DEM COMPUTATIONAL SIMULATION OF THE POLISHING OF THE TAGUA (PHYTELEPHAS AEQUATORIALIS) PALM NUTS
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SIMULACIÓN COMPUTACIONAL EN MED DEL PULIDO DE LAS NUECES DE PALMA DE TAGUA (PHYTELEPHAS AEQUATORIALIS)

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DOI: https://doi.org/10.35633/inmateh-70-29

Keywords: *tagua, coefficient of friction, angle of repose, particle collision, discrete element method*

ABSTRACT

For tagua, the quality of the polishing process is analyzed according to the surface finish of the material, which is obtained manually or through empirically developed machinery that does not include the study of the behavior of the material during the process, which generates an inefficient work. The objective of the work is to determine the macro structural properties of tagua nuts to simulate polishing using the discrete element method. Virtual models were developed and the corresponding physical and mechanical properties were assigned. Among the main results, a tagua nut model was achieved, with m=30.22 g and ρ=1327.3±11.23 kg/m^3, friction coefficient for wood of μ_e = 0.411±0.0006 and angle of repose of β=24.644°±0.201°. These properties are the variables used as input data for the DEM model. Finally, the suitability of the Hertz-Mindlin model to simulate the process of mechanized polishing of tagua nuts is demonstrated.

RESUMEN

Para la tagua, la calidad del proceso de pulido se analiza en función del acabado superficial del material, el cual se obtiene manualmente o a través de maquinaria desarrollada empíricamente que no incluye el estudio del comportamiento del material durante el proceso, lo que genera un trabajo ineficiente. El objetivo del trabajo es determinar las propiedades macro estructurales de las nueces de tagua para simular el pulido mediante el método de elementos discretos. Se elaboraron los modelos virtuales y se asignaron las propiedades físicas y mecánicas correspondientes. Entre los principales resultados, se logró un modelo de nuez de tagua, con m=30.22 g y ρ=1327.3±11.23 kg/m^3, coeficiente de fricción para la madera de μ_e = 0.411±0.0006 y ángulo de reposo de β=24.644°±0.201°. Estas propiedades son las variables utilizadas como datos de entrada para el modelo MED. Finalmente, se demuestra la idoneidad del modelo Hertz-Mindlin para simular el proceso de pulido mecanizado de nueces de tagua.

INTRODUCTION

Tagua is a product obtained from Phytelephas aequatorialis palms, which grow in the humid forests of Ecuador, Colombia, Peru, Panama, among others. The nuts are composed of a white endosperm, as they are exposed to the sun, this hardens and through polishing a product visually similar to ivory is obtained, so it is also called with the name of vegetable ivory *(Pánchez et al., 2017*).

This material is transformed by artisans (micro-entrepreneurs who make handicrafts) into buttons, figures, key chains, ornaments, among others (*Torres et al., 2019; Vélez, et al., 2018)*. To obtain the tagua nuts, the cluster of nuts is subjected to natural drying by solar radiation, during an interval of 35 to 40 days, this time allows to obtain a hardening or maturation of the nuts, generating the vegetable ivory. With smaller time intervals, tagua nuts are obtained crystalline or hollow inside, which generates considerable economic losses to the artisans. *(Vélez et al., 2018*). The previous processes for the polishing of tagua nut, can be enunciated in, drying, classification, cutting or turning and binding.

Polishing is a very laborious task, especially when it is done manually, which is why the more resourceful producers have empirically developed machines to carry out this task. The design and construction of these machines have not taken into account the characteristics or properties of the material to be processed, which causes the accumulation of material on the walls of the polishing machines, prolonged work time, energy costs and consequently a decrease in the quality of the polished tagua nuts.

With the development of computational means, the application of numerical methods has allowed the solution of problems related to the agricultural sector *(Espinosa, 2017; Marín Cabrera and García de la Figal Costales, 2019; Velloso et al., 2018*).

Within these methods, the discrete element method (DEM) is (*Maamer et al., 2019*) seen as one of the most promising ones, since it has made possible the study of granular materials subjected to different processes in the agricultural sector, such as cutting, mixing, packaging, and transportation, among others *(Ghodki and Goswami, 2017; Romuli et al., 2017; Scheffler et al., 2018*). The increase in computational capabilities over the last decade has increasingly broadened the scope of this method, as fluid-coupled or thermodynamic (CFD) models have begun to be introduced, as well as solid and particle DEM and FEM problems *(Ambaw et al., 2017; Du et al., 2019; Gao et al., 2018*).

