The paper was published in the proceedings of XVI Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVI PCSMGE) and was edited by Dr. Norma Patricia López Acosta, Eduardo Martínez Hernández and Alejandra L. Espinosa Santiago. The conference was held in Cancun, Mexico, on November 17-20, 2019.

Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190310

Influence of Water Treatment Sludge Addition on the Compressibility and Shear Strength Parameters of Two Lateritic Soils

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Abstract. This article analyzes the influence of the addition of water treatment sludge (WTS) on the compressibility and shear strength parameters of two Brazilian lateritic soils (a clayey sand and a clay) in order to enable the waste reuse at geotechnical works. The lateritic soils, the WTS and the mixtures were geotechnically characterized and subjected to compaction, one-dimensional consolidation and undrained triaxial compression tests. WTS addition altered the compaction parameters of the soils by decreasing the maximum dry unit weight and increasing the optimum water content. The mixtures presented higher values of compression indexes than the soils, and correlations are presented relating compression index to WTS content. The effective cohesion decreased with WTS addition and the effective friction angle increased. Nevertheless, some the obtained values for compressibility and shear strength parameters can still be allowable for earthworks, depending on the structure requirements.

Keywords. Water treatment sludge, lateritic soils, compaction, compressibility, shear strength.

1. Introduction

Water treatment plants (WTPs) produce potable water by removing impurities from raw water. In a conventional WTP the main treatment processes are flocculation, decantation, filtration, pH correction, disinfection, and fluoridation. During the treatment process, several chemicals are added to the water, such as a coagulant agent (ferric chloride, aluminum sulfate, polymers, among others) for the coagulation/flocculation stage. Washing of sedimentation basin and granular media filters generates a residue commonly known as drinking-water sludge or water treatment sludge (WTS), composed of water and organic and inorganic solids: chemical compounds, bacteria, viruses, algae, organic matter, and soil particles. WTS has very low solids content, between 18 and 25%, which in geotechnical engineering means water content of 455 and 300%, respectively.

A single WTP may generate thousands of tons of WTS every year. Safe and low-cost disposal options are limited. Nowadays, one of the biggest concerns for WTPs is the destination of WTS, since discarding in watercourses, which was a common practice,

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is no longer permitted in most countries. In Brazil, an environmental act prohibits releasing untreated WTS into watercourses [1]. Hence, WTPs dispose their sludge in sanitary or industrial landfills, or discharge it into sewage treatment plants.

New alternatives for WTS destination are urgently needed. A promising alternative is its reutilization as a construction material at earthworks [2]. However, because of the very high "natural" water content, WTS is not an adequate material for geotechnical works unless the water content is drastically reduced. On the other hand, drying WTS is an expensive and time-consuming process. A favorable alternative is to blend WTS with natural soil in a ratio that warrants the geotechnical properties of the soil are not significantly altered [3].

This paper shows the results of an investigation that studied the influence of WTS addition to two lateritic soils, a clayey and a sandy soil, on the compressibility and shear strength behavior in order to use the soil-WTS mixtures for geotechnical works.

2. Materials

2.1. Water treatment sludge

The sludge was collected at Cubatão Water Treatment Plant (WTP), one of the largest WTPs in the State of São Paulo. Cubatão WTP has a production capacity of 4500 L/s of potable water and the treatment process uses ferric chloride ($FeCl_3 \cdot 6H_2O$) as coagulant. After sedimentation, the sludge with 2% of solids content is dewatered by centrifuges, generating approximately 60 tons per day of sludge with solids content of 20 to 25%.

The sludge is classified as a silt of high plasticity (MH) [3] according to the Unified Soil Classification System (USCS) [4]. The sludge presents high percentage of iron oxides (46% of dry mass), high cation exchange capacity (CEC = 255.2 $mmolc.kg^{-1}$), and low organic matter content (OM = 26 g/kg) [3].

2.2. Lateritic soils

Two Brazilian lateritic soils were used in this research, a clayey sand and a clay, which are representative of large areas of the State of São Paulo. The clayey sand was collected in Botucatu city, it is classified as clayey sand (SC) according to USCS [3,5], and as a lateritic clayey sand (LA') according to MCT (Miniature-Compacted-Tropical) [6] a Brazilian classification system for tropical soils [7]. The clay was collected in Campinas city, classified as a clay of low plasticity (CL) according to USCS [8], and as lateritic clay (LG') according to MCT [9].

