Evaluation of solids content in settling, compressibility, and consolidation of a low-density tailings

Christ Jesus Barriga Paria[1], Eleonardo Lucas Pereira[2]

[1] National University of Moquegua, Ancash Street, Moquegua, Peru (cbarrigap@unam.edu.pe)
[2] Federal University of Ouro Preto, Morro do Cruzeiro, Ouro Preto, Brazil (eleonardo@ufop.edu.br)

ABSTRACT

The use of saline water, a product of the sea water osmosis process, for the processing of the mineral from the Bayovar Mine in Peru, is part of the process of final disposal of the studied tailings. In this sense, this paper presents an experimental program implemented for the correct evaluation of this fine low-density phosphate tailings, the behavior of six solids contents prepared in the laboratory with limits between the range 8.5% to 21% were analyzed. The results achieved, from settling and consolidation tests by hydraulic consolidation test, attested to the effectiveness, in addition to being representative, based on the analyzes and comparisons instituted and the definition of the compressibility and consolidation characteristics of the phosphate tailings of the evaluation. The relations of compressibility and permeability through the curves of effective stress versus void index and void index versus hydraulic conductivity. The different systematized analyzes, when compared, proved that phosphate tailings experience a greater volume reduction in the settling phase, with a greater variation in the void index in the sedimentation stage. The tests also showed that the presence of NaCl acts as a flocculant, making these materials more compressible.

1. Introduction

The management of the disposal of low-density tailings by the wet way, such as phosphate, is extremely relevant in the mining industry, and a detailed characterization of the fine tailings is essential, whose densification process is not governed by the proposed Terzaghi theory for Classical Soil Mechanics (Terzaghi et Frölich, 1936). Much of the literature presents conventional characterization tests of the material, involving several limiting assumptions, such as small deformations and constant coefficients of densification and hydraulic conductivity. Thus, it is essential to carry out studies improving a fundamentally consistent depositional model, related to the large deformations experienced by the tailings during the consolidation process. Therefore, this paper has developed an analysis methodology from the sedimentation process (through cylinder tests), the consolidation process, carried out by the hydraulic consolidation test (HCT, a non-conventional test in particular).

The tailings coming from the beneficiation stage of the Bayovar Mine, in Peru, allowed to assemble the specimens for different solids contents, with values of 8.5%, 11%, 13.5%, 16%, 18.5% and 21%. To accurately determine the settling rate and the compressibility and permeability ratios for low density tailings pulps, referring to the different conditions of the solids content. The high salinity of the waste because of the beneficiation process in which sea water treated by the reverse osmosis process is used, the water reaches an average content of 4576 ppm in the final disposal of the waste.

2. Materials and Methods

2.1. Phosphate deposits of Sechura

According to McDonald (1956) the coastal platform in the Sechura desert, in northern Peru, you will find fine marine sandstones with marine clay, diatomite-phosphate clays and shales with the presence of limestone sandstones. Fassbender (1967) the layers are mainly massive, but friable, with no apparent stratification, and their potential for the effect of phosphate increases by decreasing the size of the particles.

Manheim et al. (1975) the platform of the Peruvian coast shows sediments with high characteristics of softness, a green coloration, rich in chlorophyll and pheophytin, have a high water content, smell of H2S. Cheney (1979) These deposits are different from other important marine deposits in that they consist mainly of phosphate and diatomite and the pellets are composed of a fluorine-deficient carbonate hydroxyl apatite of a type not known in other marine deposits.

Rodríguez et al. (2011) the phosphate deposits whose mineral reserves are estimated at 816 million tons, equivalent to 262 million tons of phosphate rock concentrates at 30% P_2O_5, the potential reserves are estimated at 10,000 million tons.

2.2. Study Place

The tests required for this study were carried out at the Technological Center for Applied Geotechnics (CTGA) of the Geotechnical Center of the Escola de Minas (NUGEO). The samples from the Bayovar Mine in Peru come from marine sedimentary rock, as described in the previous point.

A thin part of the tailings and saline water constitutes the pulp released into storage tanks and the launching system was directly sampled. Thus, we tried to preserve the initial solids content of the material in an average of 15 and 16%. Subsequently, settling cylinder tests were performed with material under natural conditions, but with different solids contents.

2.3 Settling test

Settling was carried out using the cylinder test. This test is particularly applied using graduated cylinders and depending on the objectives, the characteristics are put into practice (Been and Sills, 1981; Santos, 2001; Silva, 2008). To start the test procedure, the tailings was homogenized in a reservoir under controlled agitation, with a speed of 500 rpm for a period of 10 minutes, using a Fisatom Metal stirrer with a long stem, avoiding a greater amount of solids at the bottom of the reservoir. than on the surface. The levels of solids employed were 8.5%, 11%, 13.5%, 16%, 18.5% and 21%, for phosphate tailings, carefully obtained and guaranteed with constant tests in the stove with representative samples.

Then, each sample representing a solid content was transferred to a 1000 ml beaker, the sample was manually stirred by inverting the beaker for 1 minute with less agitation to obtain a uniform mixture. Settling time was the main monitoring variable. The settling rate was calculated from the initial decrease in the tailings height (h) versus the settling time (t), three stages are observed in the phosphate tailings sample and the behavior of the displacement of the supernatant/tailings water interface was evaluated. by means of settling tests in beakers with the known volume. As shown in Figure 1, the typical phosphate tailings sedimentation curve is shown, and the Initial Settling Rate (ISR) can be evaluated.