During the strength analysis of a given material using the discrete element method, the properties and parameters that define its strength at the microstructure level, which are closely related to the material's macrostructure properties, are taken as input variables (*Roselló et al., 2016*). The properties to be used will depend on the model describing the characteristics of the material to be simulated and the contact *(Araújo et al., 2015; Jiménez et al., 2018*).

The formulation of a discrete element model requires the prior definition of the models of the materials to be simulated, as well as the particle-particle or particle-geometry contact models *(Cundall and Strack, 1979*). The Hertz-Mindlin (no-slip) contact model assumes that during collisions between particles or particle-geometry a no-slip friction arises in the tangential direction which is governed by the Coulomb creep criterion $F_y \leq \mu_p F_n$. This property at the micro level is related to the angle of repose, properties that define the frictional behavior of the material at the macrostructure level.

In this model, the contact between particles at the microstructure level will be governed by the stiffness of the particles in tangential stiffness (k_s) and normal stiffness (k_n), variables that are related to the elasticity of the material at the macrostructure level, which is quantified through Young's modulus (E) and Poisson's coefficient (υ). The shear modulus (G) allows relating both variables.

Finally, the Hertz-Mindlin contact model understands that during the tangential contact between both particles at the micro level there is a damping (ξ_n) that characterizes the degree of conservation of kinetic energy in a collision between particles. The damping constant is related to the critical damping coefficient (β) and the coefficient of restitution (e), parameters that can be determined directly at the macrostructure level.

Namely, the properties and parameters included in the Hertz-Mindlin contact model have not been investigated so far, so the present work aims to determine the macro structural properties of tagua nuts, required for the simulation of the polishing process using the discrete element method *(Maamer et al., 2019*).

MATERIALS AND METHODS

The experimental investigations were carried out in the Physics laboratory of the Institute of Basic Sciences (ICB) of the Technical University of Manabí. For the determination of the macrostructural properties of tagua nuts, initially the sample size was determined, for which 30 experiments were conducted with three replicates each. The selection of tagua nuts is done randomly from a cluster of tagua nuts (Figure 1).

Fig. 1 - Set of tagua nuts after the sanding process

With the data from the analysis of descriptive statistics of the properties, the confidence interval is calculated for 95% for the density of the material, according to equation 1, we have:

$$\vartheta = \bar{X} \mp Z_{\alpha/2} \frac{\sigma}{\sqrt{n}} \quad (1)$$

where:

$\bar{X}$ - is the average;

$Z_{\alpha/2}$ - confidence level;

n - the sample;

σ - standard deviation;

$\vartheta =$ range of values.

Methodology to determine the macrostructural properties of tagua nuts (Phytelephas aequatorialis):

Length (l) *and equatorial diameter* (d)

Measurements were made with a WEZU brand caliper of 250 mm±0.05 mm of error, the length comprised the distance between the farthest ends of the nut (Figure 2a), as for the equatorial diameter is considered the width of the nut, (Figure 2b).

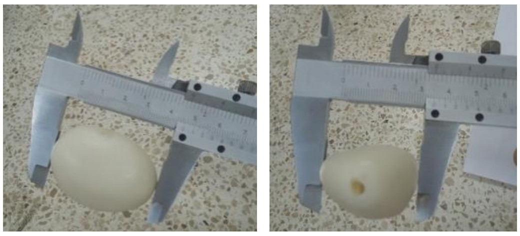

Fig. 2 - Length (a) and equatorial diameter (b)

Mass (m) *and volume* (v)

A precision balance AE ADAM CQT601 of 600g±0.1g of error is used, which has a digital indicator to show the weight (Figure 3a). For the volume, a measuring cylinder with a measurement in cm^3 is used; the value of this variable is obtained by means of the difference in volume that occurs when the tagua nut is submerged in a known volume of water (Figure 3b). With the collection of mass and volume data, the real average density of the sample can be known.

Fig. 3 - Nut mass (a) and volume (b)

The actual density of a material is denoted by the following equation:

$$\rho = \frac{m}{v} \tag{2}$$

where:

ρ - density, [kg/m^3];

m - mass of the particle, [kg];

v - volume of particle, [m^3].

Mechanical properties:

Static friction coefficient (μ_e)

It was determined using the inclined plane method, the instrument used has a scale to measure the angle of inclination, and three sliding surfaces were used: wood, stainless steel and aluminum (Figure 4).