3. Methods

The research comprised six stages: mixtures preparation, geotechnical characterization, compaction tests, specimen preparation, compressibility tests, and shear strength tests only with Campinas clay and clay-sludge mixtures. Montalvan [3] previously conducted compaction, compressibility and triaxial compression tests with Botucatu sand and sand-sludge mixtures. All tests were carried out according to procedures from the standards of the American Society for Testing Materials (ASTM).

3.1. Preparation of Soil-WTS mixtures

Mixtures of the two lateritic soils with WTS were prepared at three ratios (soil:sludge) by wet weight: 5:1, 4:1, and 3:1 for Botucatu sand, and 4:1, 3:1, and 2:1 for Campinas clay. Throughout the paper, Botucatu sand mixtures will be referred to as BC (Botucatu-Cubatão) and Campinas clay mixtures as CC (Campinas-Cubatão).

3.2. Geotechnical characterization

The geotechnical characterization of the soils, the sludge, and the mixtures comprised determination of grain size distribution (GSD) curves, Atterberg limits, and specific gravity of solids. The characterization of the soils was conducted using samples air-dried to hygroscopic water content. However, the characterization of the sludge and the mixtures was carried out without drying, since previous researches showed that air-drying significantly change the values of index properties of these materials [3].

3.3. Compaction tests

Compaction parameters of the soils and mixtures were determined via the conventional Proctor compaction test using standard effort and reuse of material. The dry method was used for the soils and the wet method for the mixtures, since air-drying significantly alters compaction parameters of soil-WTS mixtures [3].

3.4. Specimens preparation

Specimens of the soils and mixtures for compressibility and shear strength tests were molded from compacted samples. The samples were compacted at its optimum water content and maximum dry unit weight obtained by compaction tests using standard effort. The compaction quality was evaluated considering an allowable water content deviation of 1% and a relative compaction ($\gamma_{d,sample}/\gamma_{d,max}$) of 97%. All specimens were sealed and stored in a moist room after compaction during a period of at least 24 h.

3.5. Compressibility tests

One-dimensional consolidation tests (oedometer test) were performed in order to investigate the constrained compressibility behavior (K_0 condition), using: load increment ratio equal to one, load increment period of 24 h, and water flooding of the specimen at the first loading stage. The specimens had diameter of 7.13 cm and height of 2.00 cm.

3.6. Shear strength tests

The shear strength behavior of the materials was investigated via Isotropically Consolidated Undrained (CIU) triaxial compression tests with pore pressure measurement.The CIU tests were carried out with three confining pressures: 50, 100 and 200 kPa. The specimens height (L) and diameter (D) were, respectively, 76 mm and 38 mm (L/D = 2). Saturation was achieved using backpressure, and the specimens were considered saturated when the Skempton B-value was equal or greater than 0.95. In the shearing stage, a loading rate of 1%/h was applied until a maximum axial strain of 15%.

4. Results and discussions

4.1. Characterization

The geotechnical characterization of the soils and mixtures is presented in Table 1. Sludge addition did not change the B-soil classification. Plasticity of C-soil mixtures increased with the increase of sludge content, reflected in gradual alteration of the classification.

Table 1. Geotechnical characterization of the soils, sludge and mixtures.

Material	w_L (%)	PI (%)	G_s	Soil Classification	Clay (%)	Silt (%)	Sand (%)
B Soil[1]	31	14	2.69	CL	24.4	9.8	65.8
AMR01 Sludge[1]	239	158	2.85 - 2.95	MH	69.3	26.1	4.6
5:1 BC[1]	32	14	2.71	CL	26.8	9.3	63.9
4:1 BC[1]	32	15	2.70	CL	23.9	8.3	67.8
3:1 BC[1]	33	16	2.69	CL	27.1	9.5	63.4
C Soil	45	18	2.98	CL-ML	51.9	26.2	21.9
AMR07 Sludge	237	138	2.94	MH	78.1	20.2	1.7
4:1 CC	46	18	2.74 - 2.78	CL-ML	44.7	35.4	19.9
3:1 CC	50	16	2.70 - 2.80	ML-MH	47.8	32.7	19.5
2:1 CC	63	27	2.77 - 2.84	MH	44.7	36.1	19.2

[1] Montalvan (2016) [3]; w_L= liquid limit, PI = plasticity index, G_s = specific gravity of solids

The specific gravity of solids of C soil is high (2.98) due to the high content of iron oxides and coherent with G_s values for lateritic clayey soils [7]. On the other hand, B soil, composed mostly of quartz (G_s of 2.648), presents G_s equal to 2.69. Addition of sludge (G_s=2.85-2.95) did not increase G_s of B soil and even decreased G_s of C soil. A possible explanation is the formation of clusters of clay particles induced by the coagulant in the sludge, trapping air inside the flakes. This effect is more evident for CC mixtures, since C soil has clay fraction of 51.9%, and the sludge addition decreased the clay fraction to 44.7%. B soil probably underwent the same phenomenon, but since B soil has lower clay content (24.4%), alterations could be inside the range of experimental errors for GSD curve.