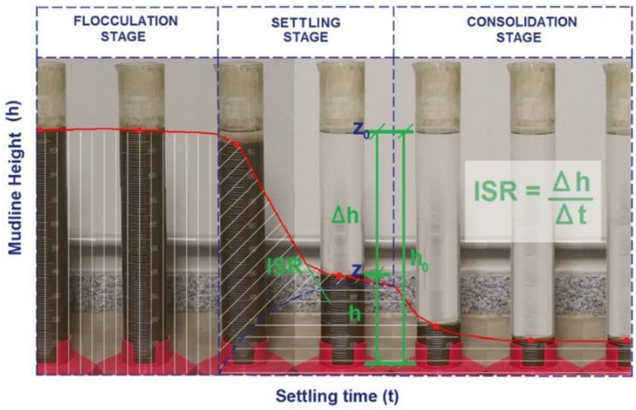

Figure 1 - Typical curve of phosphate tailings to calculate the initial settling rate based on the results of the mudline height versus settling time.

2.4 Hydraulic consolidation test

The samples used for the same solids content were tested with two flow rates, one speed for continuous flow 0.35 ml/s and a second speed that will be one tenth of the first speed for the permeability phase (0.035 ml/s). To homogenize the tailings, the same stirrer was used and mixed in a plastic beaker with a volume of 1000 ml, with a rotation frequency around its fixed axis of 500 rpm when the procedure was finished, which lasted 10 minutes, the waste was able to be standardized.

The data of the weights and heights of the sample of each content were measured manually at the beginning and at the end of the test. Then the sample was transferred to the apparatus chamber and an external chamber, the latter for tests to characterize the specimen. This remaining material was used to guarantee the initial solids content of the tailings (molding), the initial moisture content of the sample (molding) and determination of the voids index for zero effective stress (e_{00}).

To achieve zero effective stress (e_{00}), it is essential to know the value of the void index, which is why the procedures that help in obtaining it are employed, being able to make a comparison between them. According to Cançado (2010) the use of a secondary chamber, with the same characteristics as that used in the HCT test, and the adoption of a specific experimental procedure make it possible to obtain the void index for zero effective stress (e_{00}).

Other procedures depend on values obtained in the settling tests using the cylinder technique, where the initial height of the mud in the column is evaluated and then the height when the settling is finished. Obtaining the void index for zero effective stress (e_{00}) is then feasible by using the values of the initial conditions and variations in height.

For the calculation of the void index for zero effective stress (e_{00}), the data obtained from the settling tests by column were related, which lasted 13 days each considering the flocculation stages, proper settling stage and the density stage for the 6 standardized content solids. Being able to know how long settling should take place for each solids content, it was possible to obtain the optimal time for the settling to be carried out in the HCT device chamber and in the secondary chamber.

In the first stage, hydraulic-consolidation test, the equilibrium poropressure originating at the base of the specimen determines the effective stabilization stress, the same that results from the final displacement of the solid particles, vertical deformations, and the reduction of the voids index, registered by the transducer. It is also necessary to measure the final height of the specimen.

2.5 Salinity

The salt content in the phosphate tailings was obtained by tests of solids content, a representative sample of the tailings was selected, weighed, and taken to the oven for calculations. The obtained value of 4576 ppm demonstrated that the tailings had a very high salt content, a value that influenced the settling and flow-induced consolidation tests. Several researchers have studied this influence specifically on the settling rate in different environments.

According to Thill et al. (2001), regarding the salt-induced aggregation, the kinetics of the reaction depends on the electrostatic repulsion between the particles, which is dependent on the salinity for the variation of the settling rate. Maggi (2005), the presence of salt in natural water produces free cations and ions that cause a decrease in the energy barrier and, finally, an elimination for medium to high concentrations of salt.

Graham and Manning (2007) the settling rate of flakes is inversely proportional to the diameter of the equivalent spherical flake. Graham and Nimmo Smith (2010) settling rate and variations in effective density as a function of particle size show excellent agreement in a variety of salty environments. Portela et al. (2013), settling rates increased in direct relation to the increase in salinity. Ji et al. (2013) the increase in salinity considerably reduces electrostatic repulsion, the use of sea water and its salinity content is responsible for the settling rate and turbidity of mining tailings.

3 Results and Discussion

3.1 Technological characterization of the phosphate tailings

3.1.1. Determination of grain specific gravity and voids index

ASTM D-854 (ASTM, 2014) was used to determine the specific mass of the grains (ρs). An average specific mass of 2.41 g/cm³ was obtained from the tests, obtaining in addition the index of initial voids with a value of 14.42 depending on the specific mass.

3.1.2 Determination of particle size analysis

ASTM D7928 (ASTM, 2017), the standard describes the procedures for knowing the grain size of the tested sample. Figure 2 (A, without hexametaphosphate and without sonar. B, with hexametaphosphate and without sonar. C, without hexametaphosphate and with sonar. D, with hexametaphosphate and with sonar) shows the results represented in the curves obtained from the analysis of the tests that were carried out in four conditions for 6 samples (B01 to B06), however, for very thin materials, the use of the densimeter is sometimes inefficient.

In the case of phosphate tailings, it was known that it could not be carried out with the classical technique for its properties, it was decided to carry out the test using a reduced sample with 40 g and a sample with 70 g. The result with the reduced sample was not satisfactory and, therefore, was discarded.

The colloidal characteristic of the sample had no relation to the sedimentation speed, as it is a material with a clay fraction that is not very representative. On the other hand, values of relative density of low grains were found, compared to other tailings, which, with great probability, had an influence on the settling rate.

3.1.3 Determination of Atterberg limits

Phosphate tailings showed consistency with limits defined using extracted methods D4318-17e1 (ASTM, 2017). Even having a mostly granular behavior, the plasticity limit and the liquidity limit were obtained based on the procedures and the use of the Casa Grande Apparatus, the results are shown in Table 1.

