Mechanical characterization of the behavior of artificial grains with specific size and shape

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RESUMO: Materiais granulares são utilizados na construção de barragens, aterros e outras obras geotécnicas, que são suscetíveis à instabilidade. Solos granulares possuem granulometria e forma de grãos variados devido principalmente ao processo de formação desses solos. Estudos previamente publicados indicam que o comportamento mecânico de solos granulares naturais varia com a sua microestrutura, afetada principalmente pela granulometria, forma e rugosidade dos grãos. Assim, este artigo tem como objetivo avaliar o comportamento mecânico de materiais particulados abrasivos artificiais em formas esféricas e de tamanho entre 4 mm e 10 mm, e identificar os principais parâmetros físicos dos grãos que influenciam o comportamento mecânico desses materiais. Ensaios de caracterização física dos materiais artificiais (tamanho de grão, índice de vazios máximo e mínimo, e rugosidade intergranular) e ensaios de resistência ao cisalhamento (ensaio triaxial consolidado drenado) foram realizados e os resultados comparados e discutidos. Resultados experimentais iniciais de ensaios de compressão triaxial mostram que a forma do grão abrasivo influencia a resistência ao cisalhamento do solo devido ao melhor encaixe e rearranjo dos grãos angulares artificiais, e que o tamanho do grão interfere mais no comportamento mecânico dos grãos angulares do que dos grãos esféricos ao variar a consolidação do ensaio triaxial.

PALAVRAS-CHAVE: Materiais granulares; Ensaio triaxial; Materiais particulados artificiais; Resistência ao cisalhamento; Tamanho do grão.

ABSTRACT: Granular materials are used in the construction of dams, landfills, and several other geotechnical works, which are susceptible to failure. Granular soils have varied grain sizes and shape of due to the different formation agents in these soils. Previously published studies indicate that the mechanical behavior of natural granular soils varies with the microstructure of these soils affected mainly by their grain size, shape and roughness. Thus, this paper aims to evaluate the mechanical behavior of abrasive artificial particulate materials in spherical and pyramidal shapes of sizes between 4 mm and 10 mm, and to identify the main physical parameters of the grains that influence the mechanical behavior of these materials. Physical characterization tests of the artificial materials (grain size, maximum and minimum void ratios, and intergranular roughness) and shear tests (Triaxial test CD) are performed to compare the experimental results. Preliminary results from triaxial compression tests show that the shape of the abrasive grain influences the shear strength of the soil due to the better interlocking and rearrangement of the artificial angular grains, and that grain size interferes more with the mechanical behavior of angular grains than spherical grains when varying the consolidation of the triaxial test.

KEYWORDS: Granular materials; Triaxial test; Artificial particulate materials; Shear strength; Grain size

1 INTRODUCTION

The physical and chemical characterization of soils in geotechnics is crucial for the performance and durability of civil engineering structures. Studies such as those by Cavarretta, Rocchi, and Coop (2011), Wegner et al. (2014) and Marzulli et al. (2021) explore the influence of grain shape on soil shear strength.

Lambe and Withman (1969) emphasized the contribution of particle deformation and relative movement to the shear strength of granular soils, highlighting the relationship between these two behaviors. Soil compactness, discussed by Rowe (1962), also emerges as a crucial factor in the shear strength.

Wegner et al. (2014) investigated how grain shape influences dilation in granular materials subjected to shear, using a cylindrical container divided at the bottom. In the study, the authors found that uniform spherical particles, when arranged in aligned hexagonal chains in the direction of shear, counteract the effect of dilatancy, resulting in higher density in the shear zone. Additionally, they observed how packing and dilation properties vary in different types of grains, considering the diversity of sizes and shapes.

Malkorra et al. (2021) conducted triaxial tests on synthetic abrasive grains of spherical and pyramidal shapes, providing data to model the polishing process in metallic parts. Their results highlight the importance of grain shape and size in the mechanical response of granular soils. These previous contributions provide the basis for our investigation, further deepening our understanding of these materials.

