The thickness of these clay deposits varies from 6 m to 15 m and in all but three sites the clay layer reaches ground level. Also a sand layer underlies all clay layers, a common feature of coastal plains. The main geotechnical parameters of these sites, with emphasis on index and compression properties, are summarized in Table 1, except for Fluminense plains. Depending on the available data, values are presented as average values with standard deviation, absolute values or range of values.

For most sites the average plasticity index I_P is in the range 63-81%. Lower values are observed for Botafogo clay (I_P = 11%) and Uruguaiana clay (I_P = 40%). Greater values are observed for Barra da Tijuca clay (I_P = 120-250%).

Rio de Janeiro clays may be grouped in categories. Botafogo and Uruguaiana clays, located in densely populated areas, with a thick fill layer on the top have Atterberg limits lower than the other sites, as shown in Fig. 2. Their clay content and organic matter are also lower. Due to this

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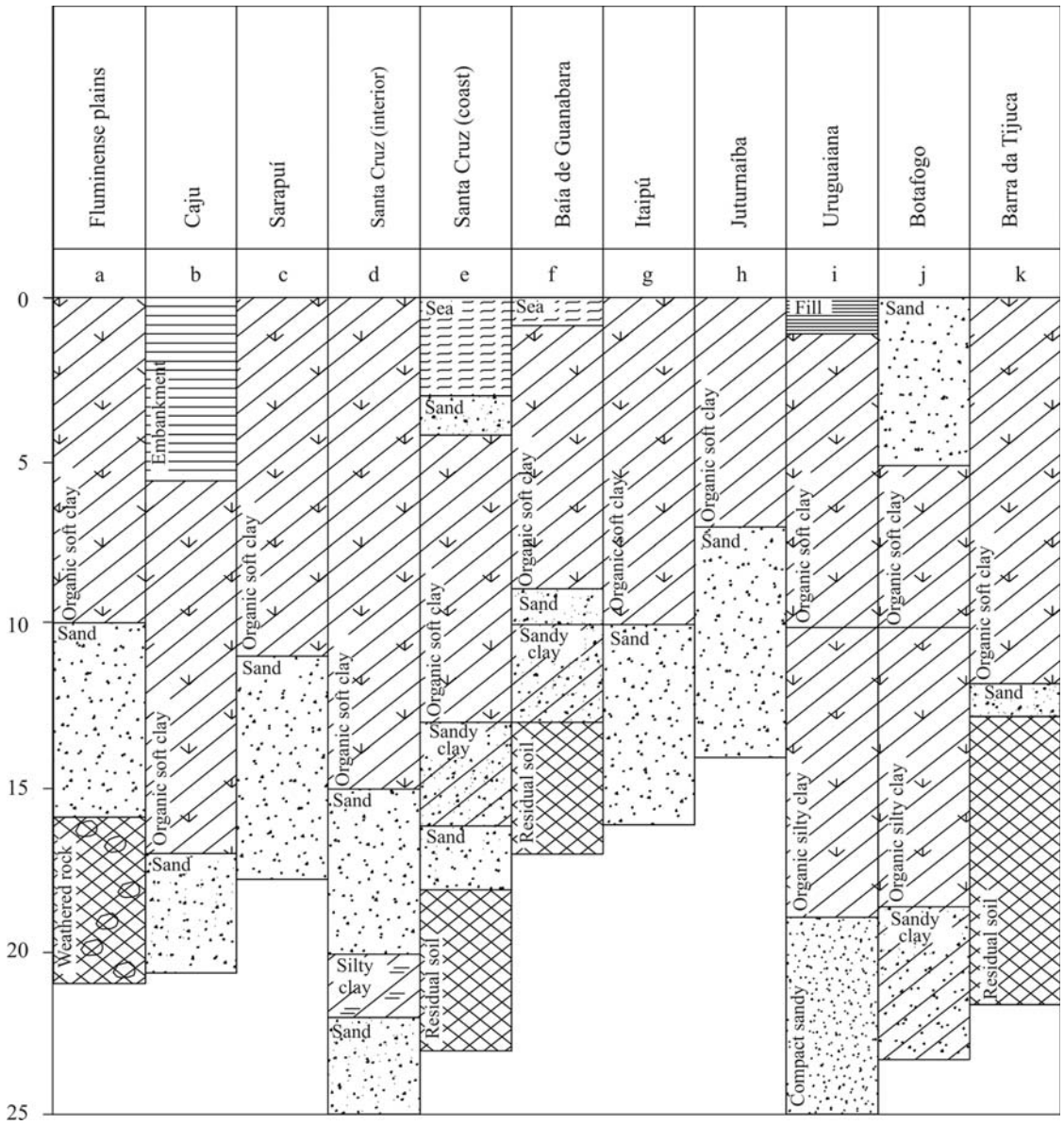

