

PHYSICAL-MECHANICAL PROPERTIES OF BRIQUETTES PRODUCED FROM CHARCOAL FINES AND WASTE OF *Pinus* spp.

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Abstract

The objective of this research was to evaluate the physical and mechanical properties of briquettes produced with charcoal fines and waste of *Pinus* spp (sawdust and wood shavings). For the production, the charcoal fines of two particle sizes (less than and greater than 5 mm) were mixed with each type of wood waste of *Pinus* spp in the proportions of 5, 10, 15, and 20%. Then, the mixtures were compacted under the pressure of 55 kgf.cm⁻² in a piston briquetter. As binder, 8% gelatinized maize starch was used. Tests were carried out on the briquettes in order to determine the apparent density, compressive strength, and friability index. Briquettes with the highest densities and compressive strengths were produced with the two lowest proportions of wood waste of *Pinus* spp (5 and 10%). The use of the charcoal fines combined with sawdust or wood shavings of *Pinus* spp is recommended for the production of briquettes with good physical and mechanical properties.

Keywords: Biomass and bioenergy, compression and friability, use of forest residues.

Resumo

Propriedades físico-mecânicas de briquetes produzidos de moinha de carvão e resíduos de Pinus spp. O objetivo desta pesquisa foi avaliar as propriedades físicas e mecânicas de briquetes produzidos com moinha de carvão vegetal, consorciada com resíduos da madeira de *Pinus* spp (serragem e maravalha). Para produção, a moinha de carvão vegetal, com duas granulometrias (menor e maior que 5 mm), foi misturada a cada tipo de resíduo da madeira de *Pinus* spp nas proporções de 5, 10, 15 e 20%. Em seguida, as misturas foram compactadas sob pressão de 55 kgf.cm⁻² em uma briquetadeira de pistão. Como aglutinante, utilizou-se o amido de milho gelatinizado a 8%. Os briquetes foram submetidos a ensaios para a determinação da massa específica aparente, resistência à compressão e índice de friabilidade. As maiores massas específicas e resistências à compressão foram observadas nos briquetes produzidos com as duas menores proporções de resíduos da madeira de *Pinus* spp (5 e 10%). Diante do exposto, recomenda-se a utilização da moinha de carvão vegetal, consorciada com serragem ou maravalha de *Pinus* spp, para a produção de briquetes com melhores propriedades físicas e mecânicas.

Palavras-chave: Biomassa e bioenergia, compressão e friabilidade, aproveitamento de resíduos florestais.

INTRODUCTION

Brazil is at the same time the largest producer and the largest consumer of charcoal in the world. Estimates indicate that during the year 2016, approximately 6.0 million tons of this input were produced, almost all the product sent to the steel sector (BRAZIL, 2017). Although it is an excellent fuel of wide application, some characteristics and properties of charcoal are unfavorable for some uses, such as its low density and high friability. In the production process and handling of the charcoal, from the carbonization furnaces to its final use, a large quantity of fines is generated.

In the production, transport, handling, and sieving phases, coal generates a quantity of fines that can reach 25% of the total produced (SANTIAGO; ANDRADE, 2005). In steelmaking, for example, the processes for meeting the grain size specifications of modern blast furnaces may also generate additional fines. Generally, only part of the fines is used for steel purposes by injection into the windows as an auxiliary fuel. The surplus is destined for other industries, such as cement, pharmaceutical, food, and the production of flowers, among other uses.

By compacting mechanisms, briquetting (agglomeration of particles of lesser size by means of pressure, with or without the use of an organic or inorganic binder) can produce a high-quality fuel with density, shape, dimension, moisture, chemical composition, and standardized mechanical properties (PEREIRA *et al.*, 2009; KALIYAN; MOREY, 2010; QUIRINO *et al.*, 2012; DIAS JÚNIOR *et al.*, 2014). As an alternative, briquetting can be extended to applications that aim to reuse other industrial wastes, such as peat, various biomasses, plastics, and metal filings (PROTÁSIO *et al.*, 2012; DIAS JÚNIOR *et al.*, 2016; MARTINS *et al.*, 2016).

