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Isotropic Behaviour of Tailings Sands with Non-Plastic Fines at High Pressures

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Abstract. This paper presents an experimental study that examines the isotropic triaxial behavior of tailings sands in a wide range of pressures, from 0.01MPa to 5MPa, varying the fine content of the specimens. The results suggest that the presence and quantity of fines influence the behavior: there is an increase in the compressibility of tailings sands deposited in a loose state, generating significant changes in the void ratio when confined throughout the range of pressures studied. Also, it is observed that the effect of the fines in the compressibility decreases with the decrease of the void ratio, exhibiting a stiffening of the sample for the densest conditions. Results of imaging performed on after-test specimens suggest that the tailings sand exhibits a slight breakage of its edges when it is consolidated at high pressures. For low void ratios, differences in fines content of up to 4% are observed for clean sand. This difference decreases when the fines content of the sand increases, suggesting that the presence of fines contributes to the stability of the granular structure, redistributing the interparticle stresses, reducing particle grinding.

Keywords. Non-plastic fines, compressibility, high pressure, tailings, consolidation.

1. Introduction

The increasing development of infrastructure has driven projects where the stress level on the ground exceeds 1 MPa. Examples of this type of projects are the tailings dams which, due to the growing mining industry, considers in their designs heights over 300 m. At this tension levels, the void ratio varies at a much lower rate with the confining pressure, which translates into a decrease in compressibility [1], [2]. The mechanisms that influence this behavior at this stress level are the stress distribution between particles, their granular rearrangement, the breakage of particles, and the effect of time, also known as creep [3], [4], [5].

Several studies on tailing sands suggest that they have greater compressibility, particularly for looser states, and in the first stage of consolidation [6], [7], [8]. Regarding

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the increase in fine content in sands, the literature has focused mainly on natural sands, which show an increase in the compressibility of the material when confined at loose states.

In the context of particle breakage, the fines content influences the distribution of stresses within the granular skeleton. Studies in natural sands show that a well-graduated material presents less rupture than a poorly graduated one [9]. This is because a poorly graduated material, under the same mineralogy, has less contact between particles, which implies greater stress concentration in these contacts [10].

In this context, the present work shows the results of 48 triaxial consolidations, at confining pressures between 10 and 50 kgf/cm^2. The tested samples contain 0%, 5%, 10% and 20% of fines, at relative densities of 15%, 65% and 90%. In addition, granulometry and post-consolidation optical microscopy tests are carried out to compare them with the intact material. The evolution of compressibility for a wide range of confining pressures is analyzed, along with the possible occurrence of particle breakage.

2. Equipment, materials and experimental program

2.1. Equipment

This study used the triaxial equipment of high pressures of the Laboratory of Solids and Particulate Medium of the University of Chile, developed by Solans in 2010 [12]. The system has a loading frame, axial load application, pressure chamber, back pressure, high-pressure triaxial cell, as well as instrumentation and data acquisition systems.

2.2. Materials

The experimental plan considers isotropic triaxial consolidations carried out in samples of tailings sands. This sand is angular as observed in Figure 1. The original material, of CF = 23%, was washed in order to extract the fine particles, obtaining almost a clean sand, with a 1% fine content, Figure 2. To develop the experimental plan, the sand is mixed with non-plastic fines to make materials of 1%, 5%, 10% and 20% fine content.

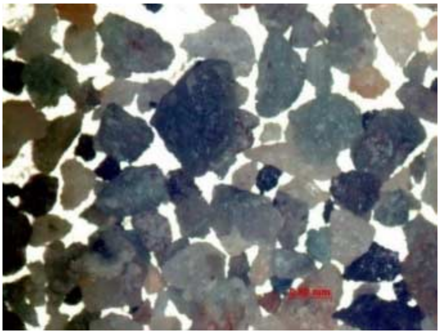


Figure 1. Washed tailings sand (cf = 1%), from the tailings dam El Torito.