Table 1: Atterberg limits of the tailings

Test	LL (%)	PL (%)	PI (%)
1	87	40	35
2	85	41	33

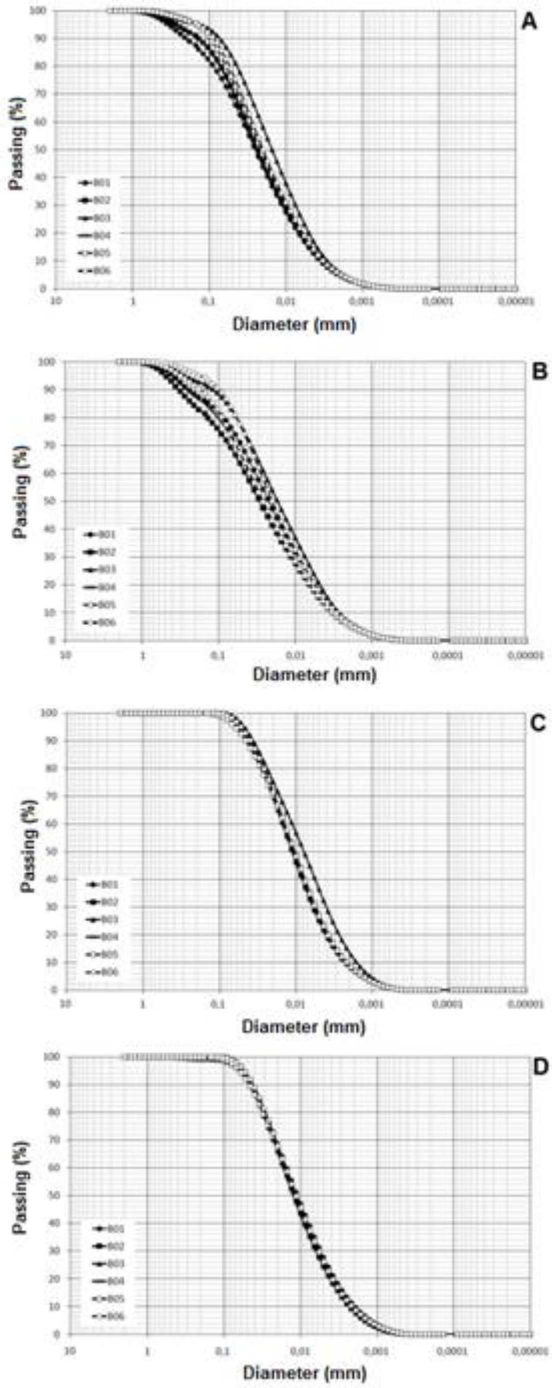

Figure 2 - Granulometric curves of the samples obtained with the laser granulometer.

3.2. Chemical and Mineralogical Analysis

Phosphate tailings have chemical and mineralogical characteristics directly related to variations in terms of concentration, mainly to the industrial processing process, covering activities that could be altered by changing the fronts of exploration. From a primary cyclone, the phosphate tailings were obtained to perform this work, their generation does not include any additions of flocculants. Concentrates are often expressed as a function of their percentage of phosphorus pentoxide (P_2O_5), a feature directly related to phosphate rock.

3.2.1 Chemical analysis

Table 2 presents the results of the chemical analysis carried out by the atomic absorption spectrometry test, one of the existing spectro-chemical techniques. It is possible to analyze the predominant existence of SiO_2 and, with low amounts, of P_2O_5, CaO and Al_2O_3, as well as an inactive characteristic of the tailings, from the point of view of contaminating elements.

Table 2 - Results of the tailings and phosphate analysis

Components	Mass fraction (%)
P_2O_5	7.2
CaO	9.3
SiO_2	61.6
MgO	1.7
Al_2O_3	6.9
Fe_2O_3	2.8
Another	10.5

3.2.2 Mineralogical analysis

For the mineralogical analysis the scanning electron microscope (SEM) was used, high magnification and resolution images are obtained by the qualified equipment, as well as by X-ray diffraction equipment, all belonging to the Postgraduate Course in Materials Engineering from the Federal University of Ouro Preto.

Particularly noteworthy are the presence of Biotite (BI), Halite (H), Bassanite (BA), Quartz (Q) Fluorapatite particles, with silicon oxides not exceeding 50 microns. The latter represent a content of almost 60%, a very significant presence.

Figure 3 shows emphasis on the identification of silicate fossils that are common in the layers and interlayer of the rock. The images obtained from electron microscopy, with different approaches, are shown in Figures 3A to 3D, with emphasis on the identification of silicatic fossils in Figure 4D.

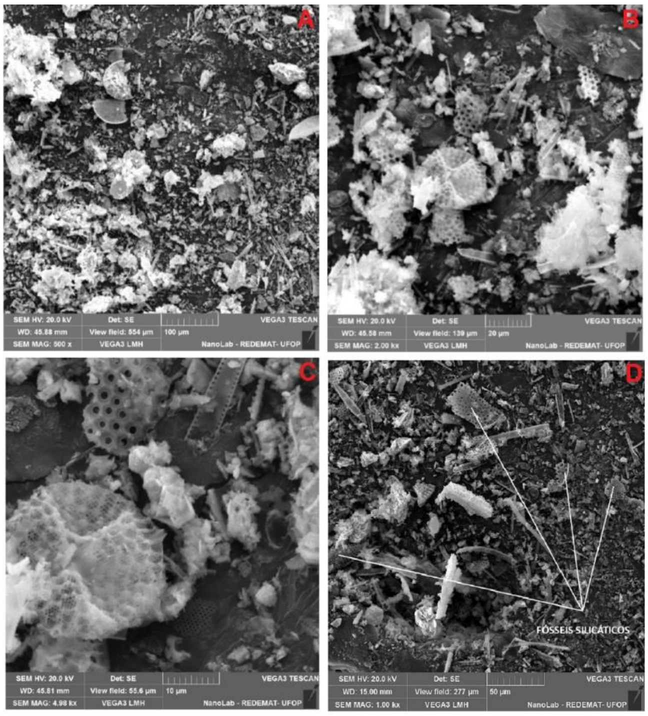

Figure 3, A - SEM of phosphate tailing - approach 500X, B - SEM of phosphate tailing - approach 2000X, C - SEM of phosphate tailing - approach 5000X, D - SEM of phosphate tailing - approach 2000X.