Figure 1 - Geotechnical profiles of Rio de Janeiro clays.

thick fill layer, in situ unit weight γ for Botafogo and Uruguaiana sites are in the range 16-17 kN/m^3 while for the remaining sites they are in the range 12-14.8 kN/m^3. Also, the vane strength, without correction, measured at Botafogo and Uruguaiana sites are in the range 70-110 kPa, thus much greater than the other sites, in the range 6-30 kPa. Therefore, Uruguaiana and Botafogo sites consist of medium to stiff clays, and the remaining sites consist of very soft to soft clays.

Barra da Tijuca, Itaipu and Juturnaíba sites have higher values of I_P, water content and organic matter content (>20%). These clays are also quite compressible. Their friction angles, ϕ', are also higher due to the presence of fibres in the organic matter.

The remaining clays (Caju, Fluminense Plains, North Coast, Sarapuí and St. Cruz) present organic matter contents below 10% that are enough to influence the behaviour of these clays. For these sites, the water content is in the range 80-150%, and close to the liquid limit, as shown in Fig. 2.

The relationship between water content and organic matter is shown in Fig. 3 for four clays, Itaipú, Juturnaíba, Uruguaiana and Sarapuí. It is well known (*e.g.*, Schofield & Wroth, 1968) that the water content is directly related to compressibility and undrained strength. Therefore, it can be concluded that organic content influences directly compressibility and strength.

Table 1 - Geotechnical properties of Rio de Janeiro clays.

Parameter / clay	Caju (b)	Sarapuí (c)	Santa Cruz (IZ) (d)	Santa Cruz (SZ) (e)	Nothern coast of Guanabara (f)	Itaipú (g)	Juturnaíba (h)	Uruguaiana (i)	Botafogo (j)	Barra da Tijuca (k)
References	Lira (1988); Cunha & Lacerda (1991)	Lacerda *et al.* (1977); Ortigão (1980); Almeida & Marques (2002)	Aragão (1975)	Aragão (1975)	Aragão (1975)	Carvalho (1980); Sandroni *et al.* (1984)	Coutinho & Lacerda (1994)	Vilela (1976)	Lins & Lacerda (1980)	Almeida *et al.* (2000)
Clay layer thickness (m)	12	12	15	10	8.5	10	7	9	6	12
w (%)	88	143 ± 21.7	112	130	113	240 ± 110	154 ± 95.6	54.8 ± 15.9	35	100-500
w_L (%)	107.5	120.3 ± 18.0	59.6	125.4	122	175.4 ± 82.6	132.5 ± 43.8	71.3 ± 30.0	38	70-450
I_P (%)	67.5	73.08 ± 16.1	32	89	81	74.5 ± 30.1	63.59 ± 22.1	40.5 ± 22.03	11	120-250
% clay	-	70	-	54	35	-	60.7 ± 12.74	39.4 ± 10.11	28	28-80
γ (kN/m^3)	14.81	13.1 ± 0.49	13.24	13.44	13.24	12 ± 1.85	12,5 ± 1.87	16.1 ± 1.39	17.04	12.5
S_t	3	2.59 ± 0.69	3.39	2-6	-	4 - 6	5-10	3.00	-	5.0
% organic matter	-	4.13 - 5.54	-	-	-	32.63 ± 20.46	19 ± 10.63	2.56 ± 1,04	-	-
$CR = C_c/(1 + e_o)$	0.27	0.41 ± 0.07	0.32	-	0.26 ± 0.15	0.41 ± 0.12	0.31 ± 0,12	0.31 ± 0.15	0.16	0.52
C_α/C_c	0.21	0.15 ± 0.02	0.10	-	0.16 ± 0.04	-	0.07 ± 0.06	-	0.19	0.10
c_v (m^2/s) x 10^{-8}		9	0.2-18.2	-	0.4	5	1-10		30	2-80
e_o	2.38	3.71 ± 0.57	3.09	3.37	2.91	6.72 ± 3.1	3.74 ± 1.89	1.42 ± 0.36	1.1	-