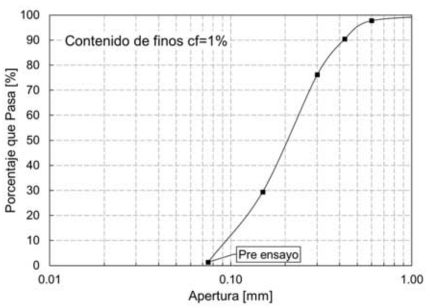
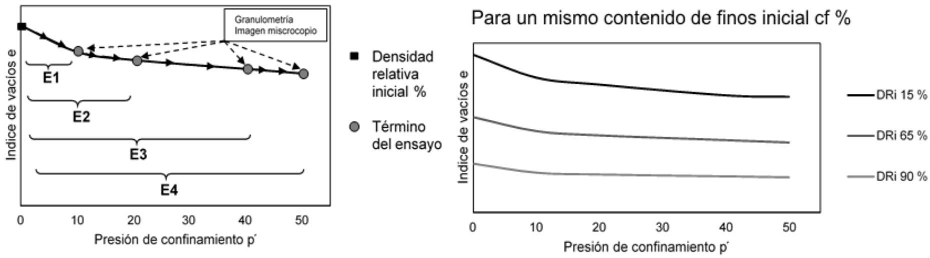


Figure 2. Granulometric curve sand base (cf = 1%).

2.3. Experimental program

The experimental program includes 48 tests of isotropic consolidation, varying the fine content of the samples, the relative density of the preparation and the confining pressure. For each fine content and relative density, four confining pressures, indicated in Figure 3, are reached to perform particle size distribution and microscopy imaging.



a) b)

Figure 3. Schematization of experimental program a) Development of the e-p 'curve for each material studied b) Scheme of the development of relative densities for each material.

3. Methodology

The preparation of tested samples considered the use of wet compaction (wet tamping), in ten equal layers in a bronze mold of known dimensions. After the preparation, the specimen is infiltrated with CO_2, distilled water, the saturation is verified by measuring parameter Skempton B [11], to proceed with the consolidation.

The confinement is increased in intervals of $1 kgf/cm^2$, allowing the drainage and stabilization of the volumetric change before the next load increment. The pore pressure, axial deformation and the volumetric change are measured at 30 seconds, 1 minute, 2 minutes. and 4 min. of consolidation, until reaching the desired final effective confinement pressure, monitoring the volumetric changes of the material.

After consolidation, the final void ratio of the test is evaluated by the method used by Verdugo, 1996 [12], which quantifies the void ratio of saturated specimens through the water content in the samples. The material is dried and sieved, to be compared with the granulometry of the material before testing. Also, microscopy samples are taken from the material retained in each sieve.

4. Experimental Results and Discussion

4.1. e_{max} and e_{min}

The fine content of a material influences its mechanical behavior, as well as on some of the state parameters that characterize it. Figure 4 shows the results of the maximum and minimum void ratio tests, using the Japanese method (JSSMFE) and slow deposition method (ASTM D 4254-00). The content of fines used varies between 1% and 50%.

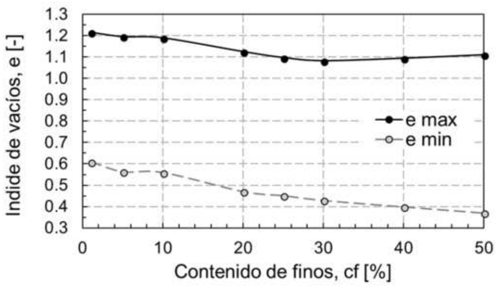


Figure 4. Results of the tests of maximum density (JSSMFE) and minimum (ASTM D 4254-00), for the sand of tailings, studied, varying the content of fines with respect to sand.