4.2. Compaction parameters

Figure 1 shows compaction curves of the soils and mixtures. B soil and C soil presented values of maximum dry unit weight equal to 19.1 and 15.7 kN/m^3, respectively. Optimum water content values were 12.4 and 26.2%, respectively. C soil presented lower maximum dry unit weight and higher optimum water content due to its higher percentage of fines.

All mixtures presented a consistent variation of the compaction parameters: the higher the sludge content, the lower the maximum dry unit weight and the higher the optimum water content. An explanation for the mixtures presenting compaction parameters similar to those of cohesive soils is based on the high plasticity and high fines percentage of the added sludge.

Compaction curves of 4:1 and 3:1-BC mixtures (Figure 1) are not complete: after sludge addition to B soil, the mixtures had a water content corresponding to wet-of-optimum and only a few points could be determined on the wet side of the curve. On the other hand, all CC mixtures presented a complete compaction curve.

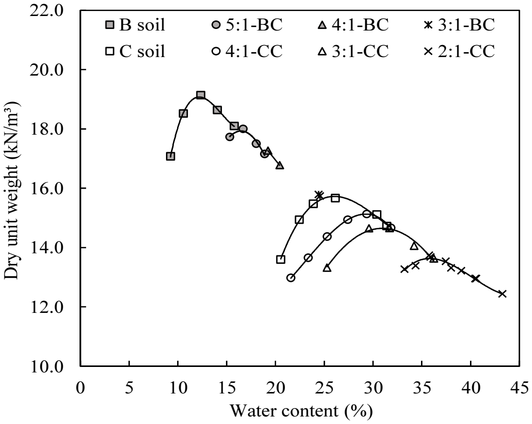

Figure 1. Compaction curves of the soils and their mixtures with sludge.

4.3. Compressibility

Compressibility (K_0-condition) or one-dimensional consolidation curves of the soils and soil-sludge mixtures are presented in Figure 2. Void ratios were calculated with G_s of the mixtures estimated as a weighted average of sludge and soil original values. All mixtures are more compressible than the respective soil without sludge addition. The addition of WTS provokes a reduction in the dry unit weight of the compacted soils (Figure 1) and in the void ratio. The C soil and its mixtures present higher void ratios than those of the B soil and its mixtures (Figure 2).

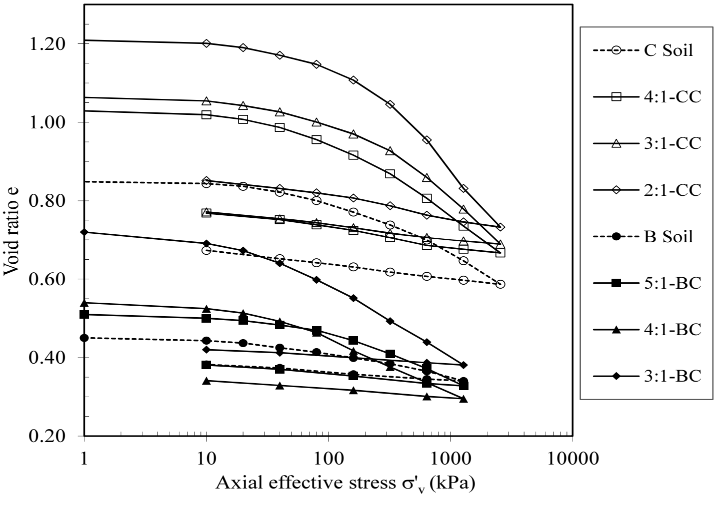

Figure 2. One-dimensional consolidation curves of the soils and soil-sludge mixtures.

Figure 3 (a) shows the variation of the compression and recompression indexes (Cc and Cr, respectively) with sludge content by dry weight (wts). Values of Cc are higher for C soil and CC mixtures than for B soil and BC mixtures.

