REVISTA FLORESTA
Engenharia Florestal

ISSN 1982-4688
Edição 54
Universidade Federal do Paraná
Setor de Ciências Agrárias

TECHNOLOGICAL PROPERTIES OF *Eucalyptus grandis* USING DIGITAL IMAGE CORRELATION (DIC)

Ângela Maria Stüpp[1*], Jorge Luís Monteiro de Matos[2], Marco André Argenta[3], Alexsandro Bayestorff da Cunha[4]

[1*]Federal University of Paraná, Postgraduate Program in Forestry Engineering, Paraná, Brazil – stuppmangela@gmail.com ; [2]matos.ufpr@gmail.com ; [3]marco.argenta@gmail.com
[4] Santa Catarina State University, Postgraduate Program in Forestry Engineering, Santa Catarina, Brazil – alexsandro.cunha@udesc.br

Received for publication: 27/04/2022 – Accepted for publication: 09/04/2024

Resumo

Propriedades Tecnológicas do Eucalyptus grandis *com aplicação de* Digital Image Correlation *(DIC).* O objetivo desta pesquisa foi caracterizar algumas propriedades tecnológicas da madeira de *Eucalyptus grandis*, e avaliar o uso do *Digital Image Correlation* (DIC) para obtenção do deslocamento, bem como do comportamento das amostras na deformação e sua relação com a tensão nos ensaios de tração e compressão paralelas às fibras. Assim, foram utilizadas peças de madeira de 23 anos, e produzidas amostras para determinação da densidade básica, coeficiente de retratibilidade, anisotropia de contração e inchamento, e das resistências mecânicas às solicitações de tração e compressão paralelas às fibras. Para o cálculo do Módulo de Elasticidade (E) foi medida, nas amostras de tração paralela, a velocidade de onda de tensão. A medida do alongamento das amostras durante o ensaio foi obtida pela leitura com DIC e, então, calculados a deformação e o E. A densidade básica da madeira foi de 0,497 g/cm³ e os valores de anisotropia de contração (1,25) e inchamento (1,27) indicaram ser uma madeira muito estável dimensionalmente. A resistência à tração paralela (118,50 MPa) foi superior ao normalmente obtido para a espécie. Os valores médios obtidos nas amostras de compressão paralela (53,06 MPa) foram similares ao encontrado na literatura. Quanto ao E, o valor médio obtido pela DIC foi de 12.664,24 MPa e pelo *stress wave timer* foi de 11.941,35 MPa. Conclui-se que a madeira avaliada é indicada para usos estruturais conforme classe C40 (NBR 7190-1997). Finalmente, A DIC foi capaz de fornecer adequadamente os valores de deslocamento ocorridos durante os ensaios, possibilitando o cálculo do E.
Palavras-chave: caracterização da madeira, método não destrutivo, propriedades físicas e mecânicas, deformação.

Abstract

This study aimed to characterize some technological properties of *Eucalyptus grandis* wood and evaluate the use of Digital Image Correlation (DIC) to obtain the displacement and the behavior of the samples in deformation and its relationship with tension in tensile and compression tests parallel to the fibers. Samples were produced from 23-year-old wood to determine the basic density, shrinkage coefficient, anisotropy in contraction and swelling, and the mechanical strength to tensile and compression parallel to the fibers. To calculate the Modulus of Elasticity (E), the stress wave velocity was measured in the tensile samples. The measurement of sample elongation during the test was obtained by DIC and then calculating strain and E. The basic density was 0.497 g/cm³ and the anisotropy values of contraction (1.25) and swelling (1.27) indicated that it was a very dimensionally stable wood. The tensile strength (118.50 MPa) was higher than normally obtained for the species. The parallel compression average values (53.06 MPa) were similar to those in the literature. As for E, the average value obtained by DIC was 12,664.24 MPa; by the stress wave timer, it was 11,941.35 MPa. The evaluated wood is indicated for structural uses according to the C40 class (NBR 7190-1997). Finally, DIC was able to adequately provide displacement values that occurred during tests, enabling the modulus of elasticity calculation.
Keywords: wood characterization, non-destructive method, physical and mechanical properties, strain.

INTRODUCTION

Eucalyptus is the most planted tree genus in the world. Its remarkable diversity, adaptability, and growth have made it a globally renewable resource (Myburg *et al*., 2014). As many as 95 countries have eucalyptus planted in silvicultural plantations, and the total plantation area has exceeded 22.57 million hectares worldwide (Zhang & Wang, 2021), with Brazil being the largest producer with 7.6 million planted hectares (Florêncio *et al*., 2022).

According to Lee *et al.* (2022), eucalyptus timber is reported to have a higher rigidity than most softwood species, making it ideal for manufacturing structural products. Additionally, the quality of the structural wood must be defined in terms of stability, strength, and stiffness. Furthermore, Lahr *et al*. (2018) stated that it is fundamental to perform physical-mechanical tests, which can help indicate the most efficient use for each wood species.

