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Challenges in the geotechnical characterisation of bauxite tailings (Red Mud)

Défis dans la caractérisation géotechnique des résidus de bauxite (Red Mud)

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ABSTRACT: The geotechnical characterisation of tailings from mining operations is a current challenge of great relevance. The geotechnical behaviour of tailings accumulation is very variable and depends on many factors, among others, the original mineralogy, the process used to obtain the ore, and the deposition form. Authors have studied tailings of various mineralogical origins, dealing with their geotechnical and geochemical particularities. The data presented in this paper comes from the study of Bauxite tailings, known as Red Mud. Tailings geotechnical characteristics are also a function of their disposal method, which depends on the percentage of solids, i.e. whether they were disposed as slurry (<50%), thickened (50% to 65%), paste (65% to 70%), or filtered (>70%), and if compaction processes were used. In this paper, the main Red Mud aspects and its geotechnical characteristics (obtained from literature) are presented, and the differences in the mechanical behaviour depending on the disposal method are discussed.

RÉSUMÉ: La caractérisation géotechnique des résidus miniers est un défi actuel de grande importance. Le comportement géotechnique des accumulations de résidus est très variable et dépend de nombreux facteurs, notamment de la minéralogie d'origine, du processus utilisé pour obtenir le minerai et de la forme du dépôt. Les auteurs ont étudié des résidus de diverses origines minéralogiques, en traitant leurs particularités géotechniques et géochimiques. Les données présentées dans cet article proviennent de l'étude des résidus de bauxite, connus sous le nom de *Red Mud*. Les caractéristiques géotechniques des résidus sont également fonction de leur processus de dépôt, qui dépend du pourcentage de solides, c'est-à-dire s'ils ont été déposés sous forme de boue (<50%), épaissis (50% à 65%), pâte (65% à 70%), ou filtrés (>70%), et si des processus de compactage ont été utilisés. Dans cet article, les principaux aspects de Red Mud et ses caractéristiques géotechniques (tirées de la littérature) sont présentés et les différences de comportement mécanique en fonction de la méthode de dépôt sont discutées.

Keywords: Tailings geotechnical behaviour; red mud; disposal method; CPTu.

1 INTRODUCTION

Red Mud results from the processing of bauxite ore to obtain alumina. To introduce and explain the site observations, based on literature, the main aspects, that are specific of the composition and behaviour of red mud are presented and are, also, described the different tailings disposal methods.

To show the differences in behaviour that will be presented in this case study, the results of CPTu tests will be used, as for the *in situ* geotechnical characterisation of tailings, is one of the tests established. One of the methods used for the separation between contractive and dilative behaviour is based on the Robertson (2016) charts.

In this paper is presented the separation between the different observed behaviours in the same red mud TSF, depending of the disposal method and are discussed the challenges felt on the TSF characterization and analysis.

2 RED MUD

2.1 Origin and composition

Red mud is a waste industrial product (tailing) from aluminium industries which is produced during the extraction of alumina from the bauxite ore. Bauxite is a weathered rock, typically with a soft structure (hardness between 1-3), containing two forms of hydrated aluminium oxide, in a quantity usually between 30-65%. These oxides are either predominantly monohydrate [AlO(OH)] or trihydrate [$Al(OH)_3$], represented by the minerals Gibbsite, Boehmite and/or Diaspore, which have a specific gravity (Gs) between 2.6-3.5. This ore has additional Fe_2O_3 as the main impurity. Although the minerals that compose bauxite ore have high Gs, the rock has a dry bulk density between 1.5 and 2.5 t/m^3 due to its high porosity.

The Bayer process is the commonly used process for the purification of this ore and it involves digesting the bauxite in a solution of NaOH at temperatures between 140 and 280°C (function of the mineralogy), under pressure. During the digestion process, aluminium reacts with the NaOH to form soluble sodium aluminate, leaving behind the Fe_2O_3 and other impurities. The process results in a highly alkaline pH=11-13 waste material, whose mineral components can include hematite, goethite, gibbsite, rutile, calcite, sodalite, and complex silicates. Notably, there is usually absence of quartz or clay minerals in this waste. The quantities of each mineral in the red mud are very variable and depend on the source bauxite and the original mineralogical composition of the ore is one of the most important factors influencing the red mud tailings properties (Table 1).

