EUROPEAN ACADEMIC RESEARCH
Vol. VIII, Issue 2/ May 2020

Impact Factor: 3.4546 (UIF)
DRJI Value: 5.9 (B+)

ISSN 2286-4822
www.euacademic.org

Elastic Modulus Determination of Açaí Seed and Sintered Calcined Clay Aggregate Using the Hertz Contact Model

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Abstract

In 2015, the United Nations (UN) presented to its member countries, among certain objectives and targets, the recommendation of using regional materials for civil construction. Such practice, according to the aforementioned international body, combined with other programs can make buildings more sustainable and, thus, provide safer and more resilient human settlements. In this context, the capital of the State of Amazonas/Brazil stands out since, due to its geotechnical characteristics, it shows a lack of natural raw materials and inputs for obtaining stone aggregates. This reality has led researchers to seek technically viable and environmentally acceptable alternative regional materials, as it is the case of the materials object of the present study, Sintered Calcined Clay Aggregate (SCCA) and Açaí seed (fruit of the Euterpe Precatoria palm). According to the experimental mechanical results, it was observed that the Açaí seed behaved like a ductile material, whose rupture process occurred slowly *and continuously, and the SCCA grain exhibited a brittle behavior, abruptly breaking when it reached the breaking stress. It was also verified, in accordance with the experimental values obtained for both materials, through the Simple Compression (SC) test, that they both obeyed the Hertzian power law (1882). The results also allowed the calculation of the Elastic Modulus of each material, with average values of 3.79GPa for SCCA and 1.81GPa for Açaí Seed, considering a Poisson's ratio equal to 0.3.*

Key words: açaí seed, sintered calcined clay aggregate and simple compression.

1. INTRODUCTION

In 2015, the United Nations (UN), of which Brazil is a member country, defined 17 objectives and 169 goals for sustainable development (SDGs), to be achieved by 2030. The text regarding SDG 11 - specific to the commitment among Heads of State – discloses that one of its purposes is to support least developed countries, including through technical and financial assistance, for the construction of sustainable and resilient buildings, emphasizing the use of regional materials.

The use of these regional materials is not always possible when the objective is to implement conventional construction techniques. An example of this scenario is the lack of stony materials (Santos et al. 2006) in the metropolitan region of Manaus/AM/BR, which is essential for manufacturing concrete, for instance. Such peculiarity arises from the geotechnical properties represented by a profile consisting of a thick layer of soil on the rocky substrate, that is, insufficiency of stone surface raw material. This reality has led researchers to study alternative materials, among which stand out the Sintered Calcined Clay Aggregate (SCCA) and the Açaí Seed, which compose the motivation of the present work.

Specifically regarding the Sintered Calcined Clay Aggregate (SCCA), the works published by the Geotechnical Research Group (GEOTEC) of the Federal University of Amazonas (UFAM) stand out: (Frota, Nunes, and Silva 2003; Frota et al. 2004; Frota, Silva, and

Nunes 2006b, 2006a; Frota et al. 2007; C. L. Silva et al. 2008; C. L. Silva, Nunes, and Frota 2008; C. L. A. Silva et al. 2009; Nunes, Silva, and Frota 2009; Sarges, Nogueira, and Frota 2010; Valença et al. 2012; A. C. L. Silva and Frota 2013; C. L. Silva, Silva, and Frota 2014; C. S. Silva, Frota, and Frota 2015; A. C. L. Silva, Frota, and Frota 2015; A. C. L. Silva and Frota 2016; Cunha et al. 2018; Spínola et al. 2019). In the aforementioned studies, the mechanical results were satisfactory, especially at high temperatures, in contrast to mixtures composed of pebble and stony aggregates.