Researching *Eucalyptus* continues to be implemented (Iejavs *et al*., 2021, for instance) because of the relevance of the genus and the wooden raw material and its complexity, which allows its use in multiple sectors and for different purposes.

Determining the technological properties allows the manufacturer to inform the end user of the raw material characteristics (Iejavs *et al*., 2021) since the parts behave in different ways due to the multiple aspects of exposure.

Due to the orthotropic characteristic of wood, these properties differ among species, age, sites, and individuals, as well as in the base-top and pith-bark directions. For all its particularities, considering the wood anisotropy and orthotropicity in its various applications, especially regarding its dimensional stability, is crucial for the structure's performance. Thus, determining the material's mechanical properties requires displacement or strain measurement.

Usually, these two properties are measured by mechanical test equipment during strength analysis, where displacement is calculated from strain results. Also, it can be obtained by an accessory fastened in the equipment, but it must be removed as soon as the yield limit is reached, otherwise, during material rupture, this accessory will break. The problem with this method is that the operator can break this component before reaching the limit, hampering the experiment.

The major complexity of the material's mechanical behavior requires more sophisticated experimental procedures for characterization. Among the numerous techniques available today, those applied in the mechanical characterization of composites include digital speckle pattern interferometry (DSPI), moiré interferometry (MI), digital image correlation (DIC), and grid methods (GM), among others. These techniques offer resources that allow inspecting several variables, such as displacement, tension, strain, acceleration, and velocity, making it easier to obtain complementary information that covers, for example, the sample's behavior during tests (Bruno, 2018).

According to Molland and Turnock (2022), DIC is a non-contact optical technique for measuring strain and displacement. High-speed full-field experimental data of structural deformations can be obtained. It is a non-contact process and is good for flexible materials. The technique involves the use of digital cameras that register a series of images of a surface on which a randomized speckle pattern is applied (Figure 1 (1)). Within the DIC software (Figure 1 (3)), the speckle pattern is mapped to calculate the deformed shape, allowing the derivation of the deflections and strains of the investigated object (Figure 1 (2)). Using two cameras in a stereoscopic configuration allows deformation to be measured both in the plane normal to the camera and out of the plane, known as 3D DIC.

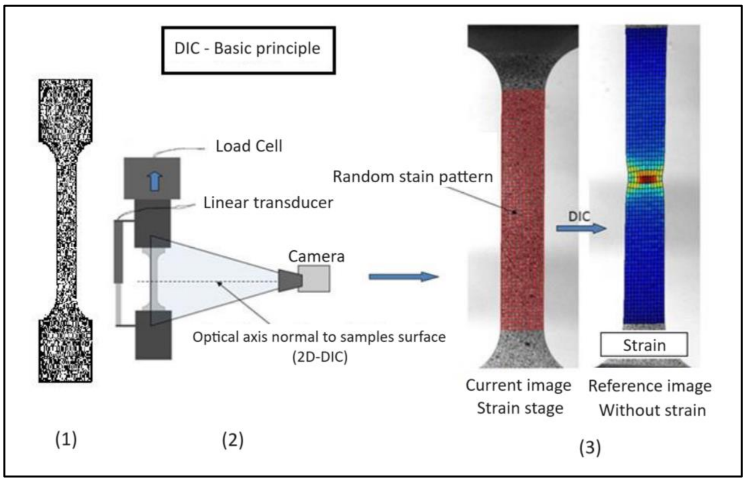


Figure 1. (1) Region standardization for tracking; (2) Displacing image capturing; (3) Gom Correlate Software Analysis.

Figura 1. (1) Região padronizada para monitoramento; (2) Captura de imagem em deslocamento; (3) Análise de Correlação pelo Software Gom.

Source: Adapted from Washington (2015).

Due to its heterogeneous and orthotropic structure, this study aimed to characterize some technological properties of *Eucalyptus grandis* wood and evaluate the use of Digital Image Correlation (DIC) to obtain the displacement and the behavior of the samples in deformation and its relationship with tension in tensile and compression tests parallel to the fibers.

MATERIALS AND METHODS

The *Eucalyptus grandis* wood used in this project was supplied by a Glued Laminated Timber (Glulam) company and comes from forest stands at Cofusa and Urufor in Uruguay, which harvests the trees at the age of 23. Once in the company, the moisture content was determined with a Marrari moisture meter, considering a density of 0.50 g/cm³, and the boards were selected according to weight to reduce uncontrolled effects. The humidity obtained varied between 11 and 12%. Pieces were then grouped according to the final sample dimensions, to facilitate processing, and sawed, generating the specimens used in the tests.