Fig. 4 - Inclined plane for the determination of static friction angles

A particle is placed on the sliding surface of the plane and the angle of inclination is varied progressively, until displacement is caused, by increasing the weight component $(m \cdot g \cdot sen\,\theta)$. Since a system of equations is generated when a particle or body slides along an inclined plane and the same starts from rest, the static coefficient of friction can be determined by:

$$\mu_e = tan(\theta) \tag{3}$$

where:

$\mu_e =$ is the static coefficient of friction, [dimensionless];

$\theta =$ angle of inclination, [°].

Angle of repose (β)

A rectangular surface base is used and a container filled with tagua material resting on the base, the container is removed in an ascending manner so that the nuts form a conglomerate in the center, with a tape measure the height of the material as a whole is indicated (Figure 5). The measurement of this variable is made by means of the trigonometric tangent function, taking the data of the right triangle that is formed (height and base). A total of 435 elements (nuts) are used for the measurement.

Fig. 5 - Measurement of the angle of repose of tagua nuts

Restitution coefficient

When a body is dropped from a known height, it collides with a surface (wood), being possible to determine the value of the coefficient of restitution by knowing the height it reaches after the first rebound (Pavioni and Ortega, 2015; Peña, 2015; Pérez et al., 2017). Considering that, in an inelastic shock, the initial height will be greater than the height after rebound. The coefficient of restitution is established as the quotient between the heights, then:

$$C_r = \left(\frac{h_1}{h_o}\right)^{\frac{1}{2}} \tag{4}$$

where:

h_1 - is the maximum height after rebound, [m];

h_o - is the initial height, [m];

C_r - coefficient of restitution, [dimensionless].

By means of a sequence of photographs, the height (h_1) reached by the particle after hitting the surface, which is dropped from a known height (h_o), is recorded. This procedure is carried out with different tagua nut particles in order to obtain a more accurate measurement.

Methodology for MED simulation of tagua nut polishing.

Computational tool.

The computer has an Intel® Core (TM) i7-8550 CPU @ 1.80GHz 1.99GHz, 32 GB RAM, 64-bit operating system, x64 processor and a video graphics card with dedicated memory of 4096 MB GDDR5. EDEM® Academic software was used, which has a virtual simulation environment based on the discrete element method, allowing the design or import of complex geometries, assigning properties to materials and linear or rotational dynamics to each of the geometries (*Yuan et al., 2016*).

Particle generation

The tagua nuts have an irregular ovoid shape. The creation of the virtual model is performed using the multi-sphere method with the Creator component of the EDEM® Academic software, these spheres are arranged in a row one behind the other, allowing interference or overlapping up to one third of their volume (Figure 6).

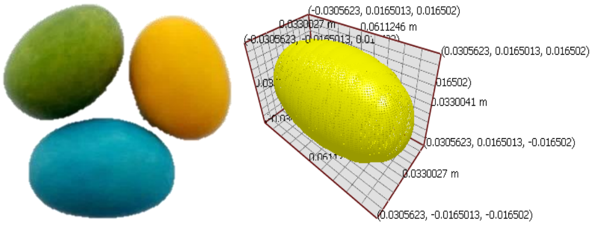

Fig. 6 - Virtual model of the tagua nut particle

The polishing material, consisting of small elements of balsa wood (Ochroma Pyramidale), its main function is to eliminate the roughness of the surfaces of the tagua, they are also used as a means of transport for polishing creams. For the creation of the virtual models of this material, the online multi-sphere creation option is used (Figure 7).

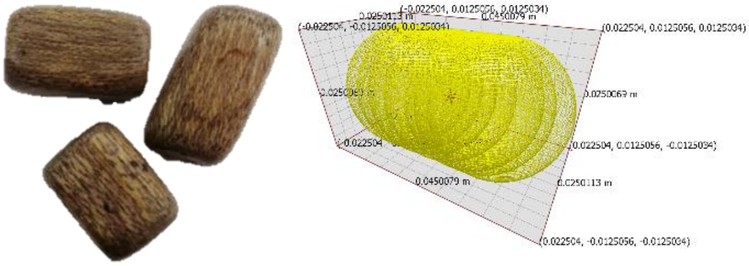

Fig. 7 - Virtual model of the raft

A two-dimensional geometric figure resides inside the rotating vessel and has the function of generating the tagua and balsa particles according to the designed virtual models, the parameters such as, aggregate velocity, generation range and so on for both materials are detailed below (Table 1).

Table 1

Particle generation data.

