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Shear Strength Characteristics of a Bauxite Tailing

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Abstract. The global demand for metals has been growing intensely in recent decades. Therefore, it increases the amount of mine waste produced in mining and beneficiation of ores, from which metals of economic interest are extracted. This increase in demand allows that areas less rich in mineral become economically feasible, thus generating millions of tons of mine waste. The disposal of the tailings requires large dams and dikes, which in turn require special care from geotechnical and environmental aspects. Thus, the use of mine waste as landfill construction material would minimize the volumes of tailings dams. To make the mine waste useable from a geotechinical point of view it is necessary to determine the geotechnical parameters involved with the application. One of the most important aspects are the shear strength. In this paper, an experimental investigation of geotechnical behavior of a bauxite tailing from Miraí mine, located in Minas Gerais - Brazil, is presented. The geotechnical characterization of a bauxite tailing is shown, and the mechanical behavior of the compacted material is given. The investigation was performed with Triaxial tests (CAU), in order to characterize the material in terms of shear strength and deformability.

Keywords. Bauxite mining, bauxite tailing, shear strength, small-strain deformation.

1. Introduction

Brazil is the third largest bauxite producer in the world, with 34.5 million of tons per year. This production position generates a quantity of mining tailings that reach 14 million of tons per year [1]. In general, the tailing has no economic value and is disposed in tailing dams. The use of mining tailings as landfill materials is an alternative to be consider improving economic and environmental aspects of the production of aluminum. The steady growth of bauxite tailings in the world requires that alternative uses of these materials be investigated [2]. Actually, there many suggestions to improve the use of bauxite tailing, but all of them is a low volume use [3], which may be different of a geotechnical use. In the specific case of bauxite red muds, the major problem is generally its high potential for contamination due to the chemical process the ore bauxite benefited is usually subjected. The initial processing of bauxite is simple since requires only the removal of clay, which can be done by a simple washing, screening, cycloning and sorting beneficiation process. In the case of the mine of Miraí, located at the state of Minas Gerais (Brazil), there is a separation of the concentrate prior to the application of

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the Bayer process, common operation in the Brazilian's bauxite treatment. The Bayer process generates a residue with potential for contamination denominated red mud. The tailings characterized for this paper has no potential for contamination, since no chemical were added to these.

The usual variability of the tailing can generate variation on the material geotechnical properties, which may create difficulties for its use. An effort should be made to reduce this variability. As a non-natural material, the tailing does not follow natural segregation and may present an unusual behavior even when compacted. For this reason, it is important to evaluate the behavior of that type of material and assess its variability. The geotechnical behavior of the bauxite tailing (most of them red mud) has been investigated by many researches under different aspects (e.g. [4], [5], [6], [7], [8], [9]). The deposition of tailing (in general) as a slurry form a beach which has its importance for the design of the tailing facilities, affecting the storage capacity, the tailing dam itself and the eventual cover when required [10], [11]. Although the use of any tailing material requires a specific process for collection and reduction of water content, the present study involved the material collected at the beach and then subjected to variations due to the process.

2. Materials

2.1. The bauxite tailing tested

The material in study is a tailing from part of the process of beneficiation of lateritic bauxite from a mining beneficiation plant and mining area located at Miraí, at the state of Minas Gerais, Brazil. A diagram for aluminum process is presented in Figure 1 showing from which part of the process the material was obtained. The process starts with grinding and crushing of the material followed by the washing and sieve separation. At this point, the bauxite ore goes for the Bayer process and the remaining of the material, at this plant, goes to the tailing dam.

Brazilian's bauxite ores presents a high amount of reactive silica, and an intermediate beneficiation plant has been introduced to reduce the amount of reactive silica before going to refinery [12]. The material tested in the present experimental program is obtained from this washing process, as indicated in Figure 1.

It is important to highlight that the characterized material differ strongly from the red mud. As described the tested material is a byproduct of mechanical processes of disaggregation without presence of chemicals. Although the process considers that only material finer than 0.6 mm is disposed into the tailing dam at Miraí, the actual material presents grains up to 10 mm.