Table 1. Examples of chemical composition of different red muds produced in the world (adapted from Reddy et al., 2021).

Location	% Composition (by dry weight)										
	$Fe_2 0_3$	Al_2O_3	TiO_2	CaO	SiO_2	Na_2O	MgO	P_2O_5	MnO	K_2O	LOI
Brazil	19.85	19.87	2.66	4.61	14.34	7.35	-	-	-	-	27.20
China (1)	10.63	22.31	6.64	20.46	18.92	5.72	-	-	-	-	-
China (2)	29.79	22.96	1.83	2.03	21.24	8.93	-	-	-	0.03	12.19
China (3)	11.60	7.34	5.36	44.69	27.99	0.58	2.01	-	-	0.43	-
Greece	46.70	18.10	5.80	8.50	7.30	2.80	-	-	-	-	8.50
Hungary	31.63	10.50	5.90	11.66	12.20	6.09	0.53	0.55	0.34	0.05	-
India (1)	35.00 - 37.00	18.10 - 21.00	17.00 - 22.50	1.70 - 2.20	6.00 - 6.84	5.20 - 5.50	-	-	-	-	11.80 - 14.00
India (2)	44.00 - 47.00	17.80 - 20.10	8.20 - 10.40	1.00 - 3.00	7.50 - 8.50	3.50 - 4.60	-	-	-	-	10.80 - 14.00
India (3)	40.00 - 45.17	18.00 -27.00	2.50 - 5.15	1.50 - 2.50	5.70 - 16.00	3.64 - 4.50	-	-	-	-	11.00 - 15.00
Iran	22.17	13.98	7.17	24.25	13.00	4.20	2.01	0.16	0.06	0.42	9.55
Jamaica	49.50	16.50	7	5.50	3.00	2.30	-	-	-	-	11.60
Spain (1)	37.22 ± 0.33	12.40 ± 1.07	20.10 ± 0.59	6.30 ± 0.20	3.81 ± 0.16	4.64 ± 0.41	0.14	0.51	0.06	0.05	11.34
Spain (2)	31.80	20.10	22.60	4.78	6.10	4.70	0.20	-	-	0.03	-
Turkey	35.04	20.20	4.00	5.30	17.29	9.40	0.33	-	-	-	8.44

2.2 Geotechnical properties

Due to the high variability of combinations found it is difficult to generalize about red mud geotechnical behaviour. Both the original mineralogy, as the disposal method, strongly influence its behaviour. Nonetheless, some aspects are specific to its nature and can be found in literature (among others Newson et al., 2006 and Reddy et al., 2021):

- It is usually found in two grades: fine-grained “red mud” and coarse “red sand”, being the “red mud” the more common type;
- Typical gradings show up to 20–30% clay sized, with most particles in the silt range, reason why some authors prefer the term *ferrosilt* to classify these materials, because of the high amount of red iron oxide and dominance of the silt size fraction. Despite that, some have been found with ≥50% of particles with less than 2 μm (clay sized), but it is a function of the digestion process used and of the characteristics of the ore body;
- Clay fraction grains microscopic analysis show equidimensional polyhedric grains with slightly rounded edges. Minerals of flat shape, typical of clay minerals, can hardly be found;
- They tend to have low plasticity (e.g., WL≈39-45%, IP≈10-15%) and are mainly ML in UCS. In spite of their IP and lack of clay minerals, they show many geotechnical properties similar to clayey tailings found in other mineral processing e.g. gold tailings;
- The specific surface area (BET) is between 10-30 m^2/g and the CEC (Cation Exchange Cap.) is comparable with kaolin or illite minerals;
- They present relatively high specific gravity (Gs=2.8-3.3), function of the strong presence of

iron minerals. Red mud tailings Gs is highly dependent on its mineralogical and chemical composition;