This article describes and analyzes an experimental study of the mechanical behavior of synthetic abrasive particulate materials, considering two different grain shapes (spherical and pyramid) and varied sizes of grains (1 mm, 4 mm, 5 mm and 10 mm). The main objective of the investigation is to identify and quantify the fundamental properties of particles that influence the overall mechanical behavior of the investigated material. Through consolidated and drained triaxial compression tests on synthetic granular materials, covering grains with varied dimensions from 1 mm to 10 mm and distinct shapes, significant contributions are sought to be provided for understanding the determining factors in soil behavior changes in granular contexts.

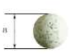
2 MATERIALS AND METHODS

To conduct the research, synthetic abrasive grains (SAG's) with different shapes and dimensions were used to simulate natural soils. The individual artificial grain that simulates the natural grain was called "Synthetic abrasive grain," and it is manufactured by the *ABC Swisstech* industry, with the function of polishing metal.

In the selection of the type of the grains, the spherical shape has a better regularity of shape, having the same width and height (height/width ratio equal to 1). The pyramidal shape, on the other hand, has a triangular shape with edges of the same size and depth (a = b). Thus, both shapes were selected for the research.

The selection of grain dimensions was guided by the need to replicate the characteristics of granular soils found in nature. Spherical and pyramidal shapes were chosen to represent different types of grains, as shown in Table 01. The diameters of the spherical grains are 1, 4, 5, and 10 mm. The pyramidal shape has a triangular base with edges of equal dimensions measuring 4 and 10 mm.

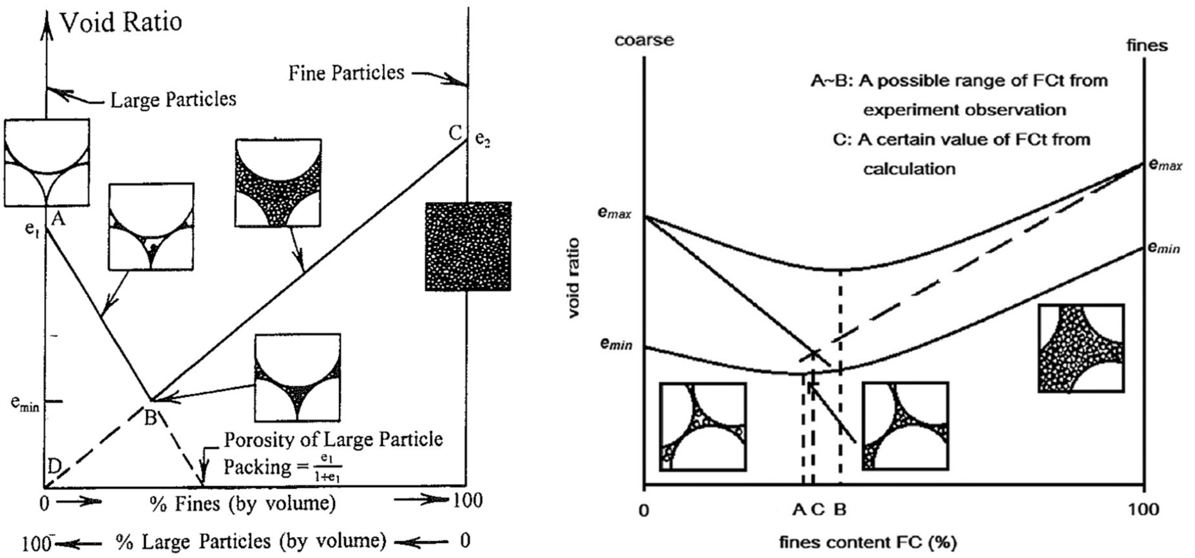
Table 1. Shape, Sizes, Surface Area, Volume, and Mass of Synthetic Abrasive Grains (SAG's)

Shape	Size (mm)		Area (mm²)	Volume (mm3)	Mass (g)
	a	b			
Spheric 	1	-	3,14	0,52	0,001
	4	-	50,24	33,49	0,090
	5	-	78,5	65,42	0,160
	10	-	314	523,33	1,690
Pyramid 	4	4	61,86	27,72	
	10	10	386,6	480,30	1,516

The reference for the tests was determined based on international standards, in the case of the e_{min} (ASTM D 4254 - Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density) and e_{max} (ASTM D 4253 - Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table) tests the American standard (AASHTO), adapted to the equipment present in the *École Nationale d'ingénieurs de Saint-Étienne* (ENISE) Soil Laboratory, with a vibratory table and a CBR mold (Figure 1).