Mitchell (1993) has shown the influence of the organic content in increasing the Atterberg limits and decreasing both the dry density and the undrained strength. For Sarapuí clay, Coutinho & Lacerda (1994) have clearly shown the influence of the organic content in increasing compression index C_c, compression ratio $CR = C_c / (1 + e_o)$, and secondary compression index $C_{\alpha\varepsilon} = C_{\alpha\varepsilon} / (1 + e_o)$.

The relationship between the I_P and the liquid limit w_L has been traditionally used to classify fine-grained soils. The usual functional relationship between I_P and w_L is:

$$I_P = A\,(w_L - B) \tag{1}$$

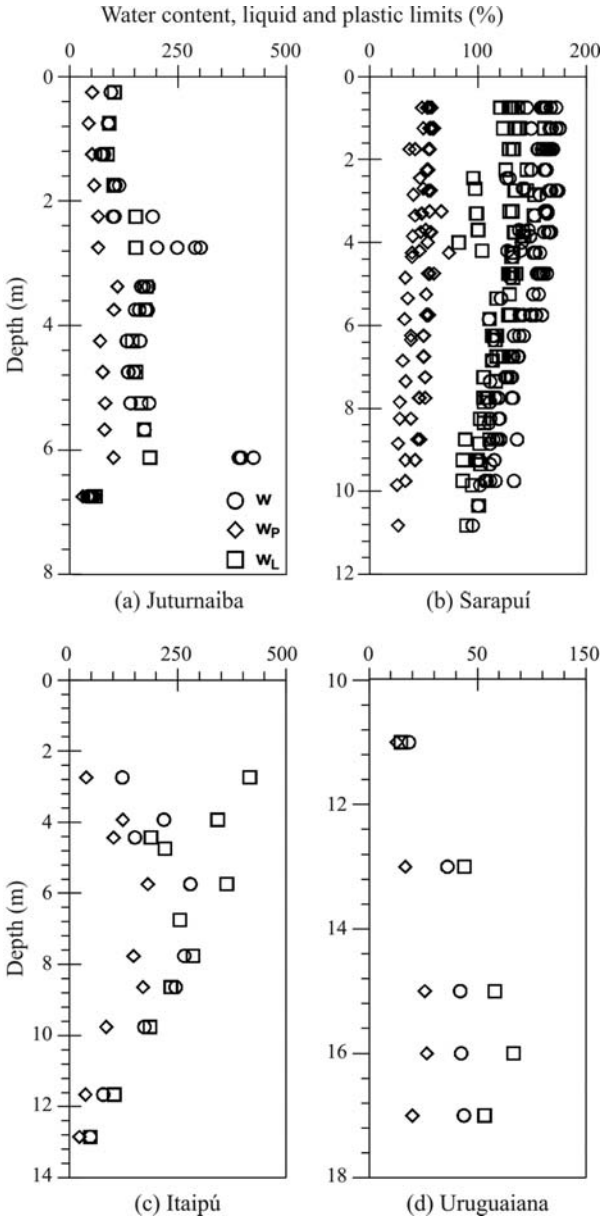

Figure 2 - Water content, liquid and plasticity limits profiles of Rio de Janeiro clays.

The Casagrande A line for soil classification gives $A = 0.73$ and $B = 20$, as shown in Fig. 4. For a large set of data of 520 soils and for I_P and w_L varying between 10-90% and 25-120%, respectively, Nagaraj and Jayadeva (1983) obtained $A = 0.74$ and $B = 8$ for organic soils, yielding a line slightly above the Casagrande line, which still agrees fairly well with data of Rio de Janeiro clays for soils with lower water content.