As a characteristic of plankton (Asteromphalus) is the significant presence of silicatic marine fossils, common in the layers and interlayer of phosphate rock. The phases observed in X-ray diffractometry were not so evident when analyzed from energy dispersion spectroscopies. A typical spectrum obtained in the analyzes showing the presence of oxygen, silicon and, to a lesser extent, calcium, sodium, and chlorine. The other spectra also showed the presence of aluminum, iron, sulfur, carbon, magnesium, phosphorus, and potassium, all in small percentages.

3.3. Results of column tests

As a Figure 1 shows z_0 as the initial height of the test tube suspension and z is the height at a point on the phosphate tailing curve to calculate the sedimentation speed, at the time in question. The maximum settling rate at the upper interface of the solids were obtained on average values of 0.08 cm/min for contents of 11% to 21%, but for 8.5% a settling rate of 0.17 cm/min was obtained. Settling rate were calculated from Equation 1 and summarized in Equation 2.

$$v_s = -\frac{d_z}{d_t} = \frac{z_0 - z}{t_0 - t} \qquad 1$$

$$v_s = \frac{\Delta h}{t} \qquad 2$$

Figure 4 shows the values of sedimentation speeds, calculated over the time column test for each phosphate tailings solids content, highlighting that at rates they maintain a similar range except for the 8.5% content that shows more advantageous because of having a larger volume of free liquid so that the particles can decant quickly without suffering any type of collision.

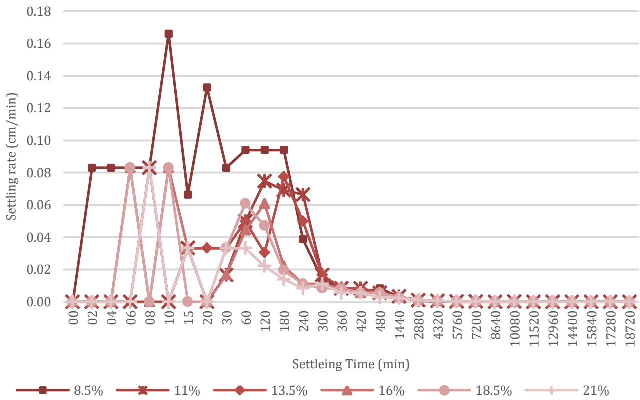

Figure 4 – Settling rate about the settling time

3.4 Hydraulic consolidation test

In this phase of the interpretation step prior to the main results, the SICTA (Seepage Indiced Consolidation Test Analysis) was used, an algorithm that covers the effect of minimizing the sum of the squares of the normalized differences between the practical laboratory data and the predictions calculated for these data (Abu-Hejleh and Znidarcic, 1992).

The software suggested to determine the constitutive relationships such as void index versus effective stress (e vs σ') and void index versus permeability (e vs k) by acquiring the constitutive empirical parameters associated with the material obtained by means of densification tests flow-induced A, B, Z, C and D, of which the mathematical models are expressed by Equations 3 (Liu and Znidarcic, 1991) and Equations 4 (Somogyi, 1979), equations further developed by the authors Abu-Hejleh (1993, 1995), Yao and Znidarcic (1997) and Yao et al. (2002).

$$e = A * (\sigma' + Z)^B \qquad 3$$

$$k = Ce^D \qquad 4$$

The HCT device was tested, and the values obtained when compared with studied material standards that gave approval for the good reproduction of the results were evaluated, the conformity to perform the experimental programming and fulfill the objectives of working with each of the standardized levels was performed successfully, since during the experimental part the phosphate tailings proved to be a material dominated by fine particles. To improve the bibliography on how to behave the tailings studies of this material were carried out for six different solids contents added in 2.5% to its predecessor to cover a wider scale, correctly extracted from the storage container where they were treated for its homogenization. Figure 5 shows the curves obtained from the pressure-versus-time ratio of the tests performed in the solids content (w_s) from 8.5% to 21%.

According to Znidarcic et al. (1992, 2000) the induced flow densification test must guarantee poropressures generated in the base, in the range of 2 to 5 kPa. To achieve these values, the average flow rate used in the laboratory in previous works was adopted, employing the value of 0.35 mL/min. The constitutive relations were built based on Equation 3 (Liu and Znidarcic, 1991) whose correspondences for the compressibility calculation are shown in Table 3 (e: void index) and in Equation 4 (Somogyi, 1979) together with the constitutive parameters for the calculation of permeability are shown in Table 4 (k: permeability). Both equations widely accepted because it would surpass previous formulations that presented a vacuum ratio close to infinity with zero effective stress, in fact the equation for calculating the permeability coefficient is very well suited for low density soils.