Figure 1. Mold with the grains and weight of 20 kg on the vibratory table to perform the test of e_{min}

To define the best percentage of fines in a soil mixture, the concept of transition of fines content (TFC) was used, where a percentage of fines is added to the coarse soil and it is verified if there was a change in the volume of the sample (Figure 2). There is no standardization for the fines content transition test (TFC), so the TFC test was performed based on what was presented by Lade, Liggio & Yamamuro (1998).



(a) (b)

Figure 2. Schematic diagram of theoretical variation of minimum void ratio in binary packings with % fines. Lade, Liggio & Yamamuro, 1998 (a) and Zuo and Baudet, 2015 (b).

The tests were performed with the isolated spherical shapes and isolated pyramidal shapes, using two binary mixtures of dimensions 10 mm + 4 mm. The test was performed in the CBR test sample mold and initially the coarser soil was added up to a height of 15 cm (0%), removed and weighed. From this moment on, 5% of the mass of the coarse soil is added to the fine soil and it is verified if there was a variation in the volume of the sample. This process is repeated successively until 50% of the mass of coarse soil is added to fine soil, after which the test is performed with only fine soil (100%).

The triaxial tests performed were consolidated drained (CD) due to the need to evaluate the effective stress of the soils, not considering the porosity. Two triaxial machines were used to perform the tests, one dynamic and one monotonic. The tests in the dynamic machine were performed with controlled deformation, while the test in the monotonic machine was performed with controlled speed, in the value of 0.05 mm/s. The maximum axial deformation defined was 20%, as this is sufficient for soil rupture.

The static machine sample has a diameter of 100 mm and height of 165 mm, while the monotonic machine has a height of 200 mm. The samples were filled with soil to ensure a relative density of 50%. With the results obtained in e_{max} and e_{min}, the void ratio of the sample was defined with correlations.

During the compaction of the pyramidal artificial grains with 10 mm (Figure 3.a), there was damage to the rubber film and grain breakage. To solve this problem, 3 rubber films were used to test these grains. In the 10 mm artificial spheres (Figure 3.b), when consolidated at 200 kPa holes occurred in the rubber film, due to stretching to the inside of the soils and possible crushing by the grains during shear. Thus, 2 films were used for the test.

(a) (b)

Figure 3. Artificial grains in the shape of spheres and pyramids in the triaxial apparatus

After closing the cell and filling it with water, an initial radial pressure (σ3) of 50 kPa was applied to allow water to circulate through the sample in order to saturate the sample and remove some of the air from the sample. When the water circulation is complete, a back pressure of 30 kPa is applied and the test begins with the saturation phase. At saturation, the radial pressure is raised to 600 kPa and the back pressure to 580 kPa over 1 day (1440 minutes).

In the second phase of the triaxial test, the B-Skempton is checked, which should be close to 1. In this phase, σ_3 is raised to 650 kPa and the back pressure is around 625 kPa. Moving on to the third phase, consolidation of the sample is performed, where the backpressure is kept constant and the σ_3 is raised to create a pressure difference that simulates the natural condition of the soil under the effect of thrust.

The consolidation was set at 100 kPa, 150 kPa, and 200 kPa to obtain the stress-strain curve and the friction angle of the soil, and because it is a granular soil, on average it took 30 minutes. When the maximum axial deformation limit (20%) is reached, the test is ended, and the samples are weighed in order to analyze the results.

3 RESULTS

The maximum and minimum void ratio (e_{max} and e_{min}) test results can be seen in Table 2, as well as the void ratio (e) value calculated for the drained consolidated triaxial test. The e_{max} of the spherical soils was between 0,80 and 0,74, regardless of size (Figure 4). The 10 mm and 5 mm artificial grains had almost the same e_{max}, and although the 4 mm and 1 mm artificial grains have varied e_{max}, the difference between the e_{max} and e_{min} values have almost the same value. The e_{min} varied between 0,69 and 0,61, with similar distribution to the e_{max}.