- Consolidation and settling has been found to be a function of the type and quantity of iron minerals i.e., Al-goethite, goethite, and hematite. In particular, very fine goethite can cause problems due to its relatively high Gs (=3.2) and high BET compared to the other oxide minerals;
- 1D compression tests indicate compression indices Cc=0.27-0.39, permeabilities $k=(2\text{-}20)\times10^{-7}$ cm/s and coefficients of consolidation $c_v=(3\text{-}50)\times10^{-3}$ cm^2/s and are therefore similar to silty-clay soils;
- Very high friction angles (ϕ') of 38-42° are also found for these materials, which are more typical of sandy soils;
- In situ undrained shear strengths are typically very high compared to uncemented clayey soils at equivalent liquidity indices (i.e. Su≥2 kPa for $I_L>1$) and sensitivities from 5 to 15 are commonly found (i.e. very low residual Su). Thixotropy has been observed with these materials and apparent preconsolidation pressures in excess of actual overburden pressures are found (apparent overconsolidation). Hence there is a strong indication that some red muds are cemented or aggregated;
- Leaching by freshwater and acid neutralization has been found to reduce in situ void ratios and compression indices.

Some examples values obtained for geotechnical properties and parameters, in different locations, are presented in Table 2, as extracted from literature. These values should only be used as reference as there is details about the tests made, and without indication, for instance, on the type of shear tests performed or on the disposal method used. This last point, as will be presented, has a big influence on the red mud tailings behaviour. To use the data here presented, or to obtain more information about the results and thier origins, it is strongly recommended to consult the original paper (Reddy et al., 2021).

Table 2. Examples of geotechnical parameters observed in different red muds produced in the world (adapted from Reddy et al., 2021).

Location		India (a)	India (b)	UK	Guinea	Spain	China	Jamaica
Physical property								
Specific gravity, Gs		2.85 - 3.45	2.85 - 2.97	3.05	3.20 – 3.70	3.44	2.77	2.70 - 3.70
pH		10.7 – 11.5	10.2 - 11.0	11.6	13.1 - 13.5	10.2	-	11.3 - 12.5
Surface area (m^2/g)		20.4 - 47.2	-	-	-	23.7	-	-
Consistency limits	**WL**	21 - 45	40 - 45	54	44 - 66	39±2	64	45
	WP	16 - 36	30 - 35	40	33 - 36	31±2	42	36
	IP	5 - 7	5 - 14	14	11 - 26	8	22	9
% Grain. fraction	**Gravel**	0	0	0	0	0	0	0
	Sand	5 - 15	10 - 14	0	36	12	5	20 - 30
	Silt	43 - 76	43 - 57	80	44	50	75	50
	Clay	22 - 35	29 - 39	20	20	38	20	20 - 30
USCS		ML	ML	MH	ML-CL	ML	MH	ML
Compaction	**γ_{dmax} (kN/m^3)**	12.5 - 17.0	14.5 - 16.4	17.5	15.5	16.9	17.0	-
	w_{opt} (%)	22 - 34	33	-	30	7 - 35	50	-
Consolidation	**c_v (cm^2/s)**	3 - 50×10^{-3}	-	-	-	-	-	7.5×10^{-4} to 3×10^{-2}
	c_c	0.093	-	0.41	0.28 - 0.38	-	-	0.268
Strength	**ϕ(°)**	34 - 42	26 - 28	38 - 42	30 - 35	-	28 - 33	37 - 45
	Cohesion (kPa)	7 - 28	10 - 20	10 - 20	-	-	11 - 35	-
	q_u (kPa)	102 - 136	143	130	-	-	-	20 - 175
Hydraulic conductivity	**k (cm/s)**	5.832×10^{-4} to $.13\times10^{-8}$	2 - 30×10^{-6}	2 - 10×10^{-7}	1.4 - 6.7×10^{-6}	-	4.5×10^{-6}	10^{-5} to 10^{-7}
Swelling property	**Free swell index (%)**	No swell	No swell	No swell	No swell	Very low	-	-

Other specific information is found in literature that is important to understand the red mud behaviour. For instance, Newson et al. (2006) observed the microstructure of a red mud specimen from a site in the UK and found that it is composed of a collection of small, apparently aggregated particles. Closer inspection shows a layer of material coating most of the particle surfaces (cementation?), composed of crystals with a cubic habit. X-ray analysis suggests that the coating is composed largely by hydroxysodalite (feldspar). Cementation can help to justify the high peak Su and the cohesion values obtained in shear testing.