In another aspect, according to data from the Brazilian (Institute of Geography and Statistics 2018) the Brazilian production of Açaí (*Euterpe oleracea*) reached the amount of 221,646 tons, of which only 17% was converted into pulp. The remainder is a by-product formed by the fiber core (Peres et al. 2018). The search for an environmentally correct end for such waste has led to studies in the most diverse areas. (Martins, Mattoso, and Pessoa 2009) state that the thermal behavior shown by the Açaí fiber reveal similarity to the main natural fibers used industrially (cotton, linen, sisal, coconut, etc.). (Pereira et al. 2011) point out that, in terms of tensile strength, açaí fiber demonstrates compatibility with coconut fiber. As a source of thermal energy for potteries, (Quaresma et al. 2015) and (Cordeiro et al. 2017) conclude that, in general, its use is viable. Such fibers presented good results among fruit and leguminous crops when they participate in the production of organic fertilizer, according to (Neto et al. 2009) and (Erlacher et al. 2014). In civil construction, (Nascimento and Oliveira 2018) and (Deus et al. 2019) concluded that the addition of ash from the Açaí seeds made Portland cement concrete more resistant and durable. Regarding paving, (Valença and Frota 2011; Valença et al. 2011) observed satisfactory mechanical results when incorporating Açaí fibers into asphalt mixtures. Aiming at different types of applications of different seeds, a great effort has been made in order to determine their mechanical properties represented by the elastic modulus, as in (Arnold and Roberts 1969), (Arnold and Roberts 1969), (Bargale and Irudayaraj 1995) and (Shelef and Mohsenin 1967).

It is noteworthy that, despite the aforementioned researches on the macroscopic characteristics of SCCA and Açaí Seed, or when they are present in compositions, there is still little knowledge regarding their individual mechanical performances. In this context, the study in question analyzed the mechanical behavior of these alternative materials according to experimental results and the classic model of spherical contact proposed by (Hertz 1881), aiming at the construction of pavements.

2. MATERIALS AND METHODS

2.1. Materials

The clay used in the making of SCCA originated from the surface layer that constitutes the geotechnical profile of the Municipality of Manaus. Initially, its potential for calcination was verified through the following tests standardized by the Brazilian Association of Technical Standards (ABNT): Particle Size Analysis (NBR 7181/17), Liquidity Limit (NBR 6459/17) and Plastic Limit (NBR 7180/16) (Brazilian Association of Technical Standards 2018, 2017, 2016). From these results, the natural soil was typified by the Unified Classification System (UCS). In the pre-calcination stage, a few tests were carried out, in which the heat rate was set at 3ºC/min. Then, the clay aggregates were molded into a spherical shape, being calcined at a temperature of 900ºC.

The Açaí seeds originated from residues of the pulp production extracted from the fruit of the *Euterpe Precatoria* palm, and came from the Municipality of Codajás-AM. The Seeds arrived at the Soil Laboratory/GEOTEC/UFAM in bags, and were deposited outdoors to dry. Then, the fibers covering the endocarp were removed. **Figure 01** shows the core configuration after this phase and ready for the physical characterization tests.

The aforementioned materials - Açaí seeds and the Calcine Clay Sintered Aggregate (SCCA) - were subjected to the tests commonly used in paving, namely: Particle Size Analysis (DNER-ME 083/98), Determination of Absorption and Density of Large Aggregate (DNER-ME 081/98) (National Highway Department 1998a; Nacional Highway Department 1998b).

Figure 01. Açaí Seed Configuration after Fiber Removal

2.2. Methods

The study was developed according to two aspects. In the experimental phase, the grains of an approximately spherical shape were individually compressed to obtain - within the elastic regime - the relationship between force and displacement (piston). On the theoretical side, the experimental results of the relationship between the applied force (F) and the piston displacement (ξ) were adjusted according to the Heinrich Hertz (Hertz 1881) contact model, through which Young's modulus (or Elastic Modulus) were obtained.

2.2.1. Mechanical Testing (Simple Compression)

The Açaí seeds and SCCA spheres were subjected to the Simple Compression (SC) test, through the use of the Universal Testing Machine (UTM/IPC GLOBAL), which belongs to GEOTEC/UFAM, containing a digital interface capable of registering the strength and the respective displacement generated every 50ms (fifty milliseconds). **Figure 02** presents the scheme for carrying out the experiment. As a methodological process, the requirements of NBR 12770 (Brazilian Association of Technical Standards 1992) were followed.

