FOREST SCIENCES (CIÊNCIAS FLORESTAIS)

Parameters to determine mechanical strength of charcoal in a hydraulic press

Jéssica Dornellas Soares[1] , Marcos Oliveira de Paula[1] , Angélica de Cássia Oliveira Carneiro[1] ,
Luciano Junqueira Costa[1] , Aylson Costa Oliveira[2]* , Barbara Luísa Corradi Pereira[2]

[1] Universidade Federal de Viçosa, Departamento de Engenharia Florestal, Viçosa, MG, Brasil. E-mail: dornelas.js@gmail.com; modepaula@gmail.com; cassiacarneiro1@gmail.com; junqueira.lct@gmail.com
[2] Universidade Federal do Mato Grosso, Laboratório de Tecnologia da Madeira, Cuiabá, MT, Brasil. E-mail: aylsoncosta@gmail.com; babicorradi@gmail.com

ABSTRACT: The friability, an important quality parameter, is the ability of charcoal to generate fines when it is moved. However, there is no standard for determining the compressive strength of charcoal beds. Thus, the objective of this work was to evaluate some test parameters for determining the generation of charcoal fines in a manual hydraulic press. Charcoal was produced with eucalyptus logs 7 years old, diameters of 10 to 12 cm, and length of 1 m in a circular surface kiln, with a maximum carbonization temperature of 400 ºC and a total time of 58 hours. For methodology evaluation, charcoal mechanical tests were performed in a manual hydraulic press, using as test variables four charcoal granulometric ranges (12.7 to 19.5; 19.5 to 25.4; 25.4 to 31.7 and 31.7 to 50.8 mm) and five compressive loads (1; 1.5; 2; 3 and 5 t). The reference was the drum test. The method of evaluating the mechanical strength using a manual hydraulic press is suitable for determining the strength of a charcoal bed, because it represents the efforts that charcoal supports in industrial systems. The test parameters recommended for determining the mechanical strength of charcoal, using a manual hydraulic press, are: compressive load of one ton; charcoal with granulometry of 19.5 to 50.8 mm; average velocity of force application of 1 mm s^{-1}; and, charcoal time under pressure equal to 1 min.

Key words: friability; granulometric; thermo-reducer

Determinação de parâmetros para avaliação da resistência mecânica de carvão vegetal em prensa hidráulica

RESUMO: A friabilidade, um importante critério de qualidade, é a capacidade de geração de finos do carvão vegetal quando ele é movimentado. No entanto, não existe normativa para a determinação da resistência à compressão de leitos de carvão vegetal. Assim, o objetivo deste trabalho foi avaliar alguns parâmetros de ensaio para determinação da geração de finos de carvão vegetal em prensa hidráulica manual. Toras de eucalipto com 7 anos, diâmetros de 10 a 12 cm e comprimento de 1 m foram carbonizadas em forno circular de superfície, com temperatura máxima de carbonização de 400 ºC e tempo total de 58 horas. Para avaliação do método, os ensaios mecânicos do carvão vegetal foram realizados em uma prensa hidráulica manual, utilizando-se como variáveis de ensaio quatro faixas granulométricas de carvão (12,7 a 19,5; 19,5 a 25,4; 25,4 a 31,7 e 31,7 a 50,8 mm) e cinco cargas compressivas (1; 1,5; 2; 3 e 5 t). O ensaio de tamboramento foi utilizado como testemunha. O método de avaliação da resistência mecânica pela prensa hidráulica manual é adequado para a determinação da resistência de um leito de carvão vegetal, por representar os esforços que o carvão vegetal suporta em sistemas industriais. Os parâmetros de ensaio recomendados para determinação da resistência mecânica do carvão vegetal, utilizando-se prensa hidráulica manual, são: carga compressiva de uma tonelada; carvão vegetal na granulometria de 19,5 a 50,8 mm; velocidade média de aplicação de força de 1 mm s^{-1}; e, tempo de permanência do carvão sobre pressão igual a 1 min.

Palavras-chave: friabilidade; granulometria; termorredutor

* Aylson Costa Oliveira - E-mail: aylsoncosta@gmail.com (Corresponding author)
Associate Editor: Rafael Rodolfo de Melo

Introduction

The use of charcoal as a raw material in the production process of Brazilian steel mills positions Brazil as the largest producer and consumer of charcoal in the world, with consumption of 5.1 million tons in 2019 (IBÁ, 2020). Charcoal is considered an excellent raw material for the steel industry due to its quality as a fuel and reducer, its high degree of purity and low polluting power (Protásio et al., 2014).