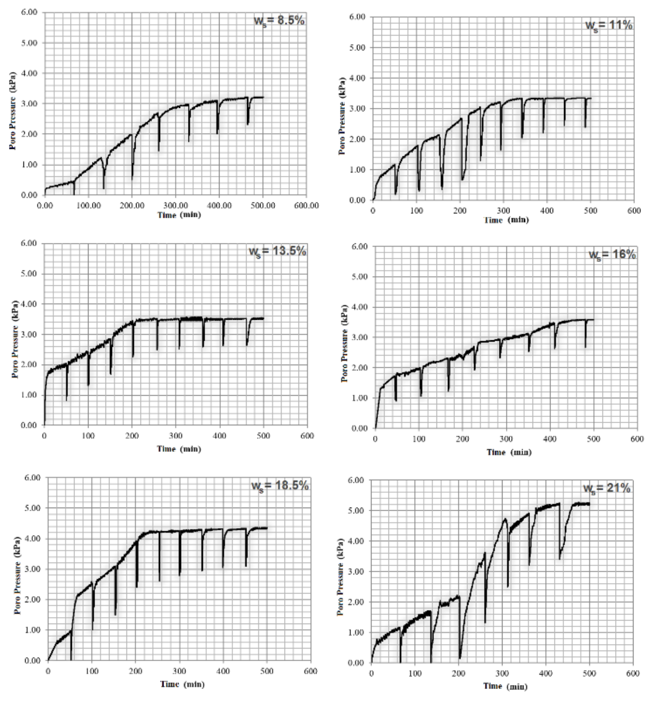

Figure 5 - Poropressure versus time curve (hydraulic consolidation test for the six solids content)

Table 3 - Constitutive relationships for Compressibility obtained in the HCT

Solids Content (%)	Constitutive relationship for Compressibility
8.5	$e = 6{,}62859 * (\sigma' + 0.00217)^{-0.52390}$
11	$e = 6{,}21310 * (\sigma' + 0{,}22840)^{-0{,}97730}$
13.5	$e = 14{,}17157 * (\sigma' + 5{,}45209)^{-0{,}36809}$
16	$e = 3{,}97881 * (\sigma' + 0{,}00005)^{-0{,}06223}$
18.5	$e = 9{,}03030 * (\sigma' + 2{,}46249)^{-0{,}28801}$
21	$e = 5{,}92216 * (\sigma' + 0{,}57434)^{-0{,}19624}$

Table 4 - Constitutive relationships for Permeability obtained in the HCT

Solids Content (%)	Constitutive relationship for Permeability
8.5	$k = 1{,}0474\text{x}10^{-4} * e^{1{,}10730}$
11	$k = 1{,}3951\text{x}10^{-9} * e^{8{,}00000}$
13.5	$k = 1{,}1120\text{x}10^{-4} * e^{0{,}10000}$
16	$k = 9{,}5203\text{x}10^{-5} * e^{0{,}91648}$
18.5	$k = 8{,}6877\text{x}10^{-5} * e^{0{,}10000}$
21	$k = 8{,}2582\text{x}10^{-6} * e^{0{,}10000}$

Abu-Hejleh et al. (1996) worked with HCT to research and obtain the voids index-effective stress index and voids-permeability ratio, for various types of very soft phosphate clays. These results were used as a basis for its application and to obtain results from the computed construction parameters and the equations obtained for the calculation of the voids index for the drawing of the compressibility curves for the six solids contents with values from 0.1 to 1000 kPa, data that were later used to calculate permeability, with the objective of designing permeability curves.

Figure 6 shows the six levels of solids used for its evaluation and behavior related to compressibility and consolidation by means of the void index - effective stress curves, the density of the low density tailings particles begins with very small effective stresses that are mainly induced by applying a small hydraulic gradient to the specimen. However, contents of very low solids presented curves very far from the other contents, with values for the voids index from 21.90 and 18.45 to 8.5% and 11% respectively for an effective stress of 0.1 kPa, the curves of these two contents are shown in Figure 7, showing values of up to 135.10 and 26.19 for an effective stress of 0.001.