Table 2. Values of e_{min} and e_{max} , relative density (Dr) obtained in the experimental study

Shape	Size (mm)	e_{Max}	e_{Min}	Dr (%)	e
Sphere	10	0,75	0,68	50	0,71
	5	0,76	0,69	50	0,73
	4	0,74	0,61	50	0,68
	1	0,8	0,66	50	0,73
Pyramid	10	0,85	0,67	50	0,76
	4	0,78	0,6	50	0,69

The experimental results suggest that the spherical artificial grains have a low difference between e_{min} and e_{max} compared to the other artificial grains, and the tendency is for the difference between the maximum and minimum void ratios to increase as the soil size decreases. For the spherical soils, there was a greater difficulty to perform compaction due to the rolling of the grains and the lack of interlocking, a behavior more prominent in the larger artificial grains due to the lower number of contacts between them.

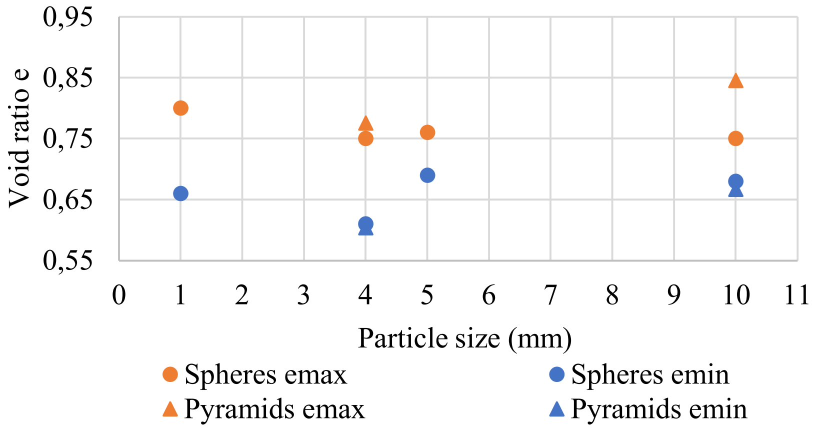


Figure 4. Variation of e_{min} and e_{max} values in relation to grain diameter and shape

The pyramidal artificial grains with 10 mm had a higher value than that of 4 mm, but the difference between e_{min} and e_{max} were practically the same. Another point to be observed, is that for the spherical soils, there was a low variation between the values of e_{min} and e_{max}, regardless of the size. For the pyramidal soils, as the artificial grain size is reduced, with also a reduction in e_{min} and e_{max}.

The results of the consolidated drained triaxial test show the spherical artificial grains with similar behavior despite variations in consolidation values (Figure 5). Notably, among the spherical artificial soils, the 1 mm variant displayed superior resistance compared to the 5 mm variant. Analysis of the stress-strain curve reveals a higher degree of uniformity in smaller artificial soil samples, characterized by the absence of abrupt reductions in Deviator stress, as observed in the 10 mm artificial soil.

In Figure 6.a, the stress-strain curves of the 4 mm pyramidal artificial soil samples are depicted. A comparison of consolidation stress values between samples compacted at 100 kPa and 200 kPa illustrates that the latter exhibited more than double the strength, despite similar deformation characteristics. This increase in strength is attributed to the greater resistance of the artificial soil to vertical deformation under confinement, leading to enhanced intergranular contact pressure and, consequently, deviator stress.

