The influence of relative density on the friction angle of iron ore tailings from the Fundão Dam

Ana Clara Frota Quintelas
Federal University of Rio de Janeiro
anaquintelas@poli.ufrj.br

Leonardo De Bona Becker
Federal University of Rio de Janeiro
leonardobecker@poli.ufrj.br

Mauro Vitor dos Santos Moura
Federal University of Rio de Janeiro
mauro.moura@poli.ufrj.br

Abstract

Brazil has about 800 tailings dams installed in its territory and mining is very important for the country's GDP. Those dams are, in essence, hydraulic fills composed by tailing pulp discharged almost randomly. That procedure results in a saturated material with high void ratios that may be susceptible to liquefaction. The knowledge of its mechanical behavior and strength parameters is essential to the stability assessment of such dams. The present work consists of an analysis of the influence of the relative density (D_r) on the friction angle and volumetric strains during shear of the sandy tailings of Fundão Dam. Samples of granular material were collected in the tailings beach before the catastrophic failure of the entire dam. The samples were classified as silty sand. Direct Shear Tests were carried out with four relative densities (D_r = 98%, 81%, 58% and 35%). The results have shown that all samples but the most compact have contracting behavior. The loosest is the sample, the greatest is its deformability, up to D_r = 58%. The peak friction angle (ϕ_p) is 37° and the constant volume friction angle (ϕ_{cv}) is 33°. The ϕ_{cv} is in good agreement with the critical state friction angle previously determined by triaxial tests.

1 INTRODUCTION

The mining activity in Brazil is very important to the economy, contributing to meet the demand for metals that serve as raw materials for all types of Brazilian and foreign industries. According to the Brazilian Mining Institute (IBRAM), Brazil exported a volume of more than 400 million tons of mineral goods in 2017, reaching US $ 28.3 billion, of which 62% corresponds to the export of iron ore (IBRAM, 2018).

Because of this massive production, large amounts of tailings are generated, and this huge volume of tailings must be considered in the long-term planning of the mining companies. The most economical and practical way often adopted in Brazil is the hydraulic disposal of waste in the form of pulp in tailings dams. This method consists of transporting the tailings in the form of pulp - mixed with water - through pipes. It results in a saturated material with high void ratios – i.e. a hydraulic fill.

Another relevant aspect is raising method of the dam. There are three possible methods of raising: upstream, downstream and by centerline, named according to the movement of the crest during raising. The upstream method, in which the dykes are raised upstream, was widely used in Brazil until recently, when it was banned by federal regulation (ANM, 2019). The tailings are used as foundation and become an integral part of the dam body. This method of raising is the simplest, cheapest and requires less available area to build the dam. However, this method requires careful attention as shown by the accidents in 2015 and in 2018 (the collapse of the Fundão dam, in Mariana and the Córrego do Feijão dam, in Brumadinho).

The beginning of a slope movement in saturated sandy tailings with high void ratios may trigger the phenomenon known as static liquefaction, characterized by expressive or total loss of shear strength due to high excess pore pressures induced by shear strains.

Liquefaction (static or dynamic) is the greatest risk associated to the collapse of tailing dams due to its great destructive power. The consequences of a dam break can be devastating for the environment and the communities downstream.

Therefore, it is essential to know the strength of the material of the dykes and inside the dam – mostly tailings, in the case of the upstream dams.

1.1 Objectives

In order to better understand the behavior of a sandy tailings, the influence of the relative density in its friction angle was assessed by direct shear tests.

2 STUDY MATERIAL

The material studied in this work is the granular iron ore tailings from the Fundão Dam, an upstream dam located in the municipality of Mariana, Minas Gerais State, Brazil. That dam was built by the upstream raising method and collapsed in November 2015 (MORGENSTERN *et al*, 2016).

The samples used in the present work were collected at the beach of the dam, two years before its collapse. The dam was part of the Germano mining plant. In that facility there were three tailings dams. The Germano Dam, used for slimes storage; Fundão Dam, used for storage of slimes and sandy tailings; and Santarém, used for water storage.

In the Fundão Dam, the sandy tailings were initially disposed in the reservoir of Dyke 1 and the slimes in the reservoir of Dyke 2, shown in Figure 1.

The collection of material samples took place at the time that the dam was still in operation, in 2013 (Flórez, 2015).

Figure 1. Fundão dam and its dykes in 2013 (Fabre, 2019)

The disturbed samples were collected at the tailings discharge points located in the beach of Dyke 1. Figure 2 shows the sampling points.