Four regions in the Plasticity chart were proposed by Futai (1999) and are represented in Fig. 4 and described in Table 2. Three of them are rather well fitted by line A, while region IV is well outside the range of Eq. (1), for Itaipú clay

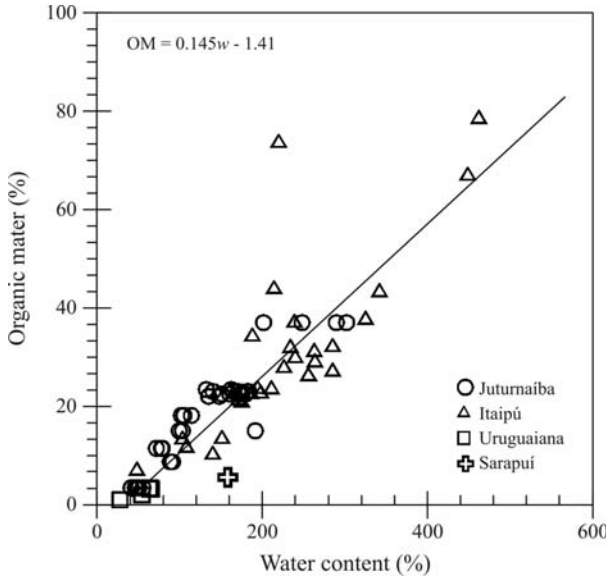

Figure 3 - Organic matter content and water content relationship for Rio de Janeiro clays.

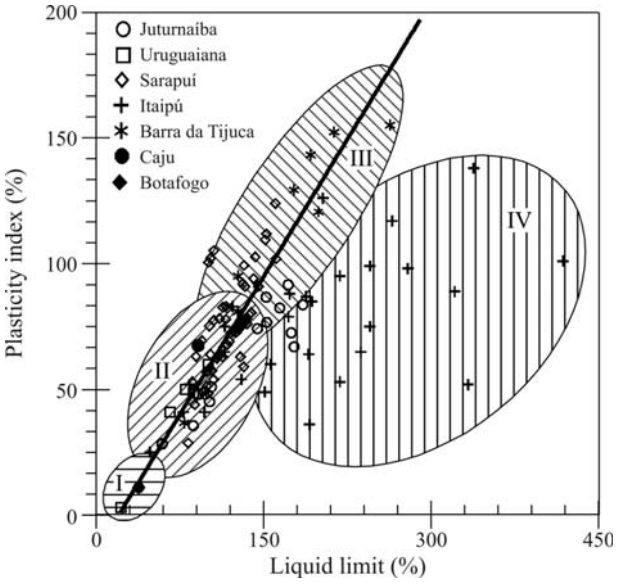

Figure 4 - Plasticity chart for Rio de Janeiro clays (Futai, 1999).

Table 2 - Classification of Rio de Janeiro clays (Futai, 1999).

Classification	Consistency	Plasticity	Compressibility	Strength	e_o	I_P	w_L (%)	$C_c/(1 + e_o)$	S_u (kPa)	ϕ' (°)	Rio de Janeiro clays
Region I	Stiff inorganic clays	Low plasticity	Slightly compressible	High undrained strength	< 2	< 10	< 40	0.15-0.35	>50	28-40	Botafogo, Uruguaiana
Region II	Slightly soft organic clays	Medium plasticity	Compressible	Low undrained strength	2-4	10-120	30-200	0.25-0.35	6-15	25-35	Cajú, Barra da Tijuca, Sarapuí
Region III	Medium soft organic clays	High plasticity	Very compressible	Low undrained strength	4-6	>80	>100	0.40-0.60	6-25	30-40	Juturnaíba, Sarapuí
Region IV	Very soft organic clays - peat	Low plasticity	Very compressible	Low undrained strength	>3.5	>130	>150	0.25-0.35	10-25	< 65	Itaipú

and also for Juturnaíba clay, due to their high value of organic matter. This classification is also a function of compressibility and the range of the strength parameters, as shown in Table 2.