Another important characteristic is red mud dispersivity. According with Rout et al. (2013), the results of the crumb tests, double hydrometer tests and turbidity tests made on red mud samples show that it is highly to extremely dispersive, with a dispersion ratio of 94% in the double hydrometer test.

One of the main parameters used to understand the tailings geotechnical behaviour is the void ratio (*e*), even though the huge difficulties in characterizing it in situ. In literature are found values for red mud bulk and dry densities, as being the parameter that gives the idea of their in situ state, but due to the high Gs of its grains, these parameters can be misleading. Newson et al. (2006), for the UK red mud analysed, obtained *e* values, both for intact and reconstituted specimens, varying between 1.76-1.45, but Carrier III et al. (1983) refers the value of 9 for the e_0 of red mud. Also here, the disposal method is very important for the void ratios obtained/observed.

3 TAILINGS DISPOSAL

Generally, tailings are the combination of the fine-grained solid materials (usually silt-sized), remaining after extraction from the ore of metals and minerals, with the water used in the recovery process. Depending on solid/liquid ratio of the tailings, they can be disposed (Figure 1 and Figure 2) as slurry (with the higher water content), as thickened tailings and paste, or as cake (often called dry stacking), that can be "wet" or "dry". The disposal can also be made in co-disposal with coarse wastes. The different solids concentrations are achieved by dewatering, and the concentrations vary for different tailings, since particle size distributions, clay mineral content, particle shape, mineralogy, electrostatic forces and flocculant dosing vary considerably and deeply influence the final result (Australian Government, 2016).

Tailings are commonly pumped as a slurry in a pipeline and discharged sub-aerially into a surface Tailings Storage Facility (TSF). The consistency of the slurry (% solids by mass) depends on the type of tailings, the particle size distribution and specific gravity, and the extent of thickening at the processing plant (Figure 1). Upon discharge (Figure 2), tailings slurry segregates, being the coarser and higher Gs particles deposited on the upper beach after which remains substantial supernatant water that carries finer and lower Gs particles forward into the decant pond. The segregation and settling of the tailing particles result in a significant curvature of the beach profile, i.e. more steep near the point of discharge and becoming flatter further down the beach profile. Thickened tailings still show some segregation, settling and bleed on placement, accompanied by some curvature of the beach profile, while paste tailings have a non-segregating, non-settling consistency that releases only small quantities of water after placement.

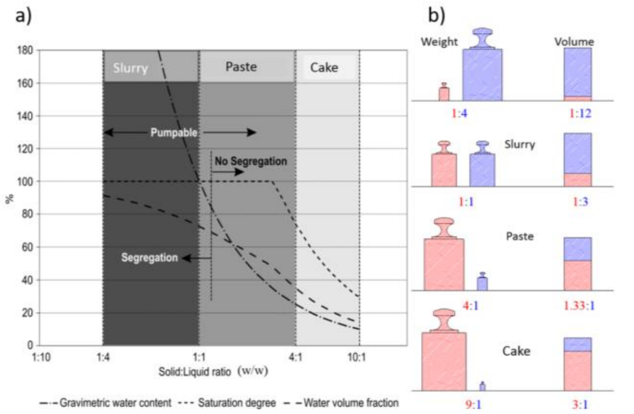

Figure 1. a) Types of mine tailings according to its solid/liquid ratio. including profiles for gravimetric water content. saturation degree. and water volume fraction and b) comparison between w/w and v/v ratios for a particle density of 3g/cm³ (Pacheco, 2018).

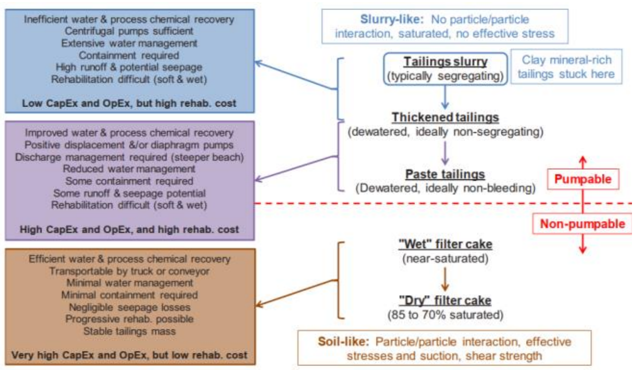

Figure 2. Tailings Continuum (Australian Government, 2016).