In evaluation of the briquettes properties, the most common tests aiming at the suitability for final use are carried out to determine the apparent specific mass, impact strength, compressive strength (burst load), abrasion resistance and drum resistance to the penetration of water (hygroscopicity), and calorific value (QUIRINO *et al.*, 2012). The tests of combustibility and rate of burning are more common in the case of domestic use, for cooking food (QUIRINO; BRITO, 1991, DIAS JÚNIOR *et al.*, 2014, DIAS JÚNIOR *et al.*, 2016).

There is also very great potential for application of briquetting in forest-based industries. Generally, the companies of this sector present low yield and generate large amounts of waste during the processing of the wood, mainly, those originating from processing. Residues generated in the form of clods, shavings, bark, sawdust, brushwood, and shavings can represent 51% of the original log volume (BOASIAKO; ACHEAMPONG, 2016). The inadequate storage of these wastes, without proper disposal, generates serious environmental problems, such as silting of rivers and ponds, as well as the risk of fire and air pollution due to open burning (BRAND, 2010; PROTASIO *et al.*, 2011). It is, therefore, necessary to determine better uses for such waste, which can lead to significant environmental problems. These wastes are an interesting raw material to be used in various applications, such as in the generation of thermal energy for various industrial segments.

On the other hand, Brazil does not yet have an industrial tradition of producing charcoal briquettes (COELHO JÚNIOR *et al.*, 2013). There is great consumer resistance to use of this product as a substitute for charcoal, due to its combustion characteristics, greater ignition difficulty, less flame generation during the combustion, and apparent formation of a larger volume of ash (BOASIAKO; ACHEAMPONG, 2016). With respect to the production of charcoal briquettes for meeting the commercial demand of the domestic segment in Brazil, little has been done at the laboratory and industrial scales. However, the main use of charcoal briquettes produced abroad, especially in Europe, are made in this sector (BOASIAKO; ACHEAMPONG, 2016).

Nowadays, Brazilian production is boiled down to the pioneering and isolated activities of small and medium-sized producers, who, despite their merit, are generally unable to achieve the qualities demanded by the consumer market. In addition, they do not reach production and marketing levels observed in other countries. This activity could solve the shortage of "clean" fuels, presenting more affordable prices for mainly domestic use (BAMGBOYE; BOLUFAWI, 2009; QUIRINO *et al.*, 2012; BOASIAKO; ACHEAMPONG, 2016; WANG *et al.*, 2017). Thus, it is hypothesized that the use of charcoal fines mixed with wood residues of *Pinus* spp in different particle sizes, can result in briquettes with good physical-mechanical characteristics to meet the demand of several industrial sectors.

The objective of this study was to evaluate the physical and mechanical properties of briquettes produced when mixing charcoal fines with sawdust and shavings of *Pinus* spp in four different proportions.

MATERIAL AND METHODS

Raw Material

Approximately four tons of charcoal grinder that were generated after successive carbonizations of *Eucalyptus* spp wood were made available by Carvalho ME Ltda, located in the municipality of Barra Mansa in the state of Rio de Janeiro. The fines were packed in polypropylene bags of 30 kg capacity and transported to the briquetting unit. The material was classified in a 5 mm square mesh sieve to obtain two fractions: one above 5 mm and the other one below 5 mm. It should be noted this is the cutting mesh used by the steel industry in the processing of charcoal. The crude fines composite was submitted to a sequence of sieves until a representative sample was obtained for the determination of the particle size distribution.

Regarding wood residues of *Pinus* spp (shavings and sawdust), two tons were collected from a company of unfolding and commercialization of improved wood, located in the municipality of Barra Mansa.