3. Compressibility and Stress History

The variation of the overconsolidation ratio OCR with depth, for eight clay deposits, is shown in Fig. 5. The OCR profile for all clays is within a narrow range, which suggests that the stress histories of the clay deposits in the Rio de Janeiro region are similar. The clay deposits sometimes present a dissecated crust with higher OCR value, which thickness can be as high as 4 m.

As seen in Table 1, the compression ratio *CR* of most clays is in the range 0.26-0.32. Outside this range are Barra da Tijuca, Itaipú and Sarapuí clays, with *CR* varying between 0.41 and 0.52, and Botafogo clay, with *CR* = 0.16. Data of compression ratio *CR* were obtained from conventional oedometer tests as well as radial oedometer tests.

Values of compression index C_c and the swelling index C_s of five clays are shown in Fig. 6. C_c and recompression index C_r values with depth present the same trend as the water content and plasticity profiles, as shown in Fig. 2.

Values of C_c of seven clays have been plotted against the water content, as shown in Fig. 7. The correlation found is $C_c = 0.013w$. Similar linear correlations have been obtained for other clays, $C_c = 0.01w$ for Chicago and Alberta normally consolidated clays (Koppula, 1981) of low sensitivity ($S_t < 1.5$); and $C_c = 0.0115w$ for a number of organic silts and clays (Bowles, 1979). Data of compressibility index of eleven reconstituted clays with liquid limit in the range 36-160% (Nagaraj & Miura, 2001) provided $C_c = 0.0103w$. The clay sensitivity is defined by the ratio between intact and remolded undrained strengths, thus it reflects the effects of soil structure cementation, thixotropy and aging, amongst other factors. It has been suggested

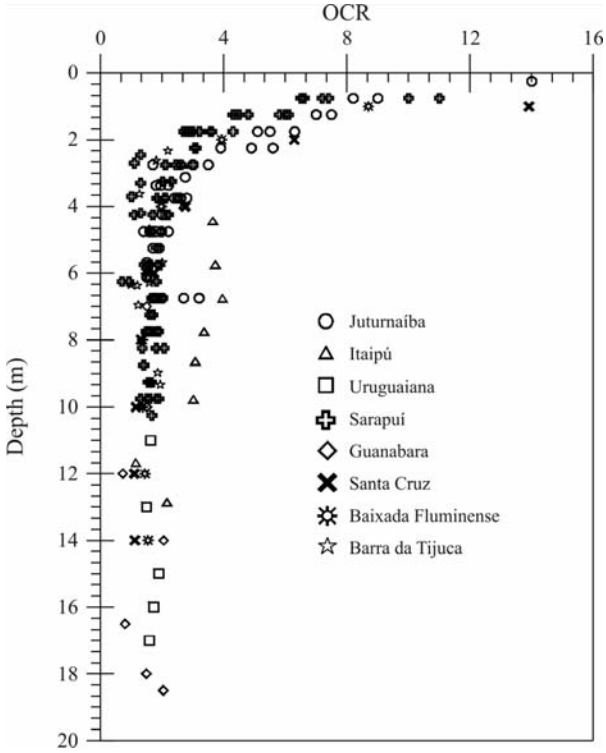

Figure 5 - OCR profiles of Rio de Janeiro clays.