Name	Tagua factory	Raft factory
Type	Dynamic	Dynamics
Dimensions	0.2 m x 0.6 m	0.2 m x 0.6 m
Total or mass of particles	400	25 kg
Generation range	125 particles·second^{-1}	6.25 kilogram·second^{-1}
Position	Random	Random
Velocity	Direction -y, -1m·s^{-1}	Direction -y, -1m·s^{-1}

Geometry generation

As a reference, the handmade machines for the polishing process are used (Figure 8). The geometry consists of a rotary drum built from oak wood. The length, thickness and type of material were used to elaborate the virtual model and imported in ".x_t" format for the EDEM® Academic software. The developed model considers an octagonal vessel, this characteristic in its geometry allows maximizing the interaction between the tagua nut particles optimizing the process. The design material for the vessel is oak wood (Quercus rubra) with a density of 710 kg·m^{-3} at 12% humidity.

Fig. 8 - Handmade tagua polishing machine with its virtual drum model

Border conditions

A total of 400 tagua units and 25 kg of polishing material are generated (Figure 9). Free movement is allowed for the particles within the geometry. In addition, a rotational kinematics is added to the geometry that simulates the mechanical energy delivered by an electric motor, which starts once the particle generation is finished. The generated particles can rotate and displace due to the impulsion of the polishing drum faces or by free fall due to the action of the force of gravity. The geometry rotates at a rate of 60 revolutions per minute.

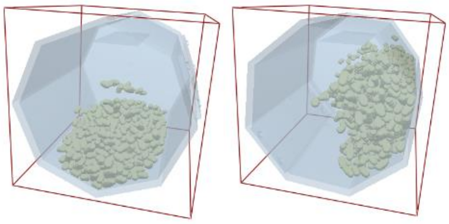

Fig. 9 - Initial particle generation and rotational motion

RESULTS

Physical properties

The results of the experimental determination of the properties are shown as the main variables that characterize the physical structure of the tagua nuts. Table 2 shows the most relevant descriptive statistics.

Table 2

Descriptive statistics of the physical structure of the Tagua nut.

Variable	Unit	Mean	E.E. of mean	Std. Dev.	Variance	Coeff. Var.	Minimum	Maximum
l	mm	39.767	0.446	2.445	5.978	6.15	36.000	46.000
d	mm	31.867	0.400	2.193	4.809	6.88	29.000	39.000
m	g	25.690	0.369	2.020	4.080	7.86	21.600	30.900
v	cm^3	19.353	0.265	1.451	2.106	7.49	16.500	22.500
ρ	kg/m^3	1327.164	5.730	31.390	985.777	2.36	1289.220	1396.980

Equatorial length and diameter

For the tagua nuts, the average length is $l = 39.77 \pm 0.45$ mm, with a deviation of 2.45 mm, this statistic assures that the data collected for the length variable does not show great dispersion. With respect to the equatorial diameter, the mean of the variable corresponds to $d = 31.87 \pm 0.37$ mm. The range for both variables is 1 cm.

Mass y volume

The sample has a mean of m=25.69±0.37g, and the deviation is 2.02 g due to the variations in length and width, and a range of 9.30 g is also obtained. The volume variable presents a deviation with a value of 1.45 cm^3 with respect to the average of v =19.35±0.27 cm^3 and the range is 6 cm^3.

Actual density

A mean for the density of ρ =1327.3±5.73 kg/m^3 is obtained, the value for the deviation is justified due to the chemical composition (percentage of water retained) and physical characteristics (dimensions) of the tagua nut. When estimating the mean of the variable with a reliability percentage of 95%, a confidence interval of ρ =1327.3±11.23 kg/m^3 is obtained. The density value is assigned to the tagua particle material and as a result the mass of the tagua particle is obtained as a function of the volume of the model (Figure 10).

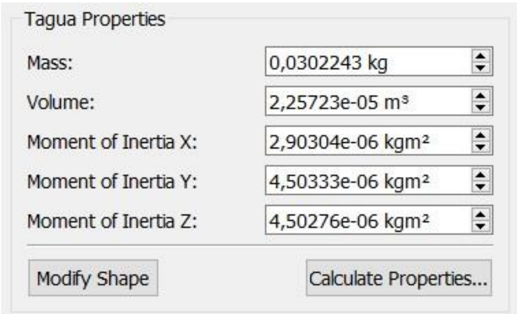

Fig. 10 - Mass and volume of the processed particle

As we can see, the mass and volume of the tagua nut particle are within the range of values of the descriptive statistics calculated for both variables.

Mechanical properties

These values show the behavior of the particles as they interact with each other or with the geometry used as a rotating vessel (Table 4).