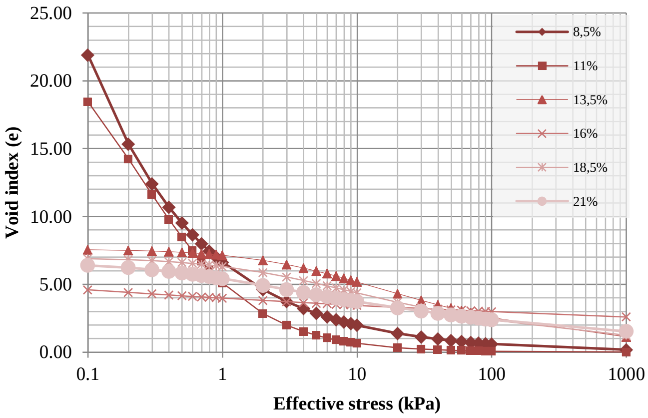

Figure 6 - Compressibility curves of the tested specimens

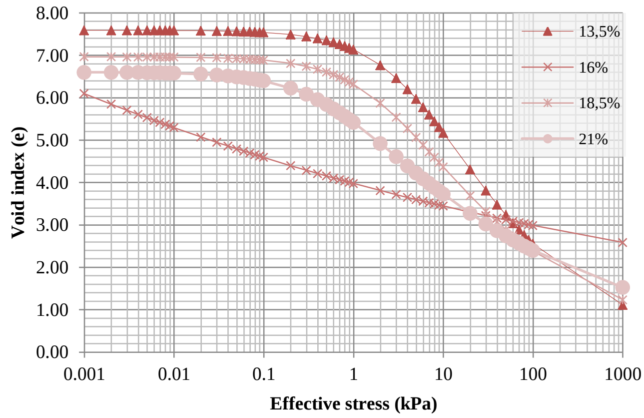

Figure 8 - Compressibility curves for specimens tested with ws from 13.5% to 21%

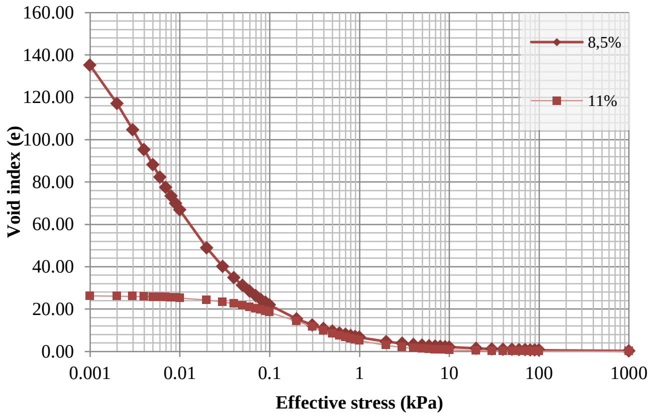

Figure 7 - Compressibility curves for specimens tested with w_s of 8.5% and 11%

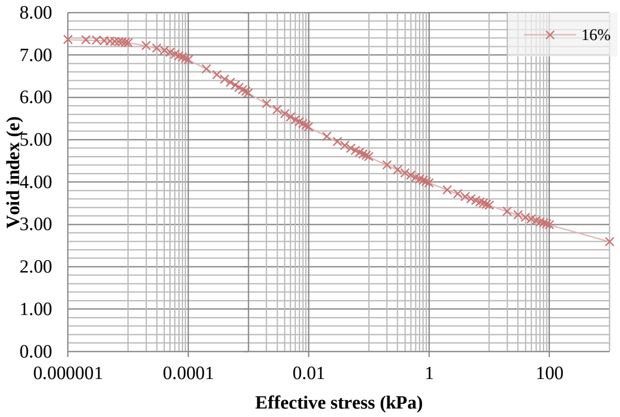

Figure 9 - Compressibility curve for the specimen with 16% w_s

The graph shows that a very low solids content such as 8.5% the void index tends to be very high, a congruence of high spaces when working with stresses of 0.001 kPa obtaining a value of 135.09 for the volume ratio pores between the volume occupied by the waste particles. For the 11% solids content it is found in an intermediate paper with a value of 26.19 voids index for the stress of 0.001 kPa, corroborating the theory of higher solids content, the smaller the pore volume.

Figure 8 presents the curves for the other solids contents that presented the closest void indices for an effective stress of 0.001 kPa, thus values of 7.59, 6.97, 6.60 for solids contents of 13.5%, 18.5% and 21% respectively. However, the 16% solids content curve showed a considerable difference compared to its competitors, which led to an effective stress of 10-5 kPa to obtain 7.36 voids index (Figure 9), showing that this content it tends to reach very low effective stresses to obtain a stable voids index.

The application of Equation 4 made it possible to obtain the values of hydraulic conductivity to perform the curves in relation to the void index, shown in Figure 10, which demonstrated that depending on the solids content these tend to be stable but quickly and with a lower conductivity.

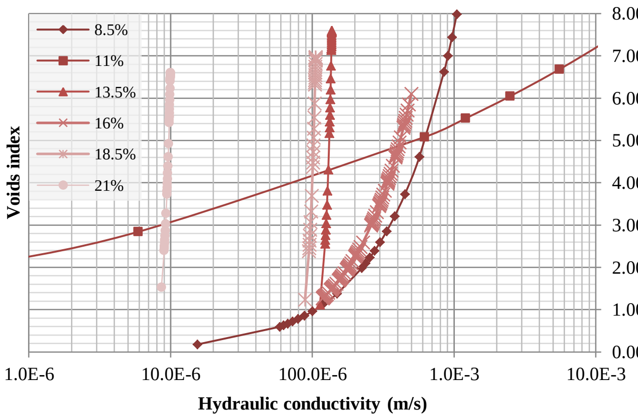

Figure 10 - Permeability curves of the tested specimens

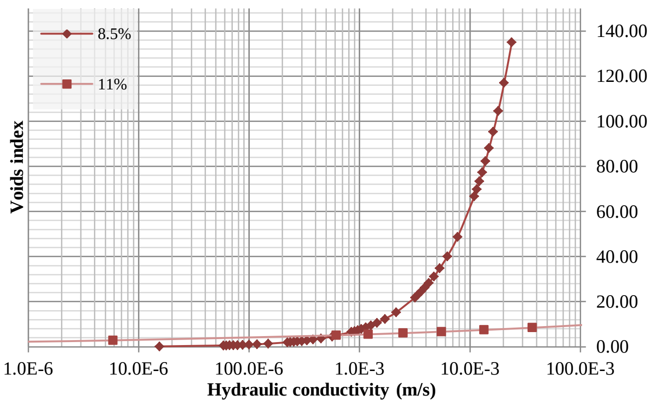

Figure 11 - Permeability curves for specimens tested with w_s of 8.5% and 11%

Figure 11 shows the curves for the solids contents 8.5% and 11% with a different trend than the other levels because these curves have very high values in the void index reflected in the hydraulic coefficient also high, which indicates a high permeability.