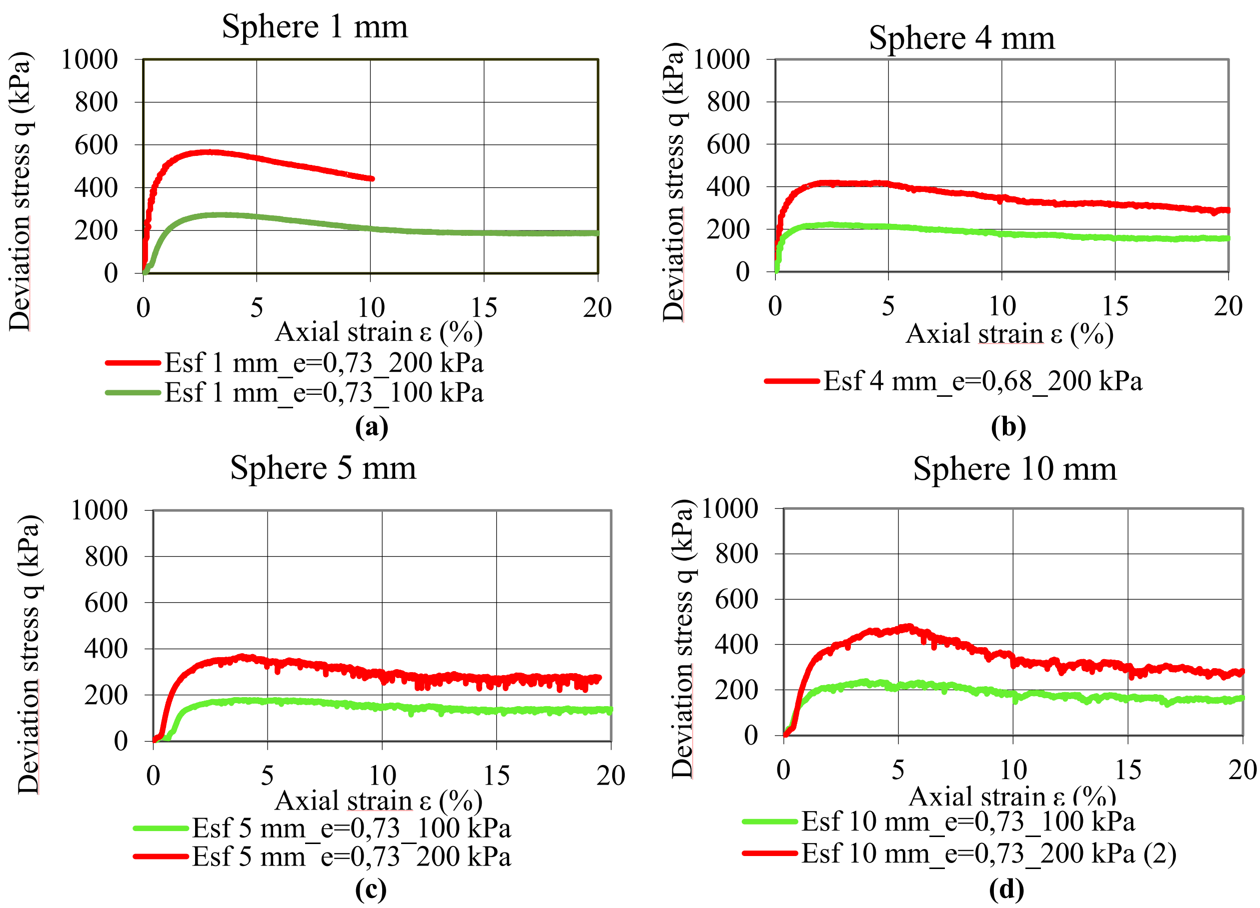


Figure 5. Stress-strain curve of 1 mm, 4 mm 5 mm and 10 mm artificial spheres with different values of σ_3.

Figure 6.b illustrates the stress-strain curves of the 10 mm pyramidal artificial soil samples. Notably, both curves lack a well-defined peak, with both samples exhibiting oscillations in deviator stress, albeit showing a tendency towards stability in axial strain during the latter stages of testing.