The use of charcoal in steelmaking processes requires a material with sufficient mechanical strength to support the layer of iron ore, without impairing the permeability of the bed. This is one of the biggest obstacles to using this thermo-reducer when compared to mineral coke (Assis et al., 2016). Thus, the mechanical strength of charcoal should be considered a quality parameter because the generation of fines inside the blast furnace decreases the permeability of the burden, which reduces productivity and compromises proper operation.

The standards currently used to determine the friability of charcoal, recommendations of the Centro Tecnológico de Minas Gerais (CETEC) described by Oliveira et al. (1982) and the Brazilian Standard NBR 8740 - Determination of the breakage and abrasion index (ABNT, 1985) do not simulate the real applicability of charcoal in industrial systems. These tests are performed by a drum test that simulates the movement of the material during handling and transport, however, these methodologies were adapted for tests with charcoal based on standards developed for coke, a less friable material. Thus, these tests overestimate the results of charcoal fines generation, impairing their accuracy.

Several studies have been conducted aiming to develop new methods for determining the mechanical strength of charcoal from the compression of individual pieces of charcoal (Costa et al., 2017; Moutinho et al., 2017). However, these tests are difficult to perform, due to the removal of crack-free specimens, and do not reproduce the actual usage scenario. This is because in steelmaking processes the charcoal load will be submitted to compression efforts in several directions of the pieces, since they are not kept arranged in an organized and oriented way (Kurauchi, 2014; Veiga et al, 2016).

Due to the need to develop more efficient and standardized methods to quantify the generation of charcoal fines caused both by friction of the pieces during handling and transport operations and by compression stress due to overload, the objective of this work was to evaluate some test parameters in a manual hydraulic press to determine the generation of charcoal fines.

Materials and Methods

Wood carbonization

For this study, randomly selected logs of Eucalyptus sp. with 7 years of age, diameter varying between 10 and 12 cm and length of 1.0 m were used. The charcoal was produced in a masonry circular surface kiln, with internal measurements of 1.20 m in diameter; 0.90 m high on the side walls and 1.10 m high in the central part, with a volumetric capacity of one meter of wood stereo. The kiln temperature was monitored from five K-type thermocouples, one installed in the canopy and four others on the side of the kiln. According to the temperatures obtained, the air inlets were closed or opened, and consequently, the carbonization was controlled. The maximum final carbonization temperature was equal to 400 ºC and total time equal to 58 hours.

Two carbonizations were necessary to produce enough charcoal for the mechanical tests. It should be noted that after the carbonizations, all the charcoal produced was mixed and homogenized, becoming a single composite sample.

Mechanical characterization of charcoal
Drumming method

The determination of charcoal friability by the drumming method suggested by CETEC and described by Oliveira et. al (1982), with adaptations. To perform the test, a sample of approximately 500 g of charcoal was weighed and classified on a 25.4 and 37.5 mm sieve. The charcoal sample was introduced into a cylindrical drum, made of steel, with dimensions equal to 30 cm in diameter and 24.8 cm in length, coupled to a motor that kept it at 30 revolutions per minute and total time of 17 minutes.

At the end of the test, the drum was opened and the charcoal sample was removed and classified on a 9.5 mm sieve, weighing the mass that passed through this sieve, which was considered as fines. The calculation of coal friability was given by Equation 1.

$$\text{Friability}\left(\%\right) = \left(\frac{\text{Mf}}{\text{Icm}}\right) \times 100 \qquad (1)$$

where: Mf: Mass of fines (g); Icm: Initial charcoal mass (g).

The classification of the fines generated by the friability test followed the methodology described by Oliveira et al. (1982), shown in Table 1. The friability of charcoal determined by the drumming method was considered as a control.

Table 1. Friability classification for charcoal by the friability test.

Classification	% of losses
Very friable	≥ 30
Quite friable	25 -29
Medium friability	15 -24
Not very friable	10 -15
Very slightly friable	< 10

Manual Hydraulic Press method

The determination of the percentage of fines generated by the method with a Manual Hydraulic Press was performed from the compression of a charcoal bed, without defined direction. We used a 15-ton hydraulic press coupled to a movable cylindrical container, made of 1045 steel, with 28.5 cm in diameter and 20.5 cm in height (Figure 1).

A.