The sandy tailings came from two concentrators. It was observed that the tailings from Concentrator I had a grayish color and those from Concentrator II a reddish color. To replicate the mixing that results from the discharge operation, both materials were mixed at equal proportions and homogenized.

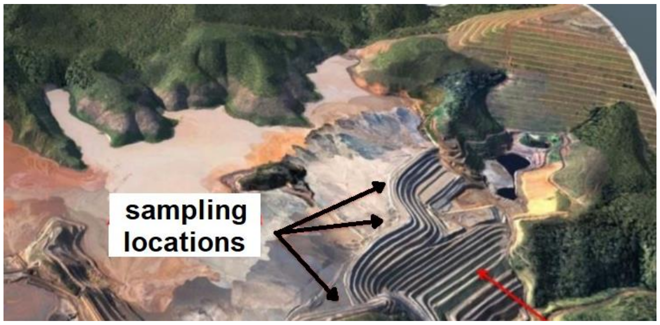

Figure 2. Sampling locations (Flórez, 2015)

After mixed and homogenized, the tailings were kept in plastic bags containing approximately 20 kg each. Later, the contents of the bags were divided into four parts, placed in metal trays for air drying and stored in smaller plastic bags of 5 kg each.

The tailings used in this work were classified as a silty sand. The sample was part of the same batch used by Fabre (2019). Characterization tests were performed by that author and the results obtained are shown in Table 1. These results are very similar to the ones reported by Telles (2017) and Flórez (2015).

Table 1. Summary of results obtained by Fabre (2019)

Clay (%) – D < 0,002mm ¹	0
Silt (%) – 0,002 ≤ D < 0,06 mm ¹	21
Fine sand (%)	69
Medium sand (%)	10
D_{10} (mm)	0,04
D_{30} (mm)	0,07
D_{50} (mm)	0,095
D_{60} (mm)	0,11
C_U	2,75
C_C	1,11
Fine content (%) ²	34
Gs	2,82
$e_{máx}$	1,00
$e_{mín}$	0,55
USCS classification	Silty Sand

¹: grain sizes according to Brazilian Standard NBR 6502:1995 (ABNT, 1995)
²: percent passing the #200 sieve

3 METHODOLOGY

Each sample passed through the following steps: (i) quartering, (ii) oven drying, (iii) measurement of water content, (iv) molding. The samples can be considered dry because their average water content was approximately 0.02%.

The material was quartered to ensure homogeneity in the samples. The tailings weight of each sample (W_s) was calculated according to Equation 1.

$$W_s = \frac{G_s \cdot \gamma_w \cdot 91,82}{e_0 + 1} \quad (1)$$

91,82 is the volume of the shear box (5cm x 5cm), in cm³ and e_0 is the desired void ratio.

The specimens were poured directly in the shear box using different funnels, in order to achieve four distinct relative densities. Light tamping was also used in the more compact samples.

Three tests per density were carried out with initial normal stresses of 100, 200 and 400 kPa, resulting in a total number of tests of 12.

The samples were not flooded, and the consolidation stage lasted until the deformations were negligible.

The velocity of all tests was 0,065 mm/min, the same used in other studies of these tailings.

4 TEST RESULTS

After the consolidation stage, the specimens showed average relative densities of 35±1%, 58±1%, 81±1% and 98±1%.

4.1 Relative Density 98%

Figure 3 shows the normalized shear stress versus horizontal displacement.

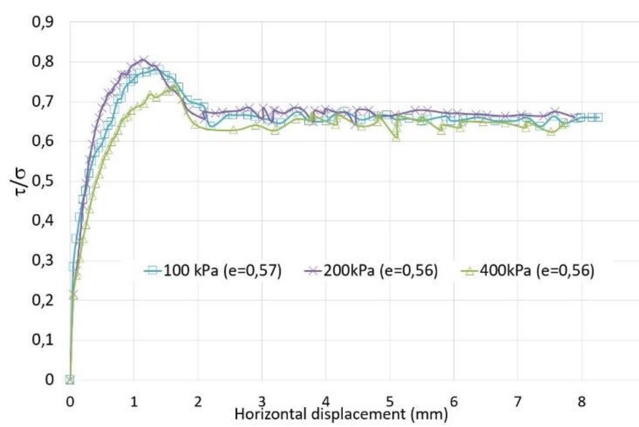

Figure 3. Normalized Shear Stress x Horizontal Displacement – D_r = 98%

The behavior of the D_r = 98% tailings shows a peak of resistance followed by quick loss of strength and stabilization.