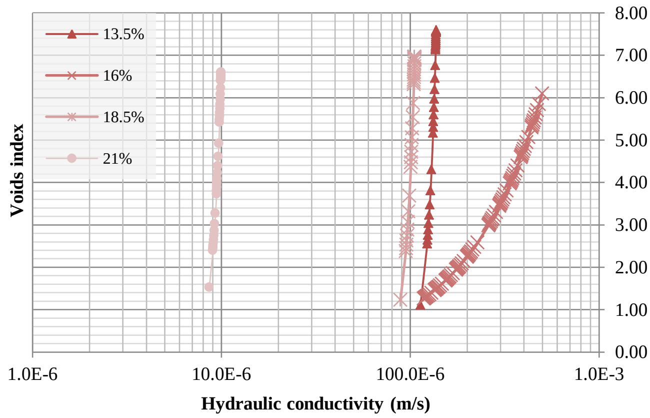

Figure 12 - Permeability curves for w_s specimens from 13.5% to 21%

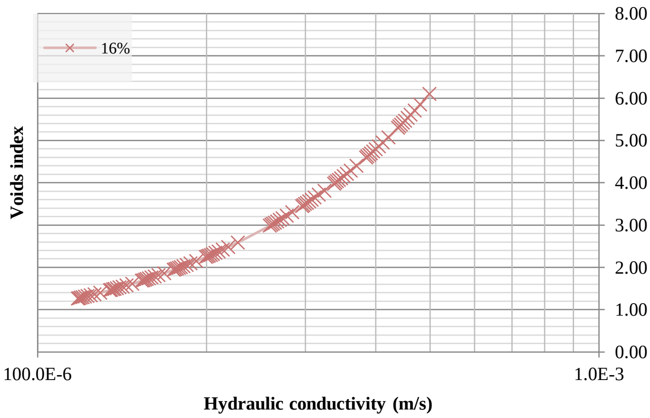

Figure 13 - Permeability curve for the specimen with 16% w_s

Figure 12 presents the other contents, in the reason that the solids content of 13% presents better values in the hydraulic conductivity than that of 16% in addition to many close to those of 18.5%, while the content of 21% by the values of voids index congruently found further away from the other curves. Figure 13 represents a typical isolated permeability curve for a solids content of 16%.

4 Conclusions

Six hydraulic consolidation tests were performed at CTGA, varying the solids content of the phosphate tailings in a 2.5% increment ratio starting with 8.5% to 21% to accurately determine the compressibility and permeability ratios for phosphate tailings with the characteristic of being of low density.

The results obtained are in accordance with published historical data and this makes the applied methodology and the HCT apparatus of the CTGA laboratory reliable as a reliable tool for the characterization of low-density tailings consolidation.

Obtaining relatively quickly and directly the constitutive parameters the correlation of the effective voids-tension index and voids-permeability index offer a detailed model of the consolidation for the phosphate tailings.

The results obtained in the settling and densification tests, proved that the Bayovar phosphate tailings experience a greater volume reduction in the settling phase, being poorly compressible for the stress levels when the solids content increases. The greatest variation in the void index occurs in the settling stage.

These models can help professionals to present good estimates about the densification behavior of fine tailings particles in the field based on this study that can be used in the design of tailings disposal strategies at all stages of mining projects.

The salt content showed control over the magnitude of the repulsive forces in the phosphate tailings by predicting an unstable suspension in a 4576-ppm solution that is just over 10% of seawater.

A saline solution can significantly reduce the electrostatic repulsion that exists between negatively charged solid particles, leading to bridge interactions in the phosphate tailings particles, improving settling.

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REFERENCES

Abu-Hejleh, A. N.; (1993) Desiccation theory for soft soils. Boulder, Colorado: Department of Civil, Environmental and Architectural Engineering, University of Colorado, (Ph.D. Thesis), 206 p.

Abu-Hejleh, A. N.; Znidarcic, D.; (1992) User manual for computer program SICTA. Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, Colorado, 101 p.,

Abu-Hejleh, A. N.; Znidarcic, D.; (1995) Desiccation theory for soft cohesive soils. Journal of Geotechnical Engineering, ASCE, v.121, n. 6, pp. 493-502.

Abu-Hejleh, A. N.; Znidarcic, D.; Barnes, B. L.; (1996) Consolidation characteristics of phosphatic clays. Journal of Geotechnical Engineering, ASCE, v. 122, n. 4, pp. 295-301.

ASTM: American Society for Testing and Materials. (2014) Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. D-854. ASTM International, West Conshohocken, PA, www.astm.org

ASTM: American Society for Testing and Materials. (2017) Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis ASTM D7928 – 17. ASTM International, West Conshohocken, PA, www.astm.org

ASTM: American Society for Testing and Materials. (2017) Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, D4318-17e1 ASTM International, West Conshohocken, PA, www.astm.org

Cançado, N. L.; (2010) Desenvolvimento de equipamento para execução de ensaios HCT com uso de bomba de fluxo; dissertação de mestrado, Núcleo de Geotecnia - Universidade Federal de Ouro Preto, Brasil, 113 p.

Cheney, T. M.; McClellan G. H.; Montgomery, E.S.; (1979) Sechura phosphate deposits, their stratigraphy, origin, and composition. Economic Geology Vol. 74, 1979, p. 232-259. DOI: 10.2113/gsecongeo.74.2.232.

Fassbender, H.W.; (1967) Los fosfatos naturales de Sechura, Perú. Turrialba, 17 (2): p. 159–164.

Graham, G. W.; Manning, A. J.; (2007) Floc size and settling velocity within a Spartina anglica canopy. Cont. Shelf Res. 27(8): pp. 1060-1079.

Graham, G.W.; Nimmo Smith, W.A.M.; (2010) The application of holography to the analysis of size and settling velocity of suspended cohesive sediments. Limnology and Oceanography: Methods 8, pp. 1-15.

Ji, Y., Lu, Q., Liu, Q., Zeng H.; (2013) Effect of solution salinity on settling of mineral tailings by polymer flocculants, Colloids and Surfaces A: Physicochemical and Engineering Aspects, Volume 430, 5, pp. 29-38.

Liu, J. C.; Znidarcic, D.; (1991) Modeling one-dimensional compression characteristics of soils. Journal of Geotechnical Engineering, ASCE, v. 117, n. 1, pp. 162-169.