Thickening tailings reduces the quantity of water delivered to the TSF, which reduces the risks of overtopping, reduces seepage, evaporation losses, and reduces the risk of TSF embankment failure by lowering the pond level and reducing the phreatic surface within the embankment. Thickening of tailings in the processing plant before disposal also enables process water to be recycled directly back to the plant, reducing water losses and reducing plant raw water demand.

Tailings can be also brought to a ‘solid-like’ state by centrifuging or filtration, producing a consistency that is potentially transportable by truck or conveyor. True dry stacking requires that the flocculated tailings be filtered, usually under pressure or possibly under vacuum to produce a product that is transportable and stackable using ‘dry’ material transportation and disposal techniques. In this state they may then be placed, spread and compacted to form an unsaturated, dense and stable tailings ‘dry stack’.

4 SITE OBSERVATIONS

4.1 Site tailings disposal description

The site in analysis is a red mud TSF where there were 3 stages of deposition, one overlapping the other. At first, the operation started with the deposition of tailings in slurry form with 30% solids. During this 1st deposition stage, tailings were in liquid state and were pumped as a wet slurry through a pipeline and discharged sub-aerially. Due to the high specific gravity of the grains, the solid phase sedimented and there was supernatant water remaining (“pond”).

In the 2nd deposition stage, after introduction of the use of drum filter and dumper in the installation, the red mud was transported in cake form, with a solid content of around 65-70%, but the discharge of the tailings was made by trucks into a “pond” (Beach Below Water Disposal - BBW).

When the surface of the TSF achieved a dry situation (without supernatant water), the 3rd deposition stage has started. At this stage, a almost dry material with 70 to 75% solids was transported using trucks and stacked, spreading and compacted using a bulldozer.

4.2 CPTu results

Two CPTu campaigns were made in the site, in different years. The CPTu data were processed following the state-of-the-art methodologies, one of which is detailed in Roberston (2016).

The results obtained were similar, allowing to separate the different stages. Nonetheless, as they were made in different moments of deposition, the number of points sampled in the red mud tailings of the different deposition stages is different, i.e. 53% in the 1st dep. stage, 31% in the 2nd and only 16% in the 3rd. An example of the results, separating the different stages of tailings deposition, above the natural soil, is presented in Figure 3.

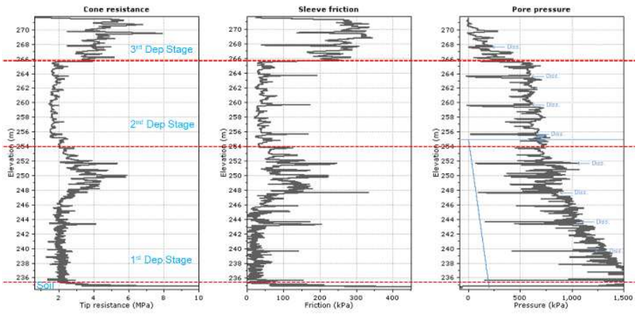

Figure 3. Example of a CPTu test made in study site, showing the division between the different deposition stages.

Being the grain size distribution of the red mud tailings, in the different deposition stages, similar, the main differences in the site are due to the disposal method and to the installed water level (WL), observed to be slightly above the top of the tailings of the 1st deposition stage.

When looking to the points plotted in the Robertson (2016) SBTn classification charts (Figure 4) it is evident the difference in the behaviour between the 1st dep. stage (slurry below the water table), where the data appear in the clay contractive (CC) area of the chart, but expanding to the CCS sensitive materials, and the dilative behaviour of the 3rd dep. stage (stacked filtered dry tailings above the WL). To note is the observed behaviour of the red mud tailings of the 2nd dep. stage, that were deposited with high solids content, but in BBW. These tailings, even though are not below the WL, are clearly close to saturation and present low resistance. When ploting in the SBTn chart they appear with a behaviour very close to the one observed in the slurry, mainly with clay contractive behaviour type.

As in all tailings, analysing and interpreting the behaviour od red mud, depends not only on the results of the site investigation tests, but also on understanding the TSF history.