Composition and production of briquettes

The wood waste of *Pinus* spp, in the proportions of 5, 10, 15, and 20%, was mixed with the charcoal fines and binder (m/m). The binder used was 8% gelatinized maize starch. The materials were homogenized in a 60-liter intensive mixer and then packed in an endless screw briquetting machine under pressure of 55 kgf.cm⁻². The compression system was continuous at a speed of 800 rpm, capable of producing briquettes of 73 mm in diameter and 100 mm in length. The briquettes were dried in an oven with forced air circulation at 110 °C. Table 1 shows the composition of the briquettes that were evaluated in this study.

Table 1. Composition of the briquettes under the conditions set out in 16 treatments.
Tabela 1. Composição dos briquetes sob as condições estabelecidas em 16 tratamentos.

Waste <i>Pinus</i> spp (%)	Particle sizes of charcoal fines			
	< 5 mm		> 5 mm	
	Sawdust	Shavings	Sawdust	Shavings
5	T1	T2	T9	T10
10	T3	T4	T11	T12
15	T5	T6	T13	T14
20	T7	T8	T15	T16

In which: Binder: 8% gelatinized maize starch; and T: treatment analyzed.

Physical and mechanical tests of briquettes produced

The physical and mechanical tests of the briquettes were carried out in the laboratories of National Steel Company (CSN) and Cimento Rio Branco S/A, both located in the city of Volta Redonda (state of Rio de Janeiro, Brazil).

The equilibrium moisture was obtained by the gravimetric method, as described in standard NBR 8293 (ABNT, 1983). The apparent specific mass of the briquette ($\text{g}\cdot\text{cm}^{-3}$) was determined according to standard NBR 9165 (ABNT, 1982). The briquette was weighed, and then, its volume was estimated by the hydrostatic method that is based on the displacement of a mass of water inside a container placed on the plate of a precision scale and caused by immersion of a body in the water, according to the principle of Archimedes.

The compressive strength ($\text{kgf}\cdot\text{cm}^{-2}$) was determined to evaluate the mechanical behavior of the briquettes when subjected to a given load or effort. The load test was performed using a universal test machine from the Instron brand. The load was applied in the longitudinal direction of the briquettes with dimensions of 50 mm in length and 40 mm in diameter. Before the tests, the briquettes were placed in a mold and sanded in the perpendicular and transverse directions, until the pre-established dimensions were reached. The methodology used reproduced the procedures described by Paula *et al.* (2011).

The friability of the briquettes, based on the abrasion resistance, was determined using a rotary drum that had two diametrically opposed sides that were 50 mm wide on its inner sides to simulate the fall effect. The drum was rotated at 15 rpm for a period of 10 minutes. The friability of the briquettes was determined after the classification of the material submitted to the drum by a 5 mm square mesh sieve, in accordance with the procedures described in standard NBR 8629 (ABNT, 1984).

Experimental design and statistical analysis of data

The experimental design was the completely randomized factorial. The effects of the average particle size of the charcoal fines (>5 mm and <5 mm), the two types of wood residues of *Pinus* spp (sawdust and shavings), and the four proportions of the residues in the briquettes composition (5, 10, 15, and 20%) were all analyzed. Thus, 16 treatments, with 10 replicates each, were completed.

Before the analysis of variance (ANAVA), the normality of the variables dependent on the Kolmogorov-Smirnov test and the homogeneity of the variances by the Levene test were verified at a 95% probability level. Based on these assumptions, the dependent variables were submitted to ANAVA and analyzed by the F test. When significant, the Tukey test was applied to compare the means of the treatments. When the variables did not fit a normal distribution or presented non-homogeneous variances, the non-parametric Kruskal-Wallis and Mann Whitney tests were applied.

RESULTS

Table 2 shows the average values of the apparent specific masses of the briquettes, produced according to the pre-established treatments.

Table 2. Apparent density of the briquettes produced.

Tabela 2. Massa específica aparente dos briquetes produzidos.