B.
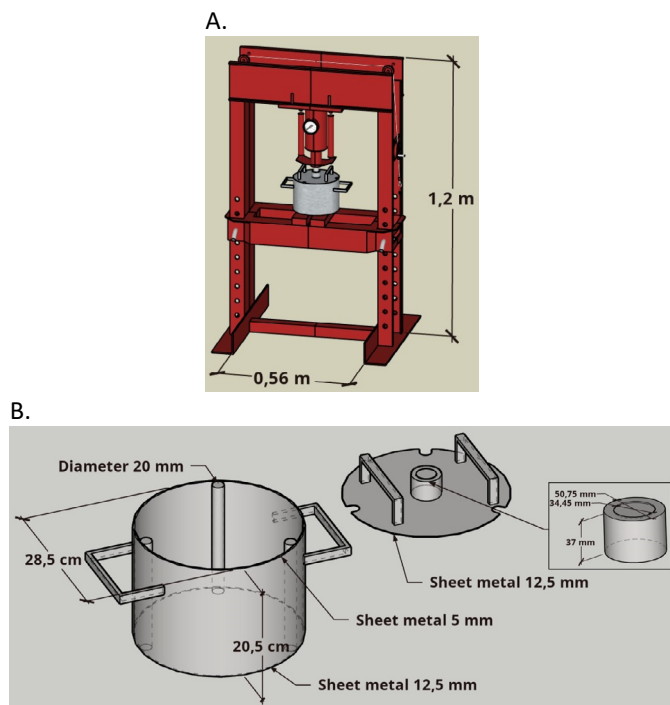
Figure 1. (A) Hydraulic press, coupled to a cylindrical container; (B) Details of the cylindrical container and its respective lid.

The container, besides the side handles that facilitate loading and unloading of the sample, also has a lid with dimensions of 20.5 cm in diameter and 1.25 cm thick with two handles on its surface to facilitate opening and closing. In order to have a uniform distribution of the compressive load on the charcoal pieces, a circular elevation of 3.7 cm in height and 5.07 cm in diameter was carried out in the center of the lid to demarcate the place where the compressive load was applied, in this way the pieces of charcoal were pressed at the same point in a homogeneous way.

To perform the test, a sample of approximately 500 g of charcoal was weighed and poured at an average height of 20 cm into the container, to ensure the random arrangement of the pieces. Subsequently, the container was closed with its respective lid.

The compressive stress was applied to the sample from the piston of the press that maintained direct contact with the lid of the container that distributed the load over the surface of the coal. After reaching the desired pressure, the sample was kept pressed into the container for one minute. This dwell time was intended to homogenize the pressure distribution in the material.

The mechanical tests using the Manual Hydraulic Press method were performed using different parameters: four charcoal granulometries (12.7-19.5; 19.5-25.4; 25.4-31.7; 31.7-50.8 mm) and five compression forces (1; 1.5; 2; 3; 5 t). For each test, the average test execution time and the distance traveled by the press piston until the total application of the desired pressure were counted, and thus the average test speed was obtained for each treatment, in order to ensure its reproduction without operator interference. After each test, the charcoal sample was classified on a 9.5 mm sieve,

and the mass of charcoal with a particle size less than 9.5 mm was considered as fines and the friability calculation was performed according to Equation 1.

Statistical analysis

The experiment was set up according to an entirely randomized design in a 5 × 4 factorial scheme, consisting of five compression forces (1; 1.5; 2; 3; 5 t) and four charcoal granulometries (12.7-19.5; 19.5-25.4; 25.4-31.7; 31.7-50.8 mm), totaling 20 treatments and the control (drumming method), with five repetitions.

The data were subjected to the Lilliefors test for normality and the Cochran test for homogeneity of variance. Then, analysis of variance (ANOVA) was performed and when significant differences between treatments were established, the Tukey test was applied at 5% significance level, and each treatment was compared with the control by the Dunnet test at 95% probability, using STATISTICA 8.0 software (Weiβ, 2007).

Results and Discussion

Mechanical characterization of charcoal

Regardless of the granulometry of the charcoal, it can be seen in Table 2 that the higher the compressive load applied, the greater the generation of fines, with average values ranging from 15.92 to 55.36%, with the most significant increase starting at a force of 3 tons. Kurauchi (2014) also found an increase in fines generation with increasing applied force during strength testing on charcoal fillers.

This occurs because charcoal is a friable material, that is, of low mechanical strength, which suffers great influence from the stresses received during the activities in which it is involved, with considerable degradation, generating a large amount of fines with each handling (Machado & Andrade, 2004). Thus, the greater the force applied to the charcoal, the greater the amount of fines generated.