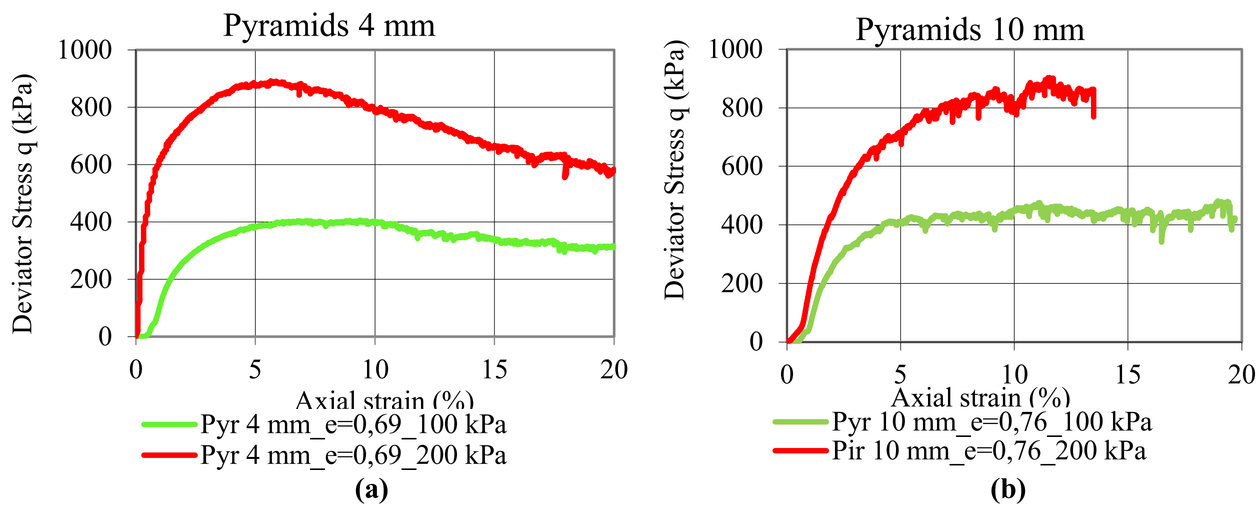
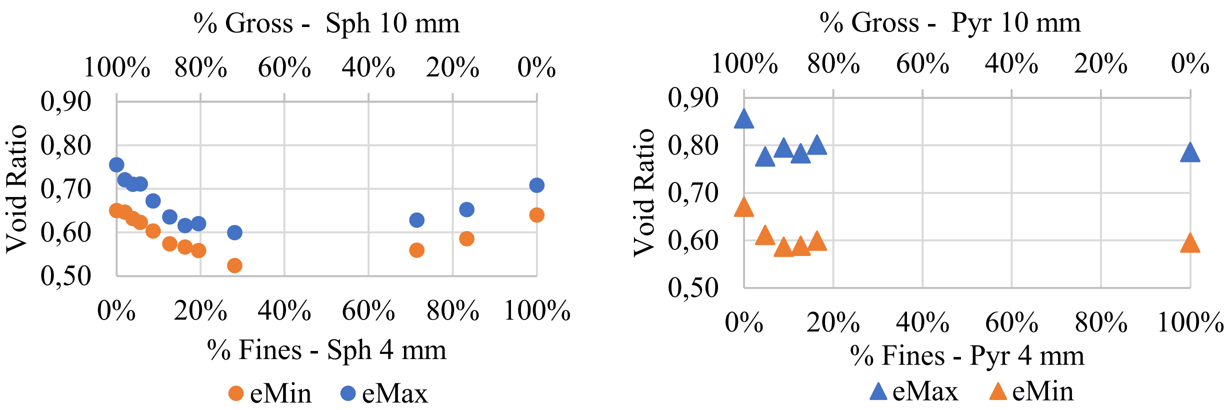


Figure 6. Stress-strain curve of 4 mm and 10 mm artificial pyramids with different values of σ_3.

The artificial soil consolidated at 200 kPa demonstrated a notable increase in q, stabilizing after 10% axial strain, whereas the sample consolidated at 100 kPa began to exhibit stability after 5% axial strain. It is notable that the 10-mm pyramids had a similar proportion in the q ratio consolidated at 200 kPa and at 100 kPa, where the first sample has a q of practically double that of the second. The difference in strength between individual spherical and pyramidal soils is remarkable, where the portion of strength due to grain interlock is demonstrated.

For the artificial spheres, the peak presented in the beginning of the stress-strain curves is due to the weak interlocking of the grains, whom after the shearing of the sample, are not able to recreate the initial bound and do not present any type of points or barriers to retard the internal movement of the grains. The artificial pyramidal grains with 10 mm, after the shearing, presented a residual stress and tends to a stabilization in the deviator stress due to the capability of regain the interlocking by the rearranging of the angular grains. For the 4 mm pyramids, the smaller size reduces the regain of the interlocking due to the small corners and surfaces, with a peak resistance.