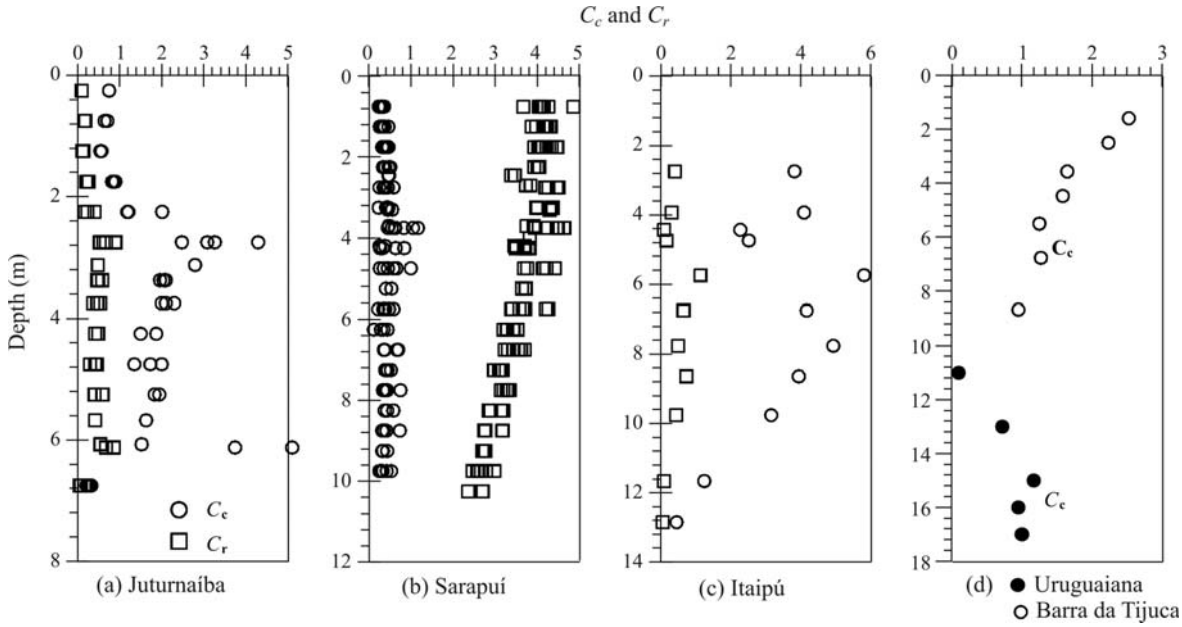

Figure 6 - C_c and C_r profiles of Rio de Janeiro clays.

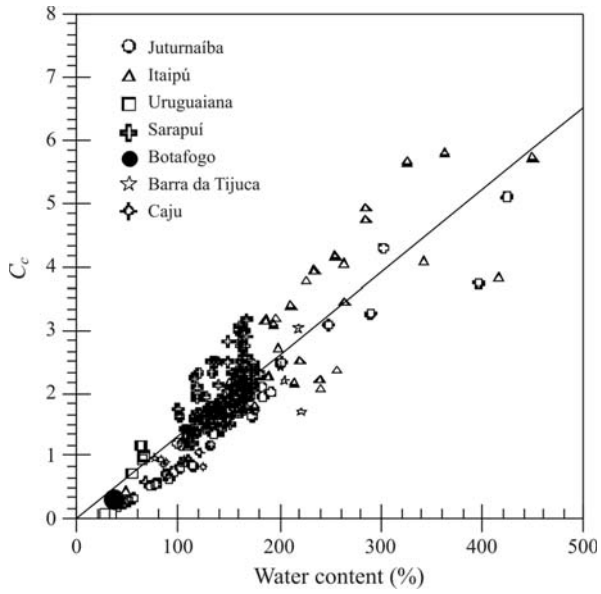

Figure 7 - Average relationship between C_c and water content of Rio de Janeiro clays.

(Leroueil *et al.*, 1983) that the compression index C_c increases not just with water content, but also with clay sensitivity S_t. This behaviour was also observed for Rio de Janeiro clays (Futai, 1999).

4. Summary and Conclusions

A summary of the geotechnical data of Rio de Janeiro clays was presented describing index properties, compressibility, stress history and undrained and drained strengths.

The majority of these clays presented high values of water and organic matter contents. The friction angle is also higher due to presence of fibres in the organic matter. The compression ratio *CR* is in the range of 0.26-0.32, however Barra da Tijuca, Itaipú and Sarapuí clays are more compressible, with *CR* varying between 0.41 and 0.52. The OCR profiles of these clays are very similar, thus indicating similar deposit formation.

The relationship between C_c and water content is $C_c = 0.013w$, well within the range of normally consolidated clays.

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The geotechnical properties of Rio de Janeiro clays, summarised herewith, result from a large number of studies, particularly master and PhD dissertations. The authors are very much indebted to all involved in these studies, which made the preparation of this paper possible.

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