Waste <i>Pinus</i> spp (%)	Apparent specific briquette mass (g.cm ⁻³)				Mean
	Particle sizes of charcoal fines(mm)				
	< 5 mm		> 5 mm		
	Sawdust	Shavings	Sawdust	Shavings	
5	0.67 ^{cB}	0.81 ^{aA}	0.83 ^{aA}	0.78 ^{aA}	0.78 ^a
10	0.80 ^{aA}	0.76 ^{abA}	0.78 ^{aA}	0.75 ^{abA}	0.77 ^a
15	0.76 ^{abA}	0.75 ^{abAB}	0.75 ^{aAB}	0.70 ^{abcB}	0.74 ^b
20	0.69 ^{cAB}	0.71 ^{bAB}	0.75 ^{aA}	0.65 ^{cAB}	0.70 ^c
Mean	0.73 ^{BC}	0.76 ^{AB}	0.78 ^A	0.72 ^C	
Mean	0.75 ^A		0.75 ^A		

Different lowercase and uppercase letters show, respectively, significant differences between the means in the columns and in the rows by the Tukey test to 95% of probability.

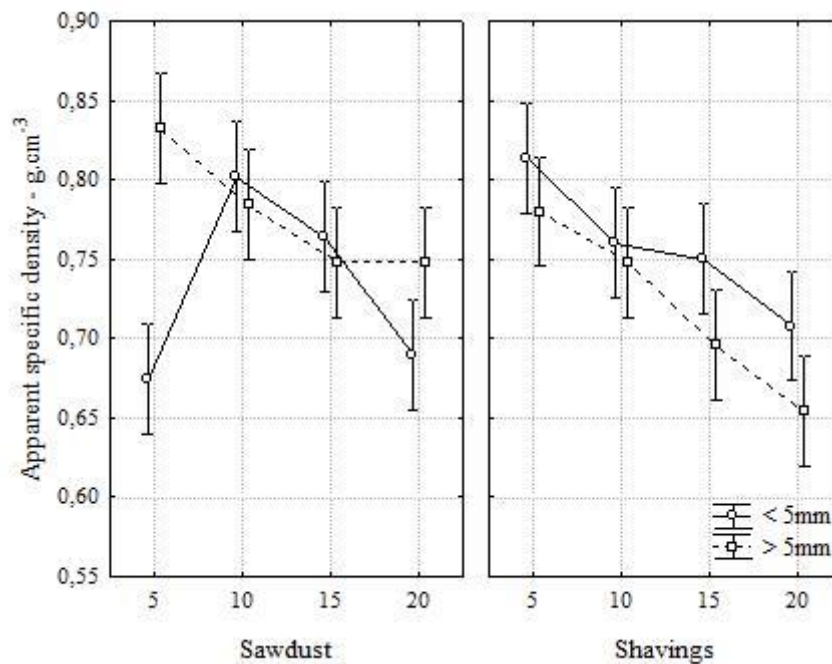
According to Table 2, it can be observed that the apparent specific mass of the briquettes varied according to the proportion of the residues of the *Pinus* spp wood used. In Table 3, it can be seen that there was a tendency to reduce the average resistance to compression as the proportion of *Pinus* spp residues in the briquettes composition decreased, except for the treatment in which 5% sawdust was included in the charcoal grinder with a mean grain size of < 5 mm.

Table 3. Resistance of the briquettes to compression according to the proportion of wood waste of *Pinus* spp and the average particle sizes of the charcoal fines.Tabela 3. Resistência dos briquetes à compressão em função da proporção de resíduos da madeira de *Pinus* spp e da granulometria média da moinha de carvão vegetal.