The curve formed by the loosest states reaches a minimum value $e_{max} = 1.082$, after that, it tends to increase, as indicated in Figure 4. The latter agrees with the behavior of natural sands with non-plastic fines exhibited by previous studies [13]. This occurs while (the majority of) the fine particles can stay in between the intergranular spaces. However, when the fine content increases, they begin to lodge between the sand particles, at the level of their contact, separating them. This agrees with the observations made by [14].

When analyzing the curve formed by the densest states, it is observed that it is decrescent for all the percentages of fines analyzed. This is due to the angular nature of the tailings sand particles and the high compaction energy, the fines, which are angular, also tend to settle in the empty spaces between the sands, decreasing the void ratio.

4.2. Compressibility

Figure 5 shows the variation of the void ratio when isotropic consolidation is performed in clean tailing sand and tailing sand mixtures samples with 20% of fine content, pressures ranging from $0.1 kgf/cm^2$ to $50\ kgf/cm^2$.

In Figure 6, the void ratio normalized by the initial void ratio during isotropic consolidation up to a confining pressure of $50\ kgf/cm^2$ is shown. The results of isotropic consolidation tests in natural Ottawa sand are also presented up to $50\ kgf/cm^2$. Figure 6 a) and c) shows that tailing sands present a greater change in their void ratio when affected by isotropic loads, in relation to rounded sands, such as the Ottawa sand.

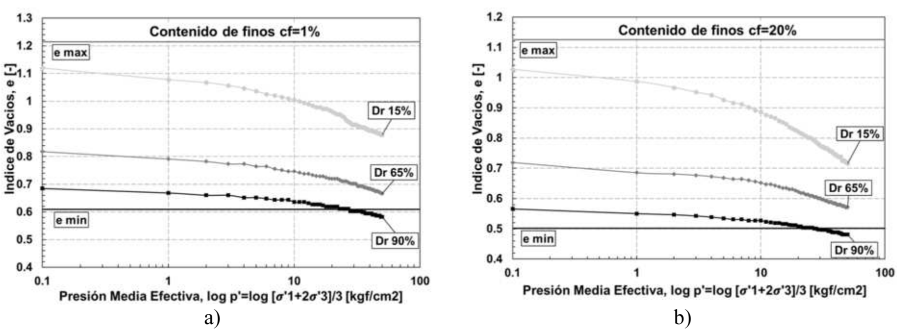
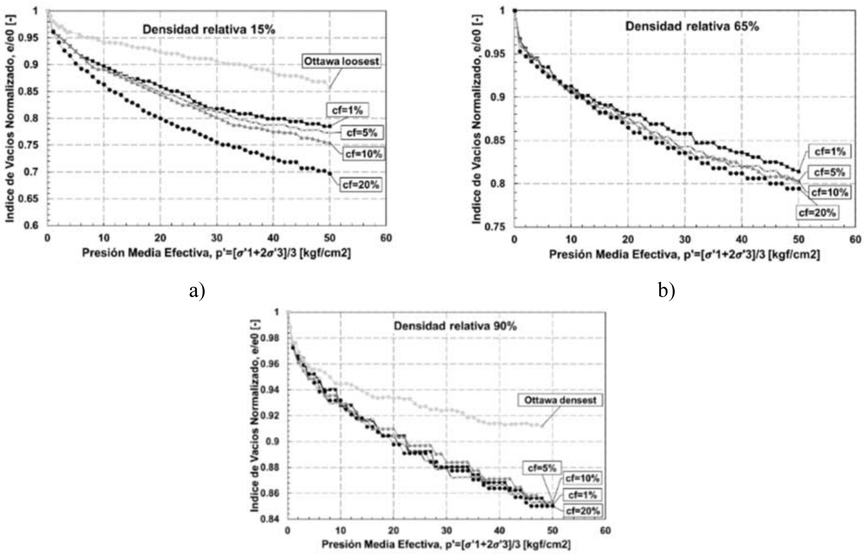


Figure 5. Contrast of the variation of the void ratio in isotropic consolidation of the materials studied with CF = 1% and CF = 20% and for all different initial states (Dr = 15%, 65% and 90%).



c)

Figure 6. Variation of the void ratio in isotropic consolidation normalized by the initial void ratio, for the three initial stages (Dr = 15%, 65% and 90%) and for the different materials studied (cf = 1%, 5%, 10% and 20%).