Maggi, F.; (2005) Flocculation Dynamics of Cohesive Sediment. Delft, The Netherlands: Delft University of Technology Ph.D. thesis, 154 p.

Manheim, F.; Rowe, G. T.; Jipa, D.; (1975) Marine phosphorite formation off Peru. Jour. Sed. Petrology, v. 45, p. 243-251.

McDonald, G. H.; (1956) Miocene of the Sechura Desert, Piura. Bol. Soc. Geol. del Perú, 30: p. 225-242.

Portela, L.I.; Ramos, S.; Trigo-Teixeira, A.; (2013) Effect of salinity on the settling velocity of fine sediments of a harbour basin. In: Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), Proceedings 12th International Coastal Symposium (Plymouth, England), Journal of Coastal Research, Special Issue No. 65, pp. 1188-1193, ISSN 0749-0208

Rodríguez, I.; Villarreal E.; Acosta J.; (2011) Metalogenia y Geología Económica por Regiones., Instituto Geológico Minero y Metalúrgico; Dirección de recursos minerales y energéticos programa de metalogenia proyecto GE 33; 95 Memoria sobre la geología económica de la región Piura INGEMMET.

Santos, D. C. D. (2001) Determinação das propriedades de compressibilidade e permeabilidade do rejeito de bauxita da barragem de Marzagão através de ensaios de laboratório e de campo. 254f. Dissertação (Mestrado) – Universidade Federal de Viçosa – UFV, Viçosa.

Silva, W. R. (2008) Nova metodologia para determinação de propriedades de sedimentação e adensamento de rejeitos de mineração. 2008. 136f. Tese (Doutorado) – Universidade Federal de Viçosa – UFV, Viçosa.

Somogyi, F.; (1979) Analysis and prediction of phosphatic and consolidation: implementation package. Lakeland: Florida Phosphatic Clay Research Project, Technical Report.

Terzaghi, K.; Fröhlich, O. K.; (1936) Theorie der setzung von tonschichten; eine einführung in die analytische tonmechanik, Leipzig Germany: F. Deuticke, 168 p.

Thill, a.; Moustier s.; Garnier j.-m.; Estournel c.; Naudin j.-j.; Bottero j.-y.; (2001) Evolution of particle size and concentration in the rhone river mixing zone: influence of salt flocculation. Continental Shelf Research 21: pp. 2127-2140.

Yao, T. C.; Oliveira Filho, W. L.; Cai, X. C.; Znidarcic, D.; (2002) Numerical solution for consolidation and desiccation of soft soils. International Journal for Numerical and Analytical Methods in Geomechanics, v. 26, pp. 139-161.

Yao, T. C.; Znidarcic, D.; (1997) User's manual for computer program CONDES0. Boulder, Colorado: Department of Civil, Environmental and Architectural Engineering, University of Colorado, 98 p.

Znidarcic, D.; Abu-Hejleh, A. N.; Fairbanks, T.; Robertson, A.; (1992) Seepage induced consolidation test, equipment description and user’s manual. Reported Prepared for Florida Institute of Phosphate Research, Department of Civil, Environmental and Architectural Engineering, University of Colorado, Boulder, Colorado, 63 p.

Znidarcic, D.; Gjerapic, G.; Carrier, D.; Zhang, P.; (2000) Crusting of phosphatic ponds due to dessication laboratory and fiel study - Report on task 17: Laboratory and centrifuge tests on phosphatic clay samples. Boulder, Colorado: University of Colorado, 63 p.

Professional profile

Doctor Christ Jesus Barriga Paria is a Mining Engineer with a Doctoral in Geotechnics in the first School of Mines in Brazil, now Federal University of Ouro Preto. In addition, he has been a national consultant and professor at the National University of Moquegua in Peru since 2015. Named Innovative Academician by the National Society of Mining, Oil and Energy of Peru. He has more than 10 years of experience with disposal of mining waste and mine closure, in addition to the application of geophysical and geochemical tools. Scientific papers related to knowing the behavior of mining waste rock and tailings.

Nombre del autor: Christ Jesus Barriga Paria
Cargo: Director de Innovación y Transferencia tecnológica de la UNAM
Empresa: Universidad Nacional de Moquegua
Correo electrónico: cbarrigap@unam.edu.pe
Teléfono / Celular: +51 996707694
Dirección: Calle Ica 289 - Moquegua

Professional profile

He holds a degree in Civil Engineering (2002), a Master's in Civil Engineering / Geotechnics from the School of Mines (2005) and a PhD in Geotechnics from the Geotechnics Center of the School of Mines of the Federal University of Ouro Preto (2017). He is currently an adjunct professor at the Department of Urban Engineering at the School of Mines and Dean of Planning and Development at the Federal University of Ouro Preto. He is a member of the Collegiate and of the NDE (Structuring Teaching Core) of Urban Engineering and a member of the Collegiate of the Postgraduate Program in Geotechnics / Master in Geotechnical Engineering at NUGEO at the UFOP School of Mines. He held the position of Director General of the Federal Institute of Education, Science and Technology of Minas Gerais-Campus Congonhas (IFMG) for 6 years. Has experience in Geotechnics, with emphasis on Laboratory Tests in Soil Mechanics and Mining Tailings, working mainly on the following subjects: laboratory tests and studies with soils, tailings and mining waste (liquefaction, densification and compressibility).

Nombre del coautor: Eleonardo Lucas Pereira
Cargo: Director de Planificación y Desarrollo de la Universidad Federal de Ouro Preto - UFOP
Empresa: Federal University of Ouro Preto
Correo electrónico: eleonardo@ufop.edu.pe
Teléfono / Celular: +55 31 87362821
Dirección: Mariana, MG.