Waste <i>Pinus</i> spp (%)	Resistance of briquettes to compression (kgf.cm ⁻²)				Mean
	Particle sizes of charcoal fines (mm)				
	< 5 mm		> 5 mm		
	Sawdust	Shavings	Sawdust	Shavings	
5	4.6 ^{bB}	9.0 ^{aA}	10.4 ^{aA}	8.4 ^{aA}	8.1 ^{ab}
10	9.4 ^{aA}	9.4 ^{aA}	9.0 ^{aAB}	8.6 ^{aA}	9.1 ^a
15	9.0 ^{aA}	7.6 ^{aAB}	8.0 ^{aAB}	6.6 ^{aAB}	7.8 ^b
20	5.0 ^{aB}	5.2 ^{aB}	6.2 ^{aB}	5.0 ^{aB}	5.4 ^c
Mean	7.0 ^B	7.8 ^{AB}	8.4 ^A	7.2 ^B	
Mean	7.4 ^A		7.8 ^A		

Different lowercase and uppercase letters show, respectively, significant differences between the means in the columns and in the rows by the Tukey test to 95% of probability.

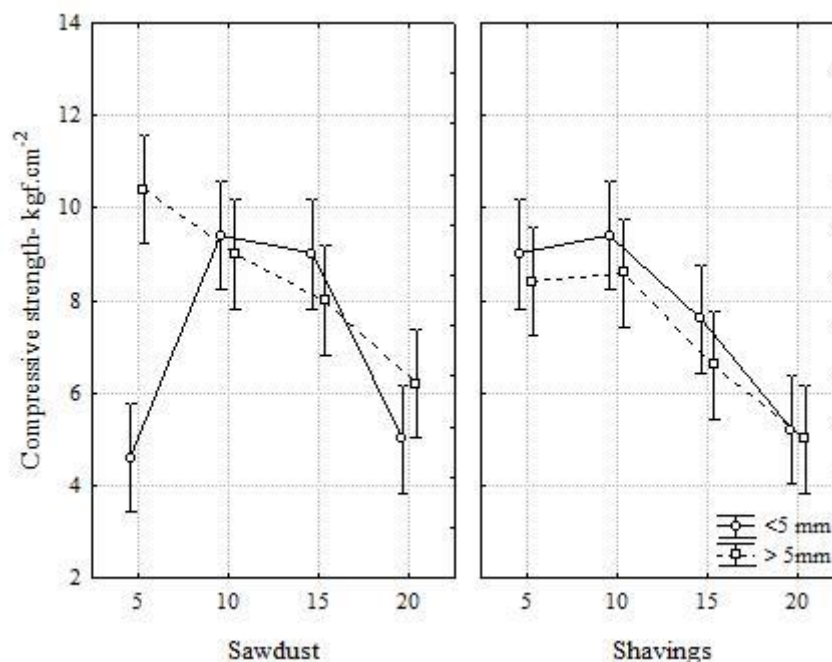
Figures 1 and 2 present the results of the apparent specific mass and compressive strength of the briquettes, as well as their respective comparisons and variations between the analyzed treatments.



Means along the same bar do not differ significantly from each other by the Tukey test at 95% probability.

Figure 1. Comparison between the apparent specific density according to the proportion of wood waste of *Pinus* spp and the particle sizes of the charcoal fines.

Figura 1. Comparação entre a massa específica aparente em função da proporção dos resíduos da madeira de *Pinus* spp e granulometria da moinha de carvão vegetal.



Means along the same bar do not differ significantly from each other by the Tukey test at 95% probability.

Figure 2. Comparison between the compressive strength of the briquettes according to the type of wood waste of *Pinus* spp, the proportion of the waste, and the particle sizes of the charcoal fines.

Figura 2. Comparação entre a resistência à compressão dos briquetes em função do tipo de resíduo da madeira de *Pinus* spp, proporção do resíduo e granulometria da moinha de carvão.

Tables 4 and 5 show, respectively, the Kruskal-Wallis and Mann Whitney test results, applied for the analysis of the friability indexes of the briquettes after the friability test.

Table 4. Friability index after friability test according to the proportion of wood waste of *Pinus* spp in the composition of the briquettes.

Tabela 4. Índice de friabilidade após o teste de tamboramento em função da proporção de resíduo da madeira de *Pinus* spp na composição dos briquetes.