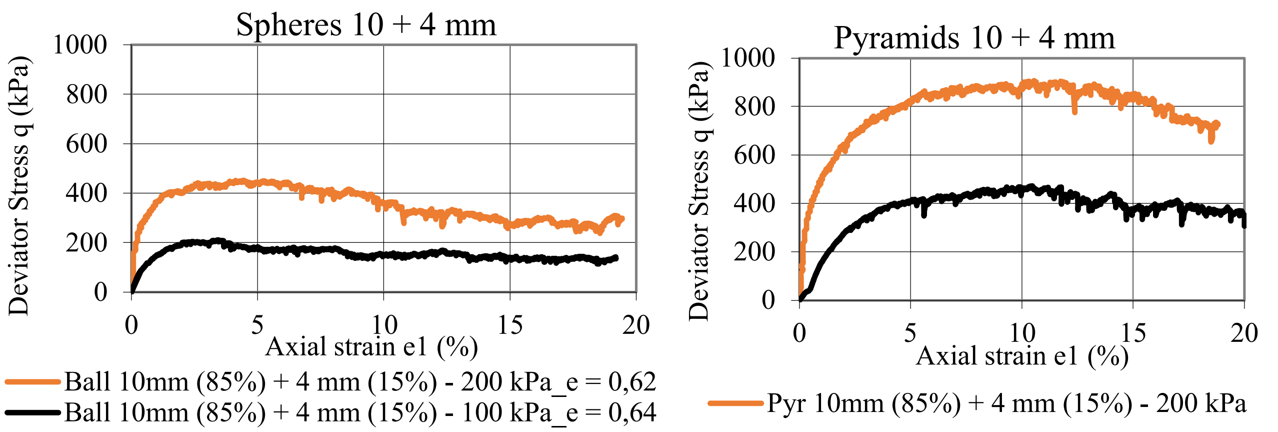
To evaluate the mixture of artificial grains with same form and different sizes, the TFC was defined for spherical and pyramidal grains of 10 mm (Gross part) and 4 mm (Fine part). The result can be seen below and the percentage of fines for the spheres was defined as 15% of the mass of 4 mm artificial spheres (Figure 7.a) and the same percentage for the mass of artificial pyramids (Figure 7.b).



(a) **(b)**

Figure 7. TFC in the mixture of artificial Spheres (a) and Pyramids (b) with 10 mm and 4 mm

The results of the consolidated drained triaxial tests for the mixtures of spheres with 10 mm and 4 mm, and pyramids with 10 mm and 4 mm can be seen in Figure 8. The values of the deviator stress presented in the stress-strain curves do not show expressive changes in the maximum values of deviator stress, for both mixtures made.



(a) **(b)**

Figure 8. Stress-strain curve of the individual mixtures of 4 mm and 10 mm pyramids and individual spheres with different values of confining pressure.

Comparing the mixtures of 10+4 mm, the spherical artificial grains presented a small value of the deviator stress for the same confining pressure, due the less surface of contact between the artificial grains, even when the voids are filled with 4 mm spheres, the contact between sphere and sphere are not as strong as the artificial pyramidal grains.

4 CONCLUSIONS

This paper describes and analyzes the results of drained triaxial tests performed on 1 mm, 4 mm, 5 mm and 10 mm spherical artificial grains and on 4 mm to 10 mm pyramids artificial grains. The article also presents and discusses the maximum and minimum void ratio (e_{max} and e_{min}) values, as well as the void ratio (e) value used for conducting the drained consolidated triaxial tests. The following conclusions are obtained:

- For the 1 mm, 4 mm, 5 mm and 10 mm spherical artificial grains, the deviator stress for the 1 mm spheres is higher due to the less voids in the sample. The 10 mm spheres presented the second higher value of the deviator stress, due to the bigger points of contacts between the spheres.

- For the pyramids, the increase of the size for 4 mm to 10 mm represented also an increase in the value of the residual stress for the 200 kPa of confining stress, due to the capability of rearranging of the angular bigger artificial grains.

- In the mixtures with spheres in proportion of 85% of 10 mm and 15 % of 4 mm, the filling of the voids in this proportions do not represent any representative change in the behavior of the samples. For de same mixture of pyramids, any representative change are presented.

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