The increase of Cc with the increment of sludge content for both soils may be represented satisfactorily by a linear correlation (R^2 of 0.90 for C soil and mixtures, and R^2 of 0.95 for B soil and mixtures). Cr of both soils did not vary significantly with WTS addition, with values of 0.02 for B soil BC mixtures, and 0.04 for C soil and CC mixtures. Possible deviations remain inside the range of variation of the experimental data.

Considering the linear correlations between Cc and wts, and between Cc and dry unit weight (γ_d), it is also possible to express the variation of Cc in terms of dry unit weight and wts, as shown in Figure 3(b).

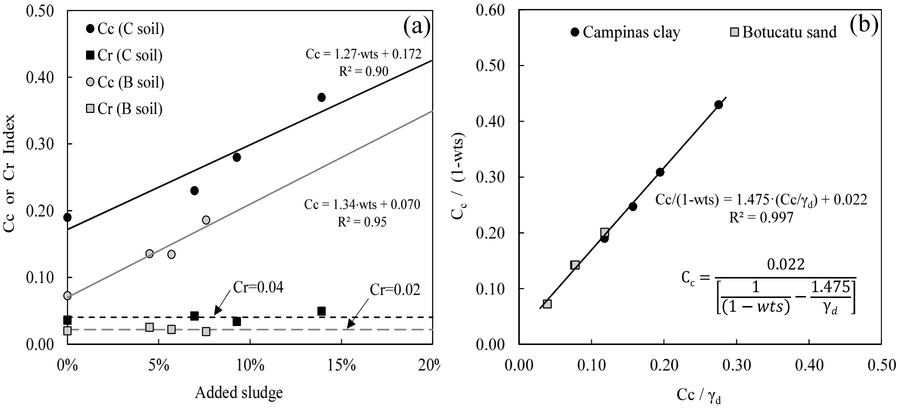

Figure 3. **(a)** Variation of compression and recompression indexes with percentage of added sludge; and **(b)** Normalized compression index.

4.4. Shear strength

Figure 4 depicts the stress paths in terms of effective stresses obtained from the CIU triaxial compression tests with C soil and CC mixtures.

It is observed that the higher the percentage of added sludge the higher the developed pore pressures. This behavior is related to a lower preconsolidation pressure and higher compressibility, although, all specimens were dynamically compacted with standard effort (Proctor compaction). Regarding to undrained behavior, it can be noticed that the maximum deviator stress decreases with addition of sludge to C soil, probably, because of the development of higher pore pressures.

The effective strength parameters of the C soil and CC mixtures were determined from the stress paths using the maximum effective stress ratio $(\sigma'_1/\sigma'_3)_{max}$ as failure criteria.

Figure 5 shows the variation of effective cohesion (c’) and effective friction angle (ø’) with the percentage of added sludge for both soils. Effective cohesion values tend to decrease with the increment of the percentage of added sludge.

For the clay (C soil), c’ values decreased from 34 kPa to 14 kPa (mixture 2:1, wts=7,5%); for the sand, from 15 kPa to 9 kPa (mixture 3:1, wts=13.9%). Authors have reported values of c’ for WTS around zero (0 kPa) [11], that could explain the decrease in c’ values for BC and CC mixtures.