According to Pereira et al. (2016), the carbonization process promotes a significant reduction in the thickness of the fiber cell wall, which shows a glassy and brittle appearance and this decrease in wall thickness is one of the factors that explain

Table 2. Mean values of the percentage of charcoal fines generated as a function of the treatments evaluated in the manual hydraulic press and drumming method.

Force (tons)	Granulometry (mm)			
	12.7-19.5	19.5-25.4	25.4-31.7	31.7-50.8
1	26.22 Da*	18.71 Db[n.s]	15.92 Db[n.s]	17.89 Eb[n.s]
1.5	36.51 Ca*	26.11 Cb*	25.28 Cb*	26.48 Db*
2	35.0 Ca*	22.96 Cc*	24.86 Cc*	30.99 Cb*
3	46.89 Ba*	39.90 Bb*	36.21 Bc*	40.50 Bb*
5	55.36 Aa*	52.96 Aa*	49.78 Ab*	51.55 Ab*
Drumming method	14.95			

Averages followed by the same lower case letters in the row (granulometries) and capital letters in the column (strengths), do not differ by the Tukey test (p ≥ 0.05). "[n.s]" indicate non-significant differences and "*"indicate significant differences between the means and the control, by the Dunnett test (all at 95% probability level).

Rev. Bras. Cienc. Agrar., Recife, v.16, n.4, e9096, 2021

3/6

the lower density of charcoal compared to wood, besides the loss of mass, a characteristic that has a high influence on strength properties. Furthermore, according to these authors, there is the formation of protuberances inside the rays, due to thermal degradation of the material, and large cavities or cracks along the rays in the heartwood region, which make the charcoal a brittle material.

When evaluating the influence of charcoal granulometry on the generation of fines, it is observed that the treatments that generated more fines were those that used charcoal with lower granulometry, in the range of 12.7 to 19.5 mm (Table 2). This fact was also observed by Kurauchi (2014), who, when evaluating the mechanical strength of charcoal, in grain sizes from 25.4 to 31.7 and 22.2 to 25.4 mm, using a universal testing machine, verified greater generation of fines for the material with lower grain size. Veiga et al. (2016), when evaluating the mechanical properties of Eucalyptus sp. charcoal using specimens of different sizes for the performance of compression tests parallel to the fibers, observed a decrease in the modulus of elasticity and compressive strength with the reduction in the longitudinal dimensions of the specimens.

This behavior would be related to the energy required to compress charcoal with different granulometries, because pressure is defined as the force applied on a given surface or area, so when the contact area where the same force is being applied is reduced, that is, charcoal pieces with lower granulometry, the pressure in the system increases, causing greater rupture of the sample. Assis et al. (2020), when studying the effect of granulometry in the compression test on charcoal beds, observed that the larger the granulometry, the more energy was required in the process to reach the rupture stress, i.e. larger pieces were more resistant to compressive stress for the same applied force.

In addition, a charcoal sample with a smaller particle size has a larger specific surface area, that is, more contact points between the charcoal pieces under pressure during the test, favoring the greater friability of this material.

However, for the 31.7-50.8 mm particle size, when compressive loads of 2 and 3 t were applied, the generation of fines was higher when compared to the 19.5-25.4 and 25.4-31.7 mm particle sizes. This fact probably occurred due to the difficulty in arranging larger pieces, which leads to greater surface abrasion and fragmentation, in addition to the heterogeneity of the charcoal pieces.

Table 3 shows that the charcoal evaluated by the drumming method (control) was classified as not very friable, while the treatments with compressive load of 1 t in particle size ranges from 19.5 mm did not differ significantly from the control (Table 2), but were classified as medium friability charcoal, i.e., with a higher percentage of fines generation. However, it is emphasized that this classification does not involve statistical tests on the results but a classification in percentage ranges for the friability value, where higher percentages indicate more friable charcoals.

The lower generation of fines by the drum test in relation to the one performed in the Hydraulic Manual Press is related

Table 3. Classification of charcoal friability, according to Oliveira et al. (1982), as a function of the treatments evaluated in the manual hydraulic press and drumming method.