Figure 4 shows the graph of vertical displacement vs horizontal displacement. All tests showed a slight contraction followed by dilation. There was no volume stabilization in the tests of 100 and 400 kPa, in spite of the stabilization of the normalized strength in all tests.

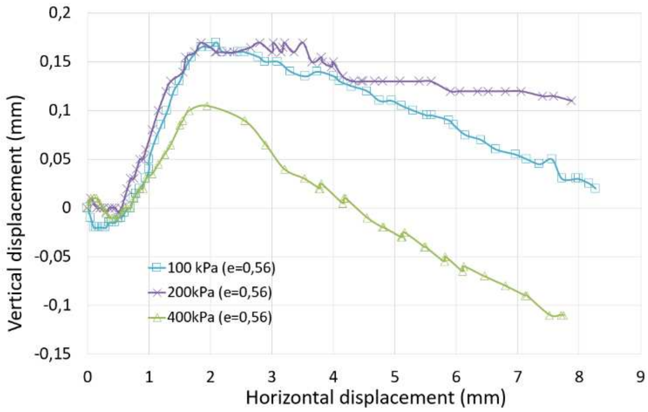

Figure 4. Vertical Displacement x Horizontal Displacement – $D_r = 98\%$

After a horizontal displacement of approximately 2.0mm, the vertical displacements of some tests exhibited a negative tendency. This lack of stabilization is probably due to uneven settlements of the top cap.

The tests indicated a peak friction angle (ϕ'_p) of 37º and a "constant volume" friction angle (ϕ'_{cv}) of 33º. It is worth mentioning that, although the ultimate normalized shear stresses of all tests have stabilized at the same approximate value, the vertical displacement vs horizontal displacement curves have not.

4.2 Relative Density 81%

These specimens had average void ratios of 0,67 and 0,64, before and after the consolidation stage, respectively.

Figure 5 shows the graph of normalized shear stress versus horizontal displacement.

Despite the average relative density after consolidation of 81%, no peak is seen in the stress-displacement curves.

The vertical displacement vs. horizontal displacement curves show initial contraction, followed by a slight expansion, especially in the test with the lowest normal stress, as shown in Figure 6. The lack of volume stabilization is seen again in the, despite the constant strength.

The test results of samples with average relative density of 81% showed a "constant volume" friction angle (ϕ'_{cv}) of 33°, equal to that measured in samples with average relative density of 98%. The same consideration made regarding the "constant volume" for the compact sample applies to this situation.

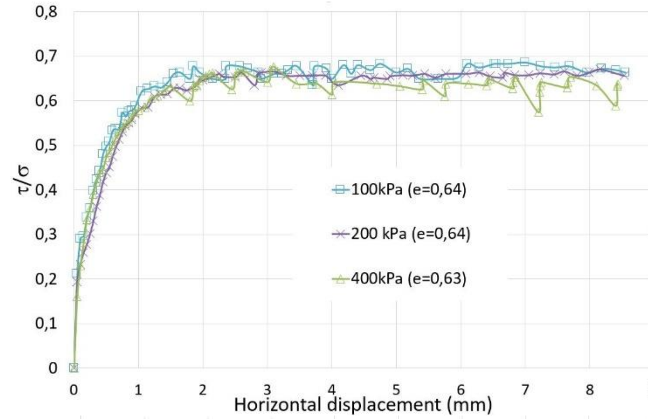

Figure 5. Normalized Shear Stress x Horizontal Displacement – $D_r = 81\%$

Figure 6. Vertical Displacement x Horizontal Displacement – $D_r = 81\%$

4.3 Relative Density 58%

These specimens had an average void ratio of 0,79 before the consolidation and 0,74 after the consolidation. The relative density after consolidation is 58%.

Figure 7 shows the graph of normalized shear stress versus horizontal displacement.

The horizontal displacement necessary to reach the stabilization of the strength in the $D_r = 58\%$ was higher than that of the samples with $D_r = 98\%$ and $D_r = 81\%$.

Figure 8 shows the graph of vertical displacement vs horizontal displacement.