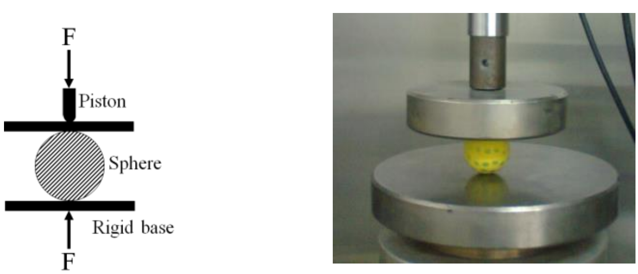

Figure 02. Scheme of the SCCA Grains and Açaí Seeds subjected to the Simple Compression Test

2.2.2. Theoretical Calculations

The relationship between force and displacement, obtained by a non-linear regression of the set of points resulting from SC tests, was adjusted to the contact model between two spherical particles proposed by Hertz **(Equation 1)**.

$$F_{ij}^{n} = \frac{2Y\sqrt{R^{eff}}}{3\left(1-\nu^{2}\right)}\xi^{3/2} \qquad (1)$$

In which, the effective radius R^{eff} is determined **(Equation 2)** by:

$$R^{eff} = \frac{R_i R_j}{R_i + R_j}, \qquad (2)$$

Y is the Young' modulus (or Elastic Modulus), R_i (R_j) is the particle radius i (j) and υ is the Poisson's ratio.

To simulate the contact force between the grains and the piston flat surface during the SC test, using the **Equation (1)** Hertzian model, the piston flat surface in contact with the grain is considered to imply an infinite radius sphere, as shown in **Figure 03**. Thus, considering R_i the radius of the grain and the R_j o the radius of the sphere that touches the piston, at the limit $R_j \to \infty$ the effective radius between the contacts is the radius of the grain itself ($R^{eff} = R_i$). For the purpose of adjusting the experimental results as a function of the Hertzian model **(Equation 1)**, the Poisson's ratio is considered to be equal to 0.3 (Shelef and Mohsenin 1967).

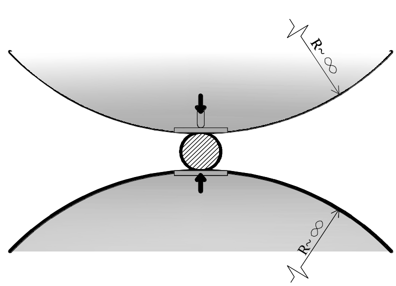

Figure 03. Contact Scheme with the Grain considered as an Infinite Radius Sphere

3. RESULTS AND DISCUSSIONS

3.1. Physical Characterization

Figure 04 presents the granulometric distribution of the raw material for composing the sintered aggregates. The distribution resulted in 60% clay, 34% silt and 6% sand, which is in accordance with the limits established by NBR 6502 (Brazilian Association of Technical Standards 1995). Thus, the resulting material is composed predominantly of fines (94%), which is - more precisely - a silty clay. The values of the liquidity limit (56%) and plastic limit (28%) characterize the material as suitable for the manufacturing SCCA, since the IP = 28% meets the prescribed IP> 20 (Nacional Highway Department 1981). Based on this information of texture and plasticity, and following the Unified Soil Classification System (SUCS), the natural soil was classified as a High Compressibility Clay (CH).

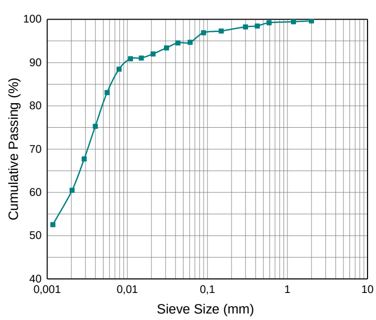

Figure 04. Granulometric Distribution of the Raw Material for manufacturing SCCA

Based on these results, in which the compliance with the specifications was perceived, the Sintered Aggregate of Calcined Clay (SCCA) was manufactured, whose granulometric curve **(Figure 05)** presents a diameter range between 9.5 mm and 20 mm, with nearly 84% of the material passing through the 12.5 mm opening sieve. The texture of the Açaí Seed was limited to the range of 4.75mm to 9.5mm, with approximately 100% of the grains passing through the 9.5mm diameter sieve. **Table 01** presents the results of the physical parameters for the two materials, highlighting the high absorption values. It must be emphasized that the high absorption of SCCA had already been observed in previous works by GEOTEC (Frota et al. 2007; C. L. Silva, Nunes, and Frota 2008; Nunes, Silva, and Frota 2009; Valença et al. 2012).