Resistance to Friability (ranks)		
Waste <i>Pinus</i> spp (%)	Rank sum	Mean (%)
5	600 ^{bc}	30.0 ^{bc}
10	502 ^c	25.1 ^c
15	925 ^{ab}	46.3 ^{ab}
20	1213 ^a	60.7 ^a

Different lowercase letters in the column indicate significant differences between the means of the treatments by the Kruskal-Wallis test at the 95% probability level.

Table 5. Friability index according to the type of wood waste of *Pinus* spp and the particle sizes of the charcoal fines in the composition of the briquettes.

Tabela 5. Índice de friabilidade em função do tipo do resíduo da madeira de *Pinus* spp e da granulometria da moinha do carvão vegetal na composição dos briquetes.

Resistance to Friability (ranks)		
Waste <i>Pinus</i> spp	Rank sum	Mean (%)
Sawdust	1534.5 ^a	76.7 ^a
Shavings	1705.5 ^a	85.3 ^a
Average particle size (mm)	Rank sum	Mean (%)
< 5	1732.5 ^a	86.6 ^a
> 5	1507.5 ^a	75.4 ^a

Different lowercase letters in the column indicate significant differences between the means of the treatments by the Mann-Whitney test at the 95% probability level.

DISCUSSION

The sharp reduction in the mean apparent specific mass of the briquettes can be attributed to the occurrence of partial failures in the homogenization or during the pressing of the analyzed materials (Figure 1). This observation corroborates the results observed by Dias Júnior *et al.* (2016), which analyzed briquettes produced from charcoal fines, bamboo waste, and pulp and paper waste (dregs). In addition, it can be assumed that the compression force applied to the residues allowed for less compaction and, consequently, favored the occurrence of greater porosity for the briquettes and, thus, lower mass per unit volume.

Except for the treatment in which 5% sawdust was included in the charcoal grinder with a mean particle size of less than 5 mm, it can be seen that there was a tendency to decrease the apparent specific masses as the proportion of the wood residues of *Pinus* spp increased in the composition of briquettes. Possibly, the inclusion of higher percentages of the residues was responsible for the decrease of the apparent specific mass of the briquettes because the wood of *Pinus* spp is usually of low density. Within the respective proportions of the residues, the briquettes produced from shavings and sawdust of charcoal with a mean particle size >5 mm presented the lowest values of apparent specific mass, as compared with the briquettes obtained from the other treatments. Again, the exception was represented by the briquettes consisting of charcoal fines with particle size <5 mm, that was mixed at the 5% sawdust proportion. The hypothesis associated to this behavior is related to the fact that smaller particle sizes favors the arrangement of the particles, favoring the compression process and, consequently, higher values of specific apparent mass (DIAS JÚNIOR *et al.*, 2014).

Analyzing the physical properties of briquettes produced with charcoal fines mixed with bamboo residues under seven different formulations, Dias Júnior *et al.* (2014) found specific apparent masses for briquettes ranging from 0.30 g.cm⁻³ (50% charcoal and 50% bamboo residues) to 0.85 g.cm⁻³ (100% charcoal fines). However, the specific mass obtained by Jacinto *et al.* (2016) was, on average, 1.14 g.cm⁻³ for briquettes produced from material derived from jatropha straws in different formulations. In the present study, the apparent specific masses of the briquettes remained closer to the second level, as observed by the first authors. Quirino *et al.* (2012) point out that, in general, briquettes are produced without an internal homogeneous density distribution, which implies low mechanical resistance and dimensional stability.

In the compressive strength test, the composition of the wood shavings was evaluated. The briquettes produced with charcoal fines with particle size <5 mm presented the greatest resistance, probably due to the best arrangement of these particles and the higher densities previously reported. As can be seen in Figure 2, such behavior was less pronounced in the case of sawdust. In general, the results for compressive strength of briquettes are associated with their respective apparent specific masses (Table 2). Thus, under the conditions in which the present research was carried out, there are indications of a positive correlation between the resistance of the briquettes to compression and their respective apparent specific masses.