Two samples were collected from the beach of the tailing dam at Miraí site, both presenting a consistency of a slurry. These samples were collected in different months of 2016 at approximately 15 m of the discharge pipe. The first one denominated B-Mir01 was collected in Feb/2016, this sample weighted approximately 15 kg. A second sample denominated B-Mir02 was collected in Sept/2016, this slurry weighted 25 kg was deposited in steel drum and was transported to the soil mechanic laboratory of São Paulo University, in São Paulo city. At the lab, the sample was homogenized and air dry for geotechnical characterization. The present paper shows the shear strength test results for samples B-Mir01 and B-Mir02.

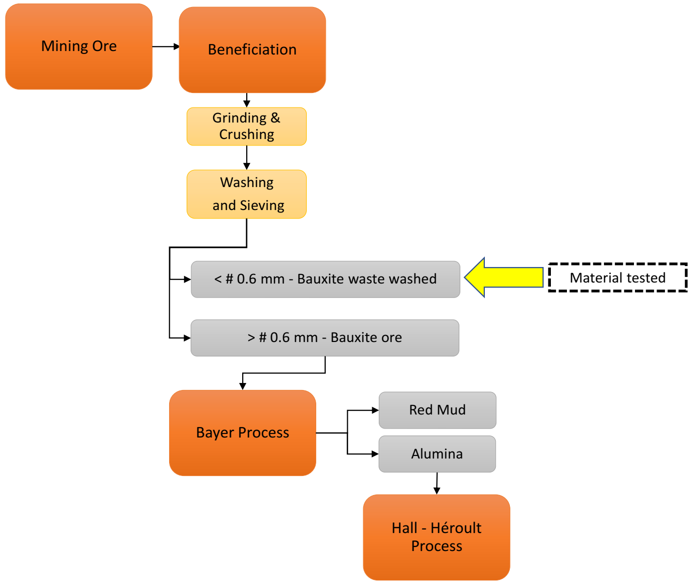

Figure 1. Conceptual Aluminum production process and the material tested.

2.2. Geotechnical Characterization

The geotechnical characterization of the material included grain size distribution, Atterberg limits and the determination of the compaction curves. The tests followed the ASTM standards.

The grain size distribution was performed using potassium hexa-metaphosphate as dispersion agent for grain lower than mesh 200. Figure 2 presents the grain size distribution curve for two samples of bauxite tailings collected at Miraí site. The grain size distribution of the bauxite ore is shown for comparison.

The sample B-Mir01 presented 38% of coarse-grained soils and 62% of fine-grained soils and a D_{60} = 0.070mm. The sample B-Mir02 presented 61.3% of coarse-grained and 37.7% of fine-grained soils and D_{60} = 0.16mm.

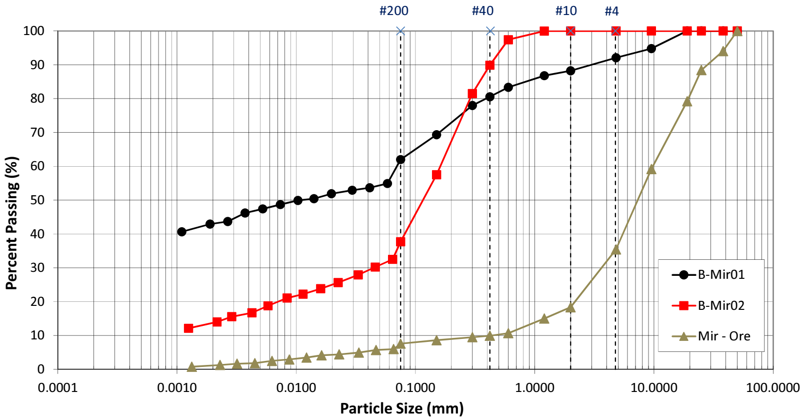

Figure 2. Grain size distribution of Miraí's bauxite tailings.

The two samples presented different grain size distribution, although these materials were collected in the same place, yet in different moments. This difference is due to changes in the exploration areas when the required ore content is exhausted.

The bauxite ore presents 92.4% of coarse-grained soils and 7.6% of fine-grained soils, with an effective diameter (D_{10}) of 0.42mm. The uniformity coefficient C_u=22.86 and coefficient of gradation C_c=3.21.

Table 1 presents the characterization data for the two samples and the bauxite ore.