5 CONCLUSIONS

Tailings studies are very challenging, and the difficulties start, frequently, with the difficulty to build the initial ground model, due to lack of data from construction period, and to define the TSF history. In the case of red mud, the challenges continue due to: its mineralogical content, that promotes cement mineral neoformation; the dominant silt fraction, that promotes partial drainage when tested; high Gs; sometimes high

e_0; and high sensitivity, with the observation of high peak strength and very low residual strength.

From the site, the results show that, as expected, the dry stacking presents mainly dilative behaviour and that slurry tailings present contractive behaviour. To note, in this site, is the clear evidence that the disposal of tailings in BBW conditions, even if they are filtered, fully saturates the materials resulting in contractive behaviour, showing the importance of the deposition on the geotechnical behaviour.

It is also important to note that, while the 3rd dep. stage materials are dilatant, there are no guarantees for the TSF stability, as stacking materials (with lower *e* and high unit weight) above contractive materials may induce excess pore pressures, being the contractive materials, the ones ruling the overall stability of the facility.

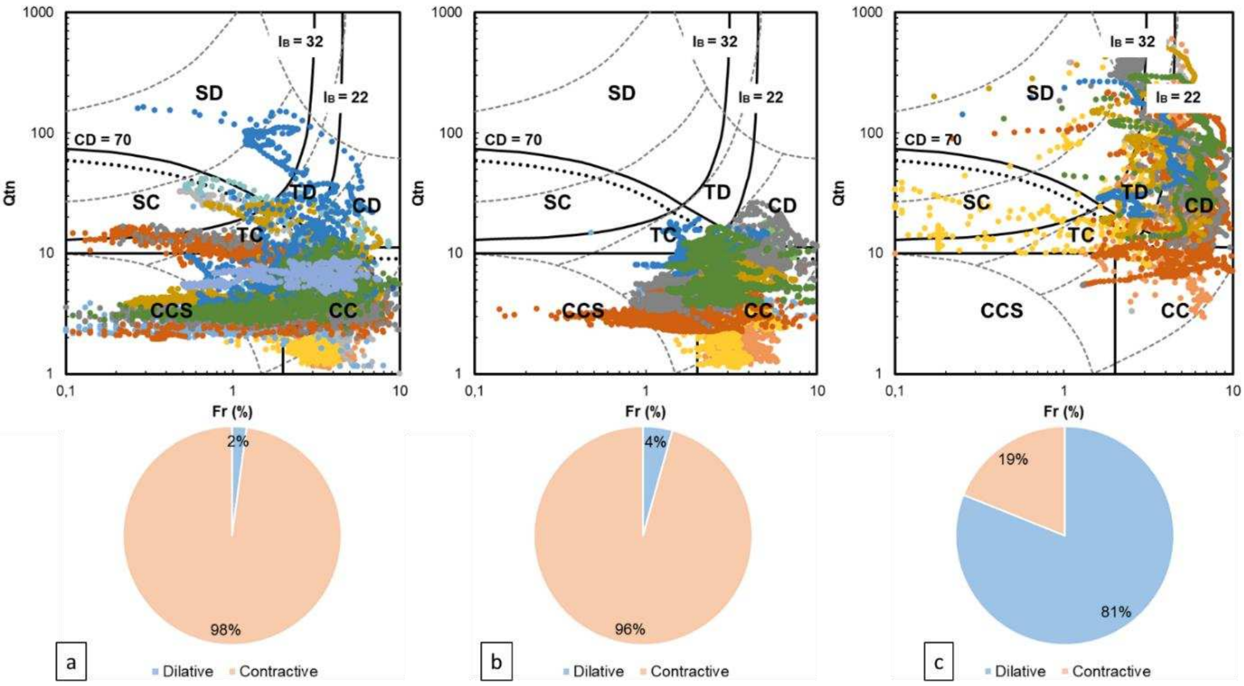

Figure 4. Red mud updated SBTn classification (Roberston, 2016) and percentage of points showing contractive or dilative behaviour in tailings disposed, in the same TSF, as: a. slurry (30% solids); b. filtered tailings (65% solids) disposed in beach below water; c. filtered tailings (70% solids) dry stacking.

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