Conversely, for the reasons mentioned earlier, Dias Júnior *et al.* (2016) detected a negative correlation between the compressive strengths and the apparent specific masses of briquettes produced with charcoal fines and bamboo residues. Araújo *et al.* (2016) highlight the relationship between these variables, as well as the influence of compression pressure on the briquettes properties. In addition, some references indicate that, in the briquetting process, materials of greater particle sizes result in briquettes with better physico-mechanical properties when compared, for example, with briquettes produced with materials of smaller particle sizes (JERSERSKA *et al.*, 2014).

In this study, the average values found for the compressive strength of the briquettes varied from 4.6 kgf.cm⁻² to 10.4 kgf.cm⁻². The highest values, most of the time, coincided with the lower proportions of wood residues of *Pinus* spp, due to low wood density. In the research conducted by Quirino *et al.* (2012), these values ranged from 13.68 kgf.cm⁻² to 48.12 kgf.cm⁻². and the highest values for briquettes were produced with higher proportions of fine sawdust from *Eucalyptus* sp, compacted under a pressure of 120 kgf.cm⁻² and temperature of 200 °C. These variations can be attributed to the differences between the processes, equipment, molds, loads, and pressing times, as well as between the morphology of the particles and the physical and mechanical properties of the residues used (ARAÚJO *et al.*, 2016, WU *et al.*, 2018). According to Wang *et al.* (2017), the maximum resistance is achieved through compression temperatures around 220 °C, another aspect that may also explain the results obtained in this research.

For iron and steel purposes, Quirino and Brito (1991) have suggested briquettes with compressive strengths around 70 kgf.cm⁻². For briquettes with low compressive strengths, some authors recommend treatments or processing that do not require excessive handling, transport over long distances, and storage for long periods of time, and it is interesting to use them as close to the production site as possible. In this context, they mention the direct burning in furnaces of stills, grain dryers, potteries, and ceramics, among other uses (DIAS JÚNIOR *et al.*, 2014; BOASIAKO; ACHEAMPONG, 2016; DIAS JÚNIOR *et al.*, 2016).

The friability indexes of the briquettes decreased as the wood residue proportions of *Pinus* spp were increased in their composition (Table 4). Similarly, Boasiako and Acheampong (2016) analyzed the friability of briquettes produced with wood sawdust of species of different densities and found that with the increase in the proportion of the wood brighter in the briquettes composition, there was a decrease in the friability two briquettes. The authors attributed this result to the good conformation between the sawdust particles of higher density, which when arranged in a more organized way, generating more resistant briquettes.

According to Table 5, the friability indexes of the briquettes were not significantly affected by the type of biomass (sawdust or wood shavings of *Pinus* spp) and by the average particle sizes of the charcoal fines. In addition, the studied variables residues and particle sizes are presented as technically feasible alternatives for the production of briquettes when considering the fine generation aspect. For Martins *et al.* (2016), Bamgboye and Bolufawi (2009), and Boasiako and Acheampong (2016), it is possible to reduce brittle friability by decreasing the humidity or increasing the compaction pressure. This is because these factors have a greater influence on the molecular interactions observed in their structures.

CONCLUSION

- The briquettes produced with charcoal fines, mixed with 5 and 10% of the residues of the wood of *Pinus* spp (sawdust or shavings), present a higher apparent specific mass and greater resistance to compression. Experimental results have also shown that briquettes produced under these conditions are less friable.
- The use of the charcoal fines, combined with sawdust or shavings of *Pinus* spp, was a technically feasible alternative for the production of briquettes, presenting good physical and mechanical properties.
- Further studies are recommended for energy assessment and reactivity tests (CRI and CSR) of briquettes produced for steel purposes. However, when the product is intended for use in the cooking of food, qualitative-quantitative studies of the gases from combustion are recommended.

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