Table 1. Materials characteristics.

	B-Mir01	B-Mir02	B-Ore
%<2µm	62	38.70	7.5
Limit liquid (w_l)	44	NP	NP
Plasticity index (I_p)	18	NP	NP
Specific Gravity	2.71	2.79	2.65
D_{10}	<0.001	<0.001	0.004
D_{50}	0.01	0.12	7
pH	4	5	5

The compaction curve using standard Proctor energy for the two materials tested are shown in Figure 3, along with the location of the six points from where specimens were prepared for the triaxial tests. The points at which the specimens were prepared are labeled according to the position in relation to its respective compaction curve (e.g. D – dry of optimum, O – at optimum and W – wet of optimum). Table 2 presents the maximum dry density and optimum water content for both tailing materials.

Table 2. Compaction characteristics.

Column1	B-Mir01	B-Mir02
Maximum dry density (g/cm³)	1.56	1.80
Optimum water content (%)	23.70	17.50

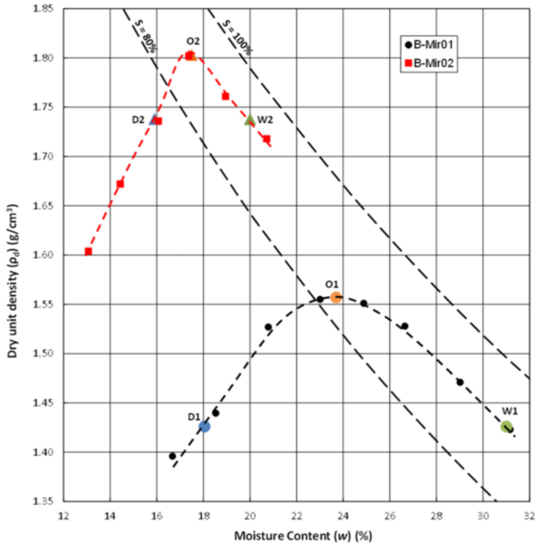

Figure 3. Compaction curve for B-Mir01 and B-Mir02 bauxite tailings and study points.

3. Methods

3.1. Preparation of specimens

Three specimens were prepared at each of the points shown in Figure 3. The specimens were statically compacted in five layers to reach the specific dry density using the defined water content. The material used to prepare the specimen was passed on No 4 (4.75mm) sieve. A cylindrical tri-part split mold with 81mm of height and 38mm of diameter was used. Initial characteristics of 18 specimens tested are shown in Table 3.

Table 3. Initial conditions of specimens for CAU triaxial test.

Specimen	σ3' (kPa)	w_i(%)	Si (%)	e	ρd(g/cm³)
D1-50	50	17.80	0.54	0.90	1.43
D1-100	100	18.35	0.54	0.92	1.41
D1-200	200	18.30	0.57	0.87	1.45
O1-50	50	23.15	0.79	0.79	1.51
O1-100	100	23.40	0.81	0.78	1.52
O1-200	200	24.15	0.86	0.76	1.54
W1-50	50	30.60	0.91	0.91	1.42
W1-100	100	30.15	0.91	0.90	1.43
W1-200	200	29.80	0.98	0.93	1.45
D2-50	50	15.85	0.67	0.66	1.68
D2-100	100	15.55	0.67	0.65	1.69
D2-200	200	15.85	0.65	0.68	1.66
O2-50	50	17.30	0.78	0.62	1.72
O2-100	100	17.45	0.76	0.64	1.70
O2-200	200	17.05	0.78	0.61	1.73
W2-50	50	20.00	0.85	0.66	1.68
W2-100	100	19.90	0.85	0.65	1.69
W2-200	200	19.95	0.84	0.66	1.68

3.2. Triaxial CAU test

Anisotropical consolidated undrained (CAU) triaxial tests were performed using a Bishop-Wesley triaxial cell with automatic control of the test and automatic data acquisition. Three sequential stages characterize the tests: Saturation, consolidation and shear.