Table 4

Descriptive statistics of the mechanical properties of tagua nuts.

Variable	Mean	E.E. of mean	Std. Dev.	Variance	Coeff. Var.	Minimum	Maximum
μ_e, steel	0.314	0.005	0.027	0.00073	8.59	0.26790	0.36400
μ_e, wood	0.411	0.006	0.035	0.00122	8.51	0.36400	0.48770
μ_e, stainless steel	0.401	0.006	0.031	0.00097	7.77	0.32490	0.46630
β	24.644	0.201	1.100	1.21000	4.46	21.73000	26.74000
C_r	0.064	0.001	0.007	0.00005	11.33	0.04800	0.07300

Coefficient of friction

In wood, the highest friction coefficient is determined, with an average of μ_e = 0.411±0.006. When evaluating the stainless-steel surface, averages of μ_e =0.401±0.006 are obtained and for steel, it is observed that sliding can be obtained with a lower amount of force, the friction coefficient on this surface is μ_e=0.314±0.005. The deviations of the data in this variable take small values. The range for stainless steel is 0.1414, wood 0.1237 and for steel 0.0961.

Angle of repose

Angle of repose. The average maximum angle of the conglomerate of the particles studied in a horizontal plane is β =24.644°±0.201° the deviation of the data is 1.1°, while the range is 5.01°. This property is considered of relevance for the design of machinery involving mass flow of material, such as conveying and storage.

Restitution coefficient

The shock that occurs between the tagua nut and a non-deformable surface, is an inelastic shock, since its value is between $0 \leq C_r < 1$, the average of this variable takes values of C_r = 0.064±0.001, this value denoted in an approximation is C_r =0.1 which is close to be considered as a perfectly inelastic shock, the deviation of the data of the coefficient of restitution does not exceed 0.007 and its range is only 0.025.

Discrete element method simulation

Kinetic energy

The kinetic energy of the tagua particles depends largely on the work done by the drum, when analyzing the graph (Figure 11), in the instant t =4s it is observed that the maximum angle of rest of the conglomerate is overcome producing significant material avalanches which registers high magnitudes of kinetic energy, progressively from the instant t =10.5s the particles share a collective rotation and the times between avalanches are reduced until establishing a continuous surface flow, the equilibrium of this state comprises energy values within the range of (6.8 to 8.5)J.

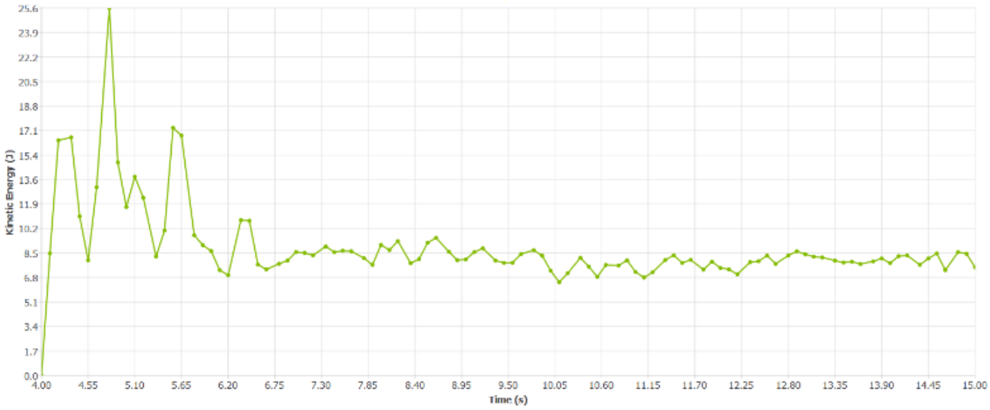

Fig. 11 - Kinetic energy of the tagua particle

Potential energy

Initially, the potential energy grows instantaneously as a result of the impulse given by the drum during the start-up stage where, in order to overcome the inertial forces (Figure 12), part of this energy is transformed into kinematic energy due to the working conditions of the vessel. In addition, during the rotation of the drum, the particles at the upper ends have higher potential energy than those at the lower ends.

The energy values when the flow is in equilibrium are in the range of (-26.2 to -29.7) J. The negative value indicates that the particles interact with the geometry surface, changing position with respect to the control level, in a correct mixing.