Force (tons)	Granulometry (mm)			
	12.7-19.5	19.5-25.4	25.4-31.7	31.7-50.8
1	QF	FM*	FM*	FM*
1.5	VF	QF	QF	QF
2	VF	MF	MF	VF
3	VF	VF	VF	VF
5	VF	VF	VF	VF
Drumming method	NVF			

Where: VF: Very friable; QF: Quite friable; MF: Medium friability; NVF: Not very friable. *: treatments that did not differ statistically from the control, by the Dunnett test, at the 95% probability level.

to the way the tests are performed. The compression test in the hydraulic press is performed on a bed of charcoal deposited randomly inside the container, so the charcoal pieces are subjected to load application in several directions. Thus, it is observed that the pieces of charcoal break and break in different regions, generating fragments in different sizes and proportions.

The friability measured by drumming occurs in a rotating drum, simulating the transport and handling of charcoal, without promoting a compressive load on the sample. Thus, the fragmentation of the charcoal occurs due to the rupture of preexisting cracks and fissures in the material, inherent to the carbonization process, and also by abrasion of the pieces, both factors contributing to the generation of fines. In this method, the fines fraction generated after the test mostly consists of charcoal dust only, and the granular fraction has a rounded appearance. This shows that the coal parts subjected to drumming suffer only wear due to abrasion of the parts and by their surface fragmentation. According to Dufourny et al. (2019), the less friable charcoal maintains its shape and integrity during the drumming test, while the more friable charcoal forms fragments of different sizes that offer more surface contact for shock and abrasion within the drum, thus increasing the percentage of fines produced.

Table 4 shows the average values of force application speed (mm s⁻¹) as a function of the treatments. The analysis of variance indicated that the speed of force application of the test had an effect only on the compressive load.

Table 4 shows that the higher the compressive load, the lower the test speed, with average values ranging from 0.67

Table 4. Average values of force application speed (mm s^{-1}) as a function of treatments in the manual hydraulic press method.

Force (tons)	Granulometry (mm)				Average
	12.7-19.5	19.5-25.4	25.4-31.7	31.7-50.8	
1	1.04	1.01	1.03	1.00	1.02 A
1.5	0.97	0.97	0.96	0.95	0.96 B
2	0.89	0.90	0.90	0.89	0.90 C
3	0.72	0.73	0.72	0.74	0.73 D
5	0.68	0.66	0.67	0.67	0.67 E
Average	0.84	0.83	0.84	0.83	0.84

Averages followed by same capital letters in the column (forces), do not differ by Tukey test (p ≥ 0.05).

Rev. Bras. Cienc. Agrar., Recife, v.16, n.4, e9096, 2021

4/6

to 1.02 mm s⁻¹. This is because for the same area, the higher the compression force applied during the test, the higher the pressure in the system and therefore the lower the test speed. This is due to the greater effort of the operator during the application of force, to reach the pressure that the system needed, spending more time for the same distance traveled by the piston.

The average time for the tests in the hydraulic press was 1.32 minutes, including the time the charcoal sample remained under pressure in the cylindrical container, one minute. The test performed from the drumming test has an average time of 17 minutes of rotation inside the drum, that is, when the test is performed from the hydraulic press there is a reduction of about 92% of the time to perform the charcoal friability test.

Even if the drumming test does not accurately reflect all the stresses submitted to the charcoal during transportation and handling, the test reproduces at least the mechanisms by which the degradation of this steelmaking input occurs, given the importance of evaluating the resistance of the charcoal against mechanical fragmentation, even if superficial, because this is directly related to the permeability of the blast furnace, influencing the speed of reaction (Veiga et al., 2016). Furthermore, the only standard with any mechanical property character is based on this methodology.

Therefore, the parameters recommended for use in determining the mechanical strength of charcoal in a manual hydraulic press were those that when compared to the tumbling test did not show significant differences, being the compressive load of 1 ton, granulometry of 19.5 to 25.4, 25.4 to 31.7, and 31.7 to 50.8 mm, average speed of force application of approximately 1 mm s⁻¹ and residence time of charcoal under pressure of 1 minute.

Conclusions

Regardless of the granulometric range of the charcoal, the higher the compressive stress the higher the generation of fines.

The particle size range from 12.7 to 19.5 mm presented greater generation of charcoal fines compared to the others.

The method of evaluating mechanical strength by hand hydraulic press is suitable for determining the strength of a charcoal bed, because it represents the stresses that charcoal endures in industrial systems.

The parameters to be adopted to standardize the method are: one-ton compressive load; charcoal with particle sizes between 19.5 and 50.8 mm; average speed of effort application of approximately 1 mm s⁻¹; and, permanence time of charcoal submitted to a compressive load of 1 minute.