The saturation procedure included a water flow to remove air from the back-pressure system lines, followed by a back-pressure application. The back pressure was increased at a rate of 60 kPa/hour until its value reached 490kPa. The effective stress during saturation was kept in 10kPa. At the end of the application of the back pressure the pore pressure parameter B was measured. Due to limitation of the pressure system the back pressure needed to be reduced to 100 kPa, keeping the effective stress at 10 kPa, prior the consolidation. A rate of back pressure reduction of 25 kPa/min was used during this procedure.

Table 4 presents the B value of all specimens and the values of the maximum deviatoric stress (q_{max}) and after peak (q_{a-pp}) with the corresponding axial strain (ε_{a-max} and ε_{a-pp}). Attempts were made to try to increase the B value for the specimens compacted at the B-Mir01 dry points, the values for that specimen varied from 0.70 to 0.78.

All specimens were anisotropically consolidated using a relation between axial and lateral stress of 0.7. Each specimen was consolidated to the designated effective stress, allowing drainage from the base of the specimen. The rate of loading was regulated according to the monitoring the pore water pressure at the top to avoid the development of excess of pore water pressure. The shear stage was performed under constant confining stress using a strain rate of 1.8 %/hour.

4. Results

4.1. CAU triaxial test

Due to limitation of space the stress-strain curves are not shown. The Mohr-Coulomb failure criterion was used to interpret the results. The tests were performed to axial strain between 8% to 16%. Table 4 presents the value of the maximum deviatoric stress, the post-peak value and the corresponding axial strain for each specimen tested. For some specimens, the post peak axial strain was not registered due to the negative pore water pressure development.

Figures 4 and 5 presents the effective stress paths of the tests performed with the two samples (B-Mir01 and B-Mir02). The first point of all stress paths represents the initial stress state for the specimen at the end of the consolidation stage (using K=0.7). The effective stress path envelope was defined from results obtained using the maximum normalized stress.

Table 4. Pore-water pressure parameter (B) and information at failure for all specimens.

Specimen	B	q_{max} (kPa)	$\varepsilon_{a\text{-}max}$ (%)	q_{pp} (kPa)	$\varepsilon_{a\text{-}pp}$ (%)
D1-50	0.74	126.2	0.75	117.0	1.97
D1-100	0.78	189.5	1.60	163.4	5.96
D1-200	0.70	299.7	1.45	244.7	6.03
O1-50	0.96	213.8	1.45	-	-
O1-100	0.95	319.4	1.37	-	-
O1-200	0.97	466.1	1.61	-	-
W1-50	0.98	113.8	1.19	-	-
W1-100	0.97	214.4	0.64	-	-
W1-200	0.98	465.6	0.32	-	-
D2-50	0.90	299.7	1.98	261.2	3.95
D2-100	0.92	451.6	1.97	413.4	4.02
D2-200	0.90	715.2	2.69	669.5	8.03
O2-50	0.93	408.2	2.88	334.3	5.98
O2-100	0.95	564.9	3.59	491.1	6.05
O2-200	0.96	780.3	2.26	773.1	6.01
W2-50	0.96	355.9	3.56	-	-
W2-100	0.96	491.3	3.98	-	-
W2-200	0.96	660.4	3.95	-	-

Figure 4 shows the stress paths for each compaction condition of the sample B-Mir01. In Figure 4a the results of the specimen compacted dry of the optimum is presented. After reaching the failure envelope, the material presented a high development of positive pore water pressure (PWP). This behavior may be related to fabric and initial void ratio. Figure 4b shows stress path of the specimens prepared at optimum water content and maximum dry density. The behavior is different from the one observed with the specimen prepared at point D1 (see Figure 3). Positive PWP development was small at the beginning of the test and at the failure the material presented a dilatant behavior. For the specimens prepared above optimum (see Figure 3) the behavior was like the one observed for the material prepared dry of optimum in terms of PWP development.

However, in Figure 4c, it was observed a sudden PWP development, far from the failure envelope, suggesting a potential liquefaction phenomenon for the specimen compacted above optimum water content. Once the envelope was reached all specimens experienced a reduction in the PWP, increasing the strength.