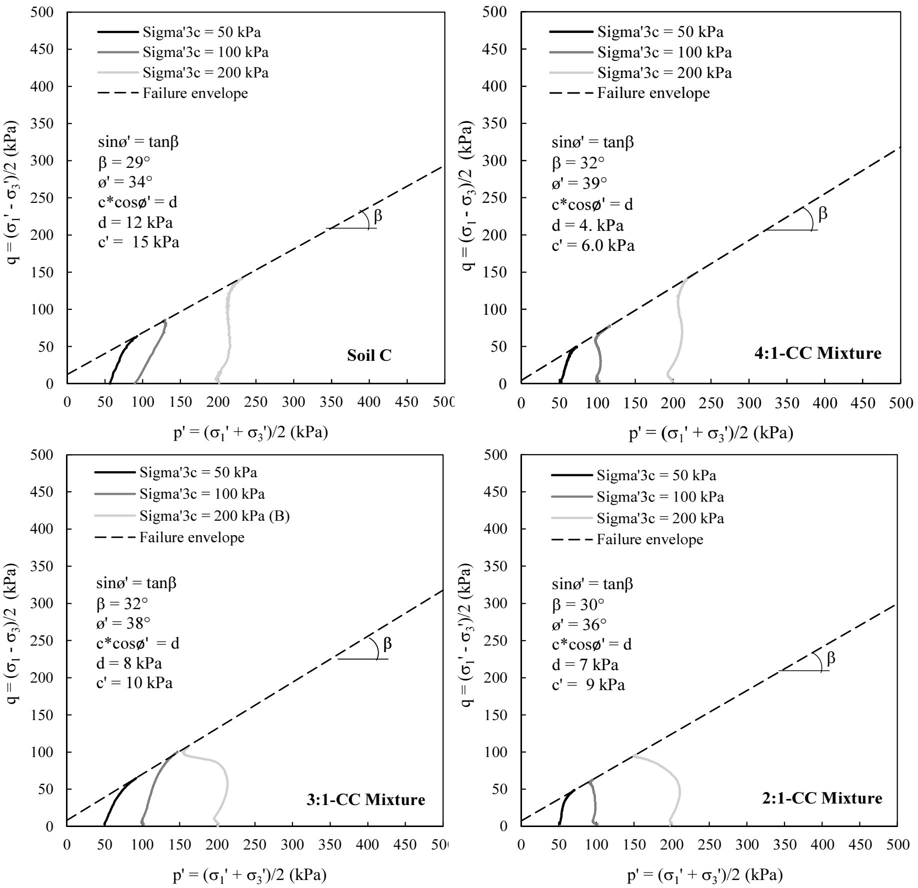

Figure 4. Stress paths from ICU triaxial compression tests with C soil and CC mixtures.

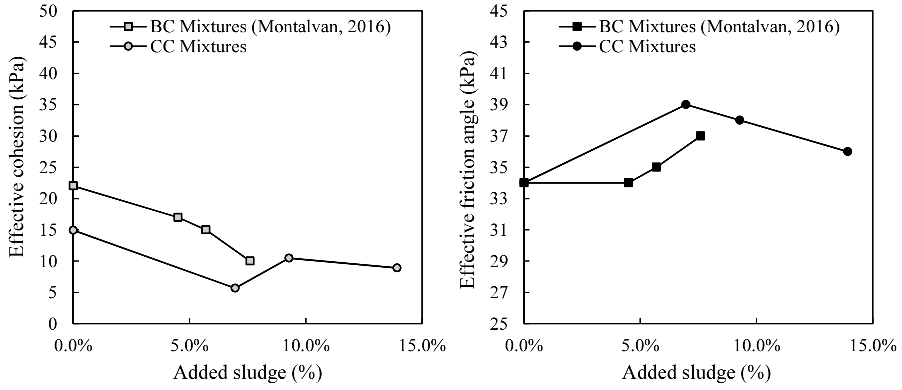

Figure 5. Effect of sludge content on the strength parameters.

The ø' values, on the contrary, tend to increase. For the clay, it increased from 34 to 36° and for the sand, from 34 to 37°. This behavior could be related to changes in the internal structure: the sludge addition could be causing a more stable structure or even particles cementation. Moreover, some authors have reported effective friction angle values for WTS higher than 40° [2, 11].

5. Conclusions

- Sludge addition at the investigated ratios did not significantly change the index properties of the studied lateritic soils. Thus, the mixtures presented the same classification as the soils.
- The compaction parameters were considerably influenced by sludge addition. The optimum water content increased, and the maximum dry unit weight decreased with sludge content. This influence was more significant for Botucatu sand mixtures than for Campinas clay mixtures.
- Sludge addition increased the compressibility of the soils. The higher the percentage of added sludge, the higher the compression index. However, recompression indexes did not alter significantly.
- Effective shear strength parameters, c' and ø', decreased and increased, respectively, with sludge addition. Nonetheless, the variations were slight and contrary to the expected behavior.
- Although compressibility and shear strength of the soils were influenced by sludge addition, the values of these parameters for the studied blending ratios are still allowable for many earthworks. Since sludge addition seemed to affect more the compressibility than the strength parameters, compressibility could be the determining factor when evaluating the suitability of soil-sludge mixtures as construction material for geotechnical structures. However, different earthworks have different compressibility and strength requirements, thus, a careful evaluation of what parameters are more important must be done.

Acknowledgements

The authors gratefully acknowledge financial support from the São Paulo Research Foundation (FAPESP, file numbers: 2013/50448-8 and 2017/24056-6), *Conselho Nacional de Desenvolvimento Científico e Tecnológico* (CNPq) and *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* (CAPES). In addition, we thank the Cubatão Water Treatment Plant for the supply of the sludge.

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