The loosest and densest states (DR = 15% and 90%), show a wide region of possible states of void ratios for all materials studied. This is due to the irregular/angular nature of the tailing sands, which makes it possible to form structures with higher void ratios compared to rounded sands that may have a more rounded surface. This translates into a greater capacity for rearrangement of particles when consolidated even at high pressures.

The results presented in Figure 6, where the void ratio its normalized by its initial void ratio, show an increase in compressibility, as the content of fines increases, for the loosest states. This difference becomes less and less noticeable when the relative density of the samples is increased. The latter behavior is because, for the denser states, the fines would be well accommodated in between the granular structure, with an already displaced and stable meta-structure [14], which would not contribute to the rearrangement of the sand particles, even restricting its change. In contrast, in the looser states, the fines would have a great influence on the compressibility of the material. The metastable structure would contribute to the rearrangement of the sand particles when they are consolidated in an isotropic manner, as it is schematized in Figure 7.

To quantify the compressibility of the sands studied at high pressures, above $10\ kgf/cm^2$, with different quantities of fine content, a compression coefficient is proposed, C_{c10}., Eq. (1).

$$C_{c10} = \frac{e_{50} - e_{10}}{\log(p'_{50}) - \log(p'_{10})} \tag{1}$$

Figure 8 shows the values of the compression coefficient for the materials tested up to $50\ kgf/cm^2$. This parameter shows the gradual increase in compressibility for the looser states. Finally, for the case of the relative densities of 90%, the results show an increase in volumetric stiffness, with decreasing variations in the void ratio as the fines content of the samples increases. The fines already accommodated in between the intergranular spaces would tend to restrict the rearrangement of the larger particles, which explains the slight increase in volumetric rigidity.

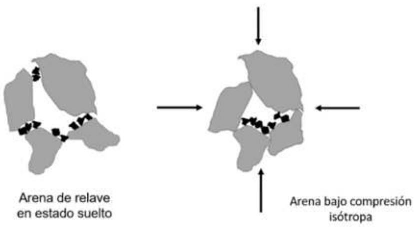


Figure 7. Schematic meta-structure mechanism for loose states of tailings sand when consolidated.

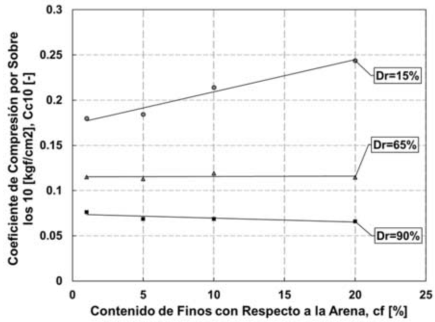


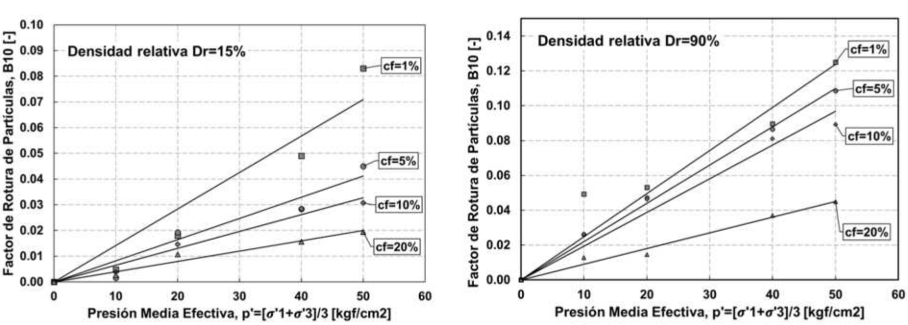
Figure 8. Variation of the compression coefficient C_{c10}, for p 'greater than 10 kgf/cm^2 when increasing the quantity of fines, for the relative densities studied (DR = 15%, 65% and 90%).