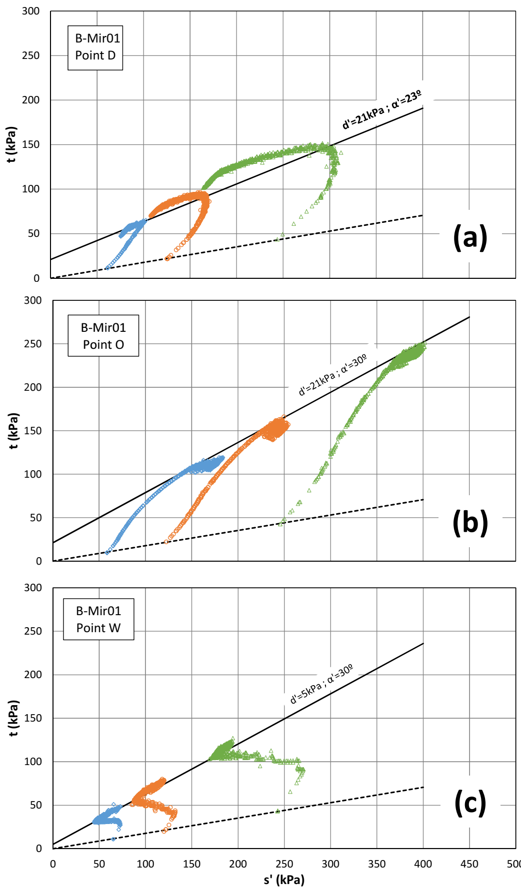

Figure 4. Effective stress paths for specimens of sample B-Mir01. (a) Point "D", (b) Point "O", (c) Point "W".

Table 5 presents the effective stress parameters for the material testes. The cohesion sample B-Mir01 was smaller than the cohesion for the B-Mir02. Considering the plasticity of the samples, this was not expected. The friction angle for the B-Mir02 was greater than for the B-Mir01, as expected.

Table 5. Compaction Characteristics.

Moisture condition	c'	φ'
Dry B-Mir01	23	25
Optimum B-Mir01	24	35
Wet B-Mir01	6	35
Dry B-Mir02	35	35
Optimum B-Mir02	32	39
Wet B-Mir02	24	37

The specimens from the sample B-Mir02 did not developed significant PWP and did not shown differences between the compaction's points (D, O and W). Figure 5 presents thee stress path of all specimens. The positive PWP development occurs only up to about 1% of axial strain, after that only negative PWP was observed.

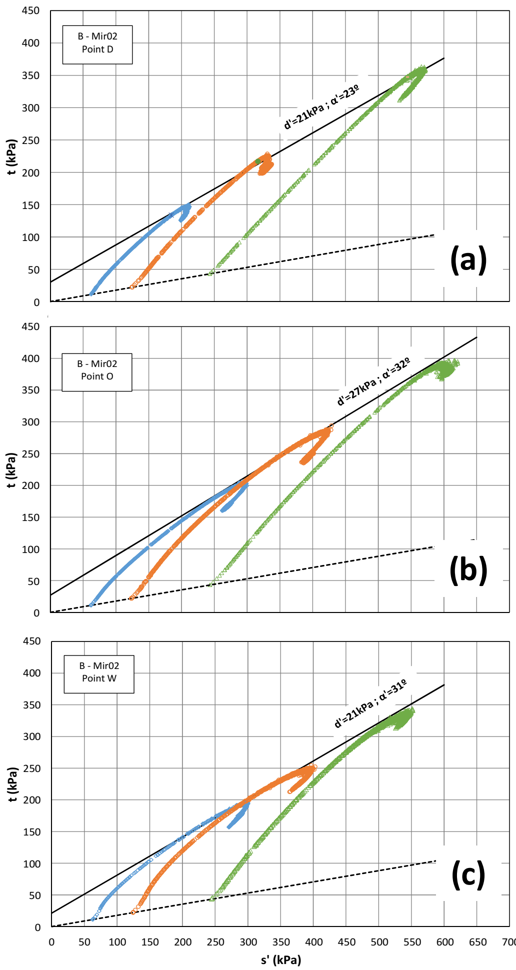

Figure 5 - Effective stress paths for sample B-Mir02. (a) Point "D", (b) Point "O", (c) Point "W".

Figure 6a and 6b show a normalized Young modulus for the two samples prepared at the conditions shown in Figure 3. An attempt was made to present the modulus for strains smaller than 0.1%, but some variability is observed to the external measurement of displacement.