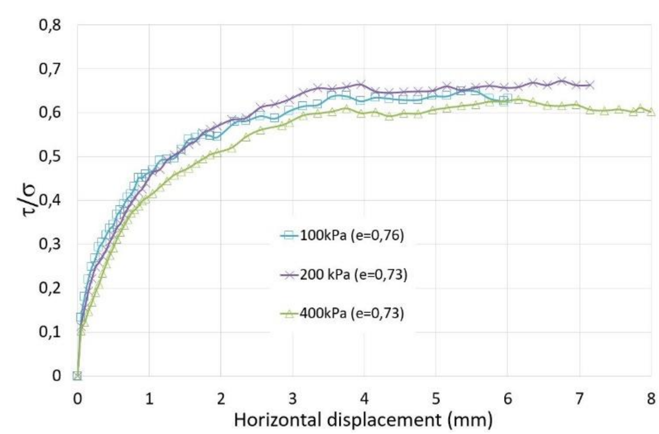

Figure 7. Normalized Shear Stress vs Horizontal Displacement– $D_r = 58\%$

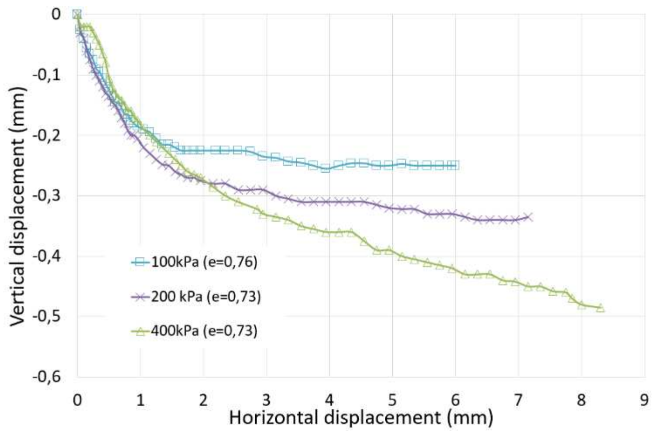

Figure 8. Vertical Displacement x Horizontal Displacement – $D_r = 58\%$

All samples with D_r = 58% showed volume reduction during shear. It is noticed that the specimens subjected to lower normal stresses showed less volume reduction.

In addition, Figure 8 shows that there was a stabilization of the vertical displacement vs horizontal displacement curve for specimens with initial normal stresses of 100 and 200 kPa. The 400 kPa showed a tendency of stabilization, but the top cap tilt probably prevented the stabilization.

The "constant volume" friction angle (ϕ'_{cv}) for this relative density was 32°.

4.4 Relative Density 35%

These specimens had an average void ratio of 0,91 before the consolidation and 0,84 after the consolidation. The relative density after consolidation is 35%.

Figure 9 shows the graph of normalized shear stress vs horizontal displacement.

Figure 10 shows the graph of vertical displacement vs horizontal displacement.

All specimens showed volume reduction, the tests of higher normal stress showing more contraction. Only the curve of the 100 kPa test stabilized.

The results showed no peak and constant strength only after horizontal displacements in excess of approximately 4 mm.

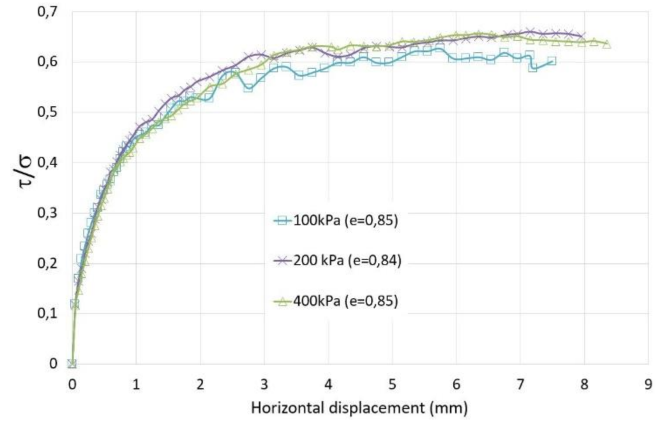

Figure 9. Normalized Shear Stress vs Horizontal Displacement– $D_r = 35\%$

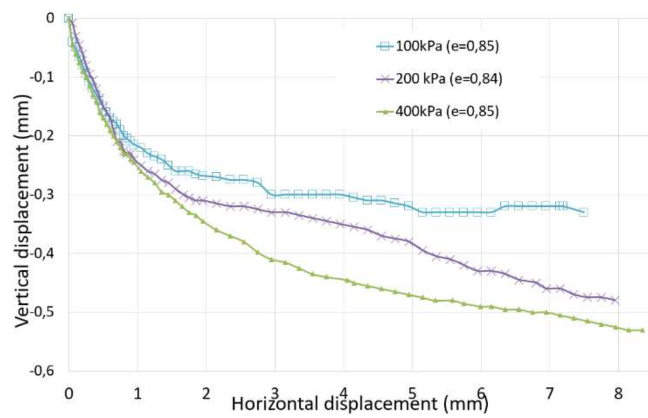

Figure 10. Vertical Displacement x Horizontal Displacement – $D_r = 35\%$

The "constant volume" friction angle (ϕ'_{cv}) for this relative density was 33°.