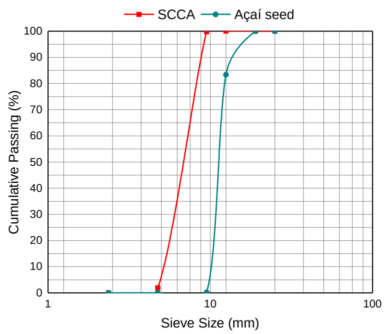

Figure 05. Granulometric Distribution of Aggregates - SCCA and Açaí Seed

Table 1. Bulk specify gravity and aggregate absorption

Properties	**Unity**	**Aggregate**	
		SCCA	**Açai seed**
Bulk specify gravity	g/cm³	2,658	1,093
Absorption	%	17,70	19,40

3.2 Mechanical Characterization

3.2.1. Mechanical Behavior

Throughout the simple compression tests (SC) of the Açaí Seed, it was noticed that the grain behaves like a ductile material, in which the rupture process occurs slowly and continuously, as the applied load increases. This performance is different from that of the SCCA grain, which being a ceramic material, demonstrates a brittle behavior, that is, it abruptly breaks when reaching the breaking stress. In **Figure 06** these observations are exposed, showing the visual aspect of the two materials after the simple compression process. In **Figure 06 B**, especially, it can be seen that the Açaí Seed tends to break along the axis parallel to the characteristic groove of its endocarp. Hence, such experiment was carried out with the external force applied along the axis perpendicular to the natural direction of those grooves.

Figure 06. Visual Aspect of the Açaí Seed (A And B) and SCCA Grains (C And D) after performing the Simple Compression (SC) Tests

3.2.2. Determination of the Elastic Modulus by adjusting the Experimental Results to the H. Hertz's Power Law.

The SC tests were carried out on six grains of SCCA and Açai Seeds. The SCCA samples were manually manufactured into an approximately spherical shape, with diameters ranging from 13.4 to 18.1 mm, within the granulometric distribution shown in **Figure 5**. The chosen Açai Seed samples had their diameters ranging between 7.7 and 13.6 mm, also complying with the granulometry shown in that figure.

In **Figure 07**, the SC test typical experimental results individually performed on SCCA grains and Açai Seeds are displayed in black, and the curves resulting from the adjustments of these results to the Hertzian contact force model, given by **Equation (1)**, are presented in red. The ξ deformation present on the abscissa axis corresponds to the deformation at the top of the grain, which consists of half of the total deformation recorded, since in the SC test the grains are compressed simultaneously by the upper and lower metal bases, each contributing to ξ. All adjustments performed presented a correlation coefficient of $R^2 = 0.998$, showing that the experimental force curves as a function of deformation follow the power-law of the Hertzian model given by **Equation (1)**. It is observed that for very small deformations, the theoretical curves slightly deviate from the experimental curves. This effect is a consequence of the non-perfect sphericity of both SCCA and Açaí Seeds grains.

Table 2 contains the geometric parameters and Young's modulus of the SCCA and Açai Seed grains for six samples containing representative diameters of each material, which were obtained from the adjustment of the experimental results to the Hertzian model in **Equation 1**. For SCCA grain samples, Young's modulus range from

1.51 to 6.68GPa, with an average value of 3.79GPa; for Açai Seed samples, Young's modulus vary from 0.93 to 2.81GPa, with an average value of 1.85.GPA.

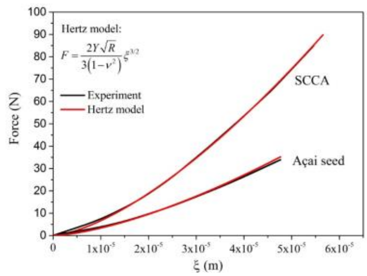

Figure 07. Simple Compression Tests (SC) on SCCA Grains and Açai Seeds

Table 2. Parameters of the SCCA and Açai Seed Samples

SCCA				Açai Seed			
Sample	R^{eff} (mm)	Y (GPa)	Y_{av} (GPa)	Sample	R^{eff} (mm)	Y (GPa)	Y_{av} (GPa)
1	8.95	1.51	3.79	1	6.80	1.11	1.85
2	9.05	3.18		2	4.15	2.58	
3	8.70	2.90		3	4.50	2.81	
4	6.70	4.58		4	3.95	2.36	
5	7.55	6.68		5	4.35	2.31	
6	6.80	3.88		6	3.85	0.93	

CONCLUSIONS

Based on the results obtained, the following can be concluded: the soil used in the present research presented satisfactory technological characteristics for the production of SCCA; both materials made the uniform granulometric distribution explicit; all grains representative of Açaí Seed and SCCA, when subjected to compression simulating the contact between spherical particles of infinite radius, presented a relationship between force and displacement that is in good accordance with the power-law model proposed by (Hertz 1881).

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