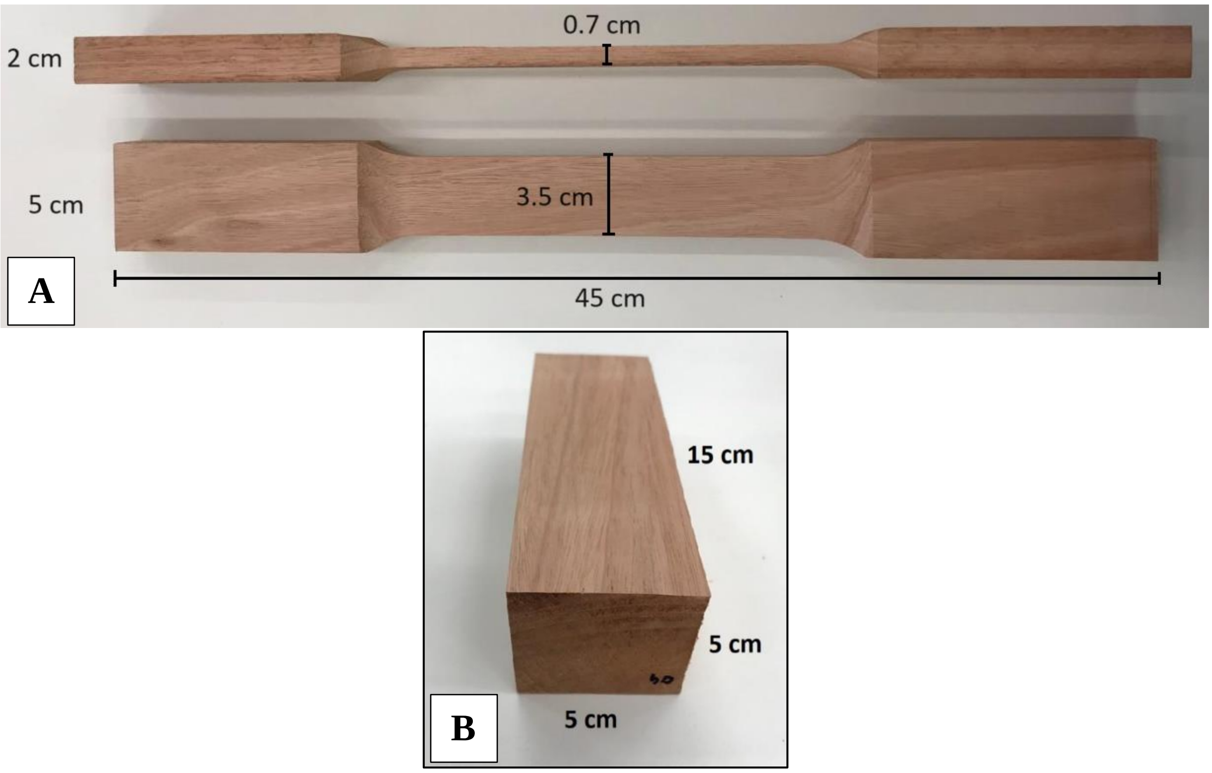
Table 1 presents the evaluated technological properties, specimen dimensions, and consulted standards.

Table 1. Tests performed, used standards, and number of samples produced.
Tabela 1. Ensaios realizados, norma utilizada e número de amostras produzidas.

Procedure	Standard	Specimen dimensions (mm)	Number of specimens
Basic density and shrinkage assessment	ASTM D 2395	20 x 30 x 50	12
Tensile parallel to the fibers test	ASTM D 4761	20 x 50 x 450	20
Compression parallel to the fibers test		50 x 50 x 150	20
Total samples			52

The procedures to determine the basic density consisted of first weighing the samples at 0% humidity and then measuring the width, thickness, and length of the saturated samples to determine the volume. Specimens were submerged in water until constant weight (with a variation of less than 0.5%) and evaluated daily. After that, samples were weighed, measured, and placed for water loss under room humidity and temperature conditions. After nine months, the specimens were dried in a forced-air circulation kiln until daily checking for constant weight. Finally, when the samples reached 0% moisture, they were weighed and measured.

The tests of tensile and compression parallel to the fibers were carried out in a universal testing machine - EMIC, DL 30000 model. For the tensile parallel to the fibers test, samples were reduced (Figure 1) to induce rupture in the reduced area and to minimize the possibility of problems, such as stress concentration near the jaws. Before machining, the stress wave velocity was measured in all specimens with a stress wave timer (Metriguard equipment) to calculate the dynamic modulus of elasticity.



REVISTA FLORESTA Engenharia Florestal
ISSN 1982-4688
Edição 54
Universidade Federal do Paraná
Setor de Ciências Agrárias

Figure 2. a. Tensile specimen parallel to the fibers with reduced central section. b. Dimensions of the compression parallel to the fiber's specimen.
Figura 2. a. Corpo de prova de tração paralela às fibras com seção central reduzida. b. Dimensões dos corpos de prova de compressão paralela.

ASTM D 7469 (2016) allows reworking samples into smaller cross-sections to minimize the effect of wood strength when evaluating finger joints. Herewith, the problems of stress concentration failure near the specimen heads are minimized. Due to the horizontal direction, only the width was changed from 5 cm to 3.5 cm. Finally, the compression parallel to the fiber of the specimens was tested.