5 ANALYSIS OF THE RESULTS

Only 1/3 of the specimens showed stabilization of the vertical displacement vs horizontal displacement curves. It is believed that this lack of stabilization is caused by the tilting of the top cap, as mentioned earlier.

The strength envelopes of the four relative densities are presented in Figure 11.

The red dashed line with 37° represents the D_r = 98% and is the only peak envelope because the other densities did not show peak.

The high R^2 values showed that the shear strength presented excellent repeatability. As mentioned earlier, the "constant volume" friction angles obtained for the all densities were practically the same (33°).

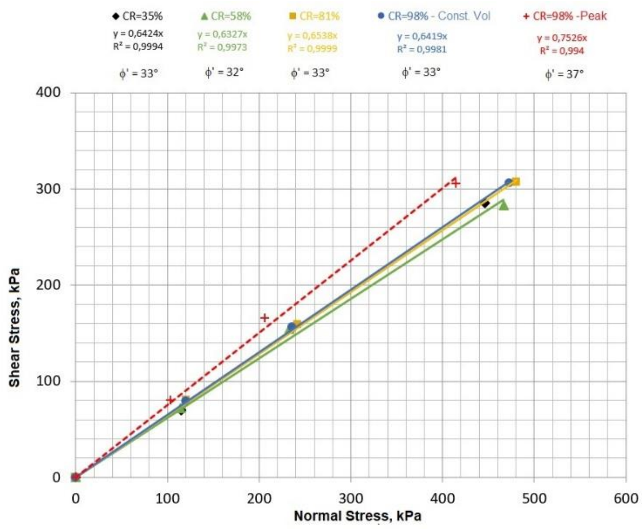

Figure 11. Strength envelope of tests performed

To verify the effects of the lack of volume stabilization the tests were separated into two groups: those that showed stabilization at some point and those that did not present volume stabilization. The friction angles of both groups were almost identical indicating that the tilting of the top cap was not enough to distort the value of ϕ'_{cv}.

6 CONCLUSIONS

The "constant volume" state friction angle determined in this work compares well to the results obtained by other authors. As ϕ'_{cv} is approximately equal to the critical state friction angle (ϕ'_{crit}) several comparisons can be made for the Fundão Dam sandy tailings. Flórez (2015) performed drained and undrained triaxial compression tests and obtained ϕ'_{crit} equal to 34,5°. A similar result was found by Telles (2017), also in triaxial compression tests (ϕ'_{crit} = 34,3°). Fabre (2019) conducted drained triaxial extension tests and found ϕ'_{crit} = 34,8°.

REFERENCES

ABNT. NBR 6502:1995 – *"Rocks and soils – Terminology"*, 1995.

ANM - Brazilian Mining Agency. Decree No. 04/2019. Seção 1 do D.O.U de 18 de fevereiro de 2019. *In Portuguese.*

Fabre, J. S. (2019). *"Ensaios triaxiais de extensão em um rejeito de minério de ferro"*. M.Sc. Thesis, *in portuguese*, Rio de Janeiro, Brasil.

Flórez, C. T. (2015). *"Estudo da alteração em laboratório de rejeitos de mineração de ferro para análise em longo prazo"*. PhD. Thesis, *in portuguese*, Rio de Janeiro, Brasil.

IBRAM – Brazilian Institute of Mining. *"Annual Report IBRAM. July 2017 – June 2018". In portuguese.* http://portaldamineracao.com.br/ibram/wp-content/uploads/2018/07/Diagrama%C3%A7%C3%A3o_Relat%C3%B3rioAnual_vers%C3%A3oweb.pdf

Morgenstern, N. R.; Vick, S. G.; Viotti, C. B.; Watts, B. D. (2016) *"The Fundão tailings dam review panel: report on the immediate causes of the failure of the Fundão Dam"*.

Telles, A. C. M, 2017. *"Análise do comportamento de um rejeito de minério de ferro no estado de regime permanente".* M.Sc. Thesis, *in portuguese*, Rio de Janeiro, Brasil.