4.3. Particle breakage evaluation

The Particle Breakage Factor B_{10} proposed by [15], and defined by Eq. (2) is used. This parameter gives values in the range from 0 to 1 and represents the change in the finest 10% of the tested sample. In Figure 9 all the relative densities analyzed are shown.

$$B_{10} = 1 - \frac{D_{10f}}{D_{10i}} \tag{2}$$

In Eq. (1) D_{10f} is the particle size for which 10% of the sample material tested is smaller, while D_{10i} is the particle size where 10% of the original sample material is smaller.



a) b)

Figure 9. Variation of the breakage factor of particles B10 (Lade, 1996) with the effective average pressure p', for samples of the relative density of preparation of 15% and 90%.

The samples tested with higher initial relative density have higher values of B_{10}, which agrees with the results of previous investigations [12], [7].

In order to analyze the influence that the fine content has on the breakage of particles, the use of the area under the curve in the B_{10}-p 'plane is proposed, defined by Eq. (3).

$$\Delta A_{B10} = \frac{\left(\frac{p'_{i+1}}{p_{max}} - \frac{p'_{i}}{p_{max}}\right) * (B_{10\,i+1} + B_{10\,i})}{2} \quad (3)$$

In Eq. (3), p': Effective average pressure and B_{10}: Particle breakage factor.

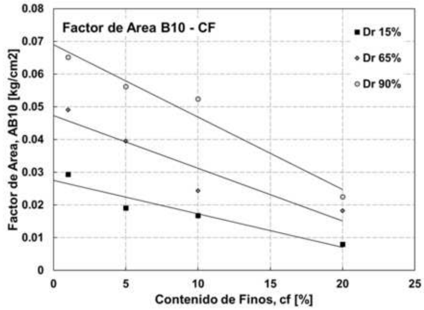


Figure 10. Area factor B10 when varying the content of fines for the densities seen in this study.

The results shown in Figure 10 exhibit a decrease in particle breakage with the increasing of fines in the samples. This tendency suggests that there is an increase in the contacts between particles when increasing the fine content, better distributing the effective tensions and decreasing the level of rupture.

Microscope images were used to compare the sand before testing with the sand after consolidation. A subtle tendency of these to be more rounded is shown. This suggests that the break seen in the consolidation tests corresponds to the breaking of the angular edges of the tailings sand.

5. Conclusions

The results of this experimental program suggest that the increase in the percentage of non-plastic fines increases the compressibility of tailing sands at low relative densities, as observed for relative densities of $D_R = 15\%$. Samples with a 20% fine content showed a volumetric variation up to 10% higher than the clean sand (cf = 1%). The previous observation results in a large variation of the samples relative density after consolidation. The presence of fines between the contacts of the sand particles of tailings in a loose state, along with the angular nature of the particles, causes large spaces in between particles, which could facilitate the rearrangement when consolidated.

The percentage of fines in tailing sands shows an influence on the level of particle breakage in consolidation tests. The results suggest that the breakage presented is increased with higher relative density of preparation and decreases when increasing the fine content of the samples.

For the loosest states (DR = 15%), the results show that the development of breakage level, given by the breakage parameter B_{10}, is almost zero until confining pressures of 10 kgf/cm^2, this is due to the great space for the rearrangement of particles delaying the breakage of the angular edges from granular interlocking in loose states.

At high pressures, the granular structure of tailing sands can achieve void ratios smaller than the one given by the standardized methods used to calculate the minimum void ratio — this factor combined with the increment of the fine content due to particle breakage results in the need to find other parameters to characterize materials at high pressures.

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