Acknowledgments

Compliance with Ethical Standards

Literature Cited

Assis, M. R.; Brancheriau, L.; Guibal, D.; Napoli, A.; Trugilho, P. F. Towards a better understanding of the mechanical behavior of a fixed bed of Eucalyptus charcoal in a blast furnace using a specific compression test. Bioresources, 15, n. 4, p.7660-7670, 2020. https://doi.org/10.15376/biores.15.4.7660-7670.

Assis, M. R.; Brancheriau, L.; Napoli, A.; Trugilho, P. F. Factors affecting the mechanics of carbonized wood: literature review. Wood Science and Technology, v. 50, p. 519–536, 2016. https://doi.org/10.1007/s00226-016-0812-6.

Associação Brasileira de Normas Técnicas - ABNT. NBR 8740: Carvão vegetal: Determinação do índice de quebra e abrasão – Método de ensaio. Rio de Janeiro: ABNT, 1985. 4 p.

Costa, L. J.; Trugilho, P. F.; Lima, J. T.; Simetti, R.; Bastos, T. A. Caracterização mecânica do carvão vegetal de clones Corymbia. Scientia Forestalis, v. 45, n. 116, p. 629-639, 2017. https://doi.org/10.18671/scifor.v45n116.04.

Dufourny, A.; Van De Steene, L.; Humbert, G.; Guibal, D.; Martin, L.; Blin, J. Influence of pyrolysis conditions and the nature of the wood on the quality of charcoal as a reducing agent. Journal of Analytical and Applied Pyrolysis, v. 137, p. 1-13, 2019. https://doi.org/10.1016/j.jaap.2018.10.013 .

Indústria Brasileira de Árvores- IBÁ. Relatório 2020: ano base 2019. São Paulo: IBÁ, 2020. 66p. https://iba.org/datafiles/publicacoes/relatorios/relatorio-iba-2020.pdf.10 Oct 2020.

Kurauchi, M. H. N. Uma abordagem de ensaio de resistência mecânica de carvão vegetal. 2014. São Paulo: Universidade de São Paulo, 2014. 102 p. Master's Dissertation; https://doi.org/10.11606/D.3.2014.tde-28042015-110831.

Machado, F. S.; Andrade, A. Z. Propriedades termoquímicas dos finos de carvão vegetal e de carvão mineral, para a injeção nas ventaneiras de altos-fornos siderúrgicos. Biomassa & Energia, v. 1, n. 4, p. 353-363, 2004.

Moutinho, V. H. P.; Tomazello Filho, M.; Brito, J. O.; Ballarin, A. W.; Andrade, F. W. C.; Cardoso, C. C. Characterization and statistical correlation between charcoal´s physical and machanical properties of Eucalyptus and Corymbia clones. Ciência Florestal, 27, n. 3, p. 1095-1103, 2017. https://doi.org/10.5902/1980509828684.

Oliveira, J. B.; Gomes, P. A.; Almeida, M. R. Carvão vegetal-destilação, carvoejamento, propriedades e controle de qualidade. Belo Horizonte: Centro Tecnológico de Minas Gerais. 1982. 173p.

Pereira, B. L. C; Carvalho, A. M. M. L; Oliveira, A. C; Santos, L. C; Carneiro, A. C. O; Magalhães, M. A. Efeito da carbonização da madeira na estrutura anatômica e densidade do carvão vegetal de Eucalyptus. Ciência Florestal, v. 26, n. 2, p. 545-557. 2016. https://doi.org/10.5902/1980509822755.

Protásio, T.P; Goulart, S. L; Neves, T. A; Trugilho, P. F; Ramalho, F. M. G; Brites, L. M. R. S. Qualidade da madeira e do carvão vegetal oriundos de floresta plantada em Minas Gerais. Pesquisa Florestal Brasileira, v. 34, n. 78, p. 111-123, 2014. https://doi.org/10.4336/2014.pfb.34.78.657.

Veiga, T. R. L. A.; Lima, J. T.; Monteiro, T. C.; Rocha, M. F. V.; De Jesus, M. S.; Goulart, S. L. Efeito do comprimento do corpo de prova nas propriedades mecânicas do carvão de Eucalyptus. Pesquisa Florestal Brasileira, v. 36, n. 88, p. 399-403, 2016. https://doi.org/10.4336/2016.pfb.36.88.1073.

Weiß, C.H. StatSoft, Inc., Tulsa, OK.: STATISTICA, Version 8. AStA, v. 91, p.339-341, 2007. https://doi.org/10.1007/s10182-007-0038-x.