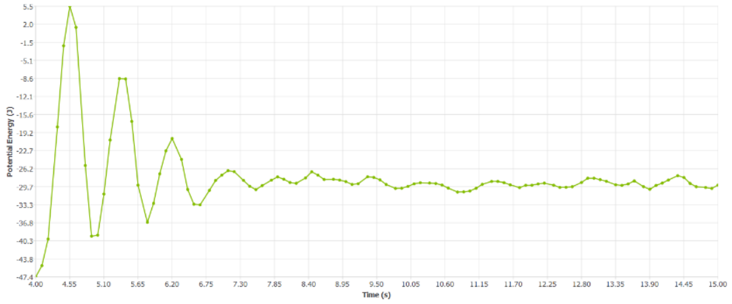

Fig. 12 - Potential energy of the tagua particle

Particle velocity

The variation of the drum speed modifies the flow of the particles inside the vessel, from this it is possible to obtain flow regimes such as sliding, cascade, waterfall and centrifugation *(Lima, 2017; Uribe et al., 2015; Yang et al., 2003*).

A high working speed generates that the particles remain adhered to the internal surface of the drum by the action of the inertia force, making the polishing process impossible, since there are not enough interactions, being determined as a centrifugation regime. For low velocities there is a greater number of collisions between particles and geometry, resulting in a smooth surface of the tagua nut and a particular brightness.

With the simulation of the discrete element method, frequent velocity levels are observed for the particles, it is possible to denote that the particles that are farther away from the center of the conglomerate move with higher velocities than the particles that are in the center, this is because several particles are in direct contact with the wall of the container that gives them a certain amount of movement, they in turn transmit movement to the others that are near the center of the rotation (Figure 13).

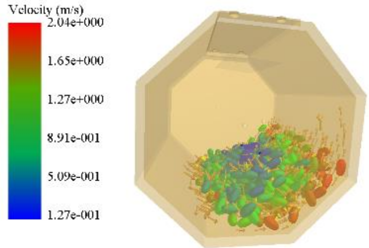

Fig. 13 - Particle velocity within the geometry

The red particles, moving at a velocity of 2.04 m/s, reside mainly on the outside of the conglomerate in direct contact with the vessel. The green particles move at a rate of 1.27 m/s, they are mainly dispersed in the center of the conglomerate, and finally we have the blue particles with velocities of 0.509 m/s, which reside in the center. The particle velocities vary over time, but remain within the values shown. The average velocity of the tagua particle when the flow is kept constant is in the range of (0.749 to 0.842) m/s (Figure 14).

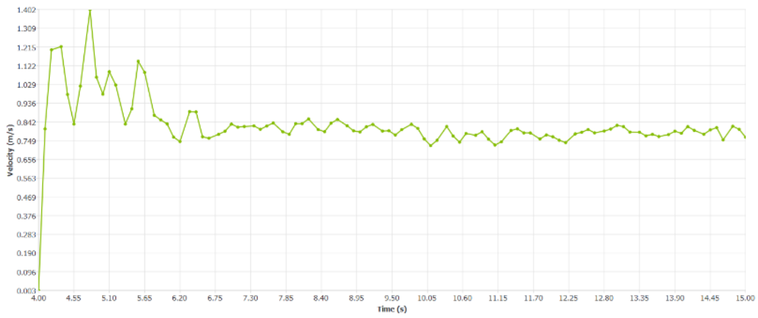

Fig. 14 - Average tagua particle velocity

CONCLUSIONS

The physical properties determined serve as a reference to generate a virtual model of the tagua particle, considering important aspects such as size and average shape to obtain the real density of the material, these variables in conjunction with the mechanical properties allow assigning to the material behavioral characteristics within the polishing process and effects on the geometry or the particles involved, besides becoming relevant parameters to determine the limits of the rotational speed of the vessel.

The simplified Hertz-Mindlin model properly describes the behavior of tagua nuts, being of great utility for the study of the efficiency of the polishing process. The developed model can be used to study the behavior of particles of different geometries of the same material that are currently marketed nationally and exported as tagua handicrafts and adjust the operating parameters of the rotary machines according to this behavior.

The virtual model of the tagua particle shows similarity with the real particle when comparing the values of mass and volume, whose values barely differ by 14.99% and 14.26% respectively for a 95% of reliability and the error for the stated values is not higher than 0.37. This allows to guarantee that the simulated behavior of the interactions between the particles and the container will have a great coincidence with the real behavior.

The properties determined allow simulating the interaction process between the tagua particles, tagua-balsa and both elements with the polishing drum, managing to compute the contacts, energy consumption and particle trajectories, showing results consistent with those described during the processing of this and other agricultural materials.

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