It can also be observed, with some interpretation, that for small deformations, between 0.01 to 0.1%, the value of the normalized Young modulus varied between 800 and 1400 for the sample B-Mir01 and from 600 to 1400 for sample B-Mir02. The data from sample B-Mir02 presented more variability. The normalized modulus at a deformation of 0.1% was similar for both samples, with a slightly tendency for the sample B-Mir01 to give higher values.

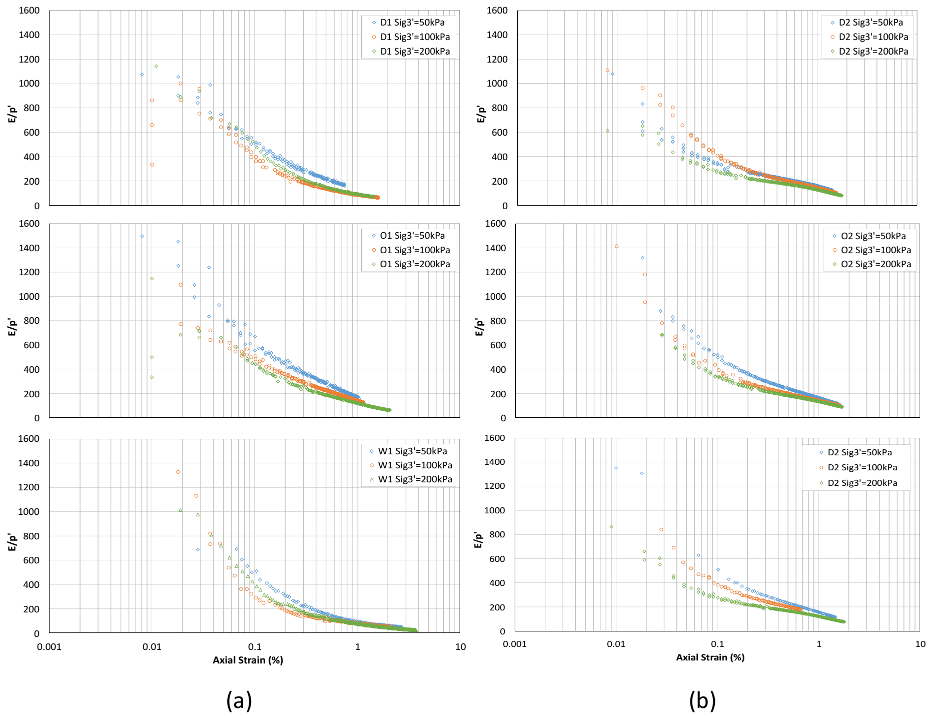

Figure 6 - Normalized Young Modulus for all specimens: (a) Samples B-Mir01 (b) Samples B-Mir02.

5. Conclusions

Two samples of Brazilian bauxite tailings obtained at the site of Miraí´s plant beneficiation, were geotechnically characterized to determine its nature and its shear strength behavior at different states..

The main conclusions from the tests performed are:

- The characterization tests show that there is a variability in the materials obtained in the samplings over time.
- The two materials tested were identified as: sandy clay (B-Mir01) collected in Feb/2016 and a non-plastic silty sand (B-Mir02) collected in Sept/2016.
- Based on the triaxial tests (CAU) it was observed that the sample B-Mir01 presented different stress paths for the three points tested. When compacting dry and wet of optimum, the material developed positive PWP to reach the failure. A singular behavior was detected in specimens compacted wet of optimum, where metastable condition was observed.
- The results from sample B-Mir02 sample, suggested that the material do not present any tendency for PWP development that can induce liquefaction.
- The maximum normalized secant deformability modulus (E/p´), that could be inferred, presented a value of about 1200 for B-Mir01 and approximately 1000 for B-Mir02.

- A great variability was observed for the effective cohesion, varying from 6kPa to 24kPa for B-Mir01 and from 24kPa to 36kPa for B-Mir02. The friction angle varied from 25° to 35° for B-Mir01 and from 35° to 39° for B-Mir02.

Full characterization of any material is required to allow the use of any tailing material as construction material. This is due not only to the characteristics of the material itself, but also due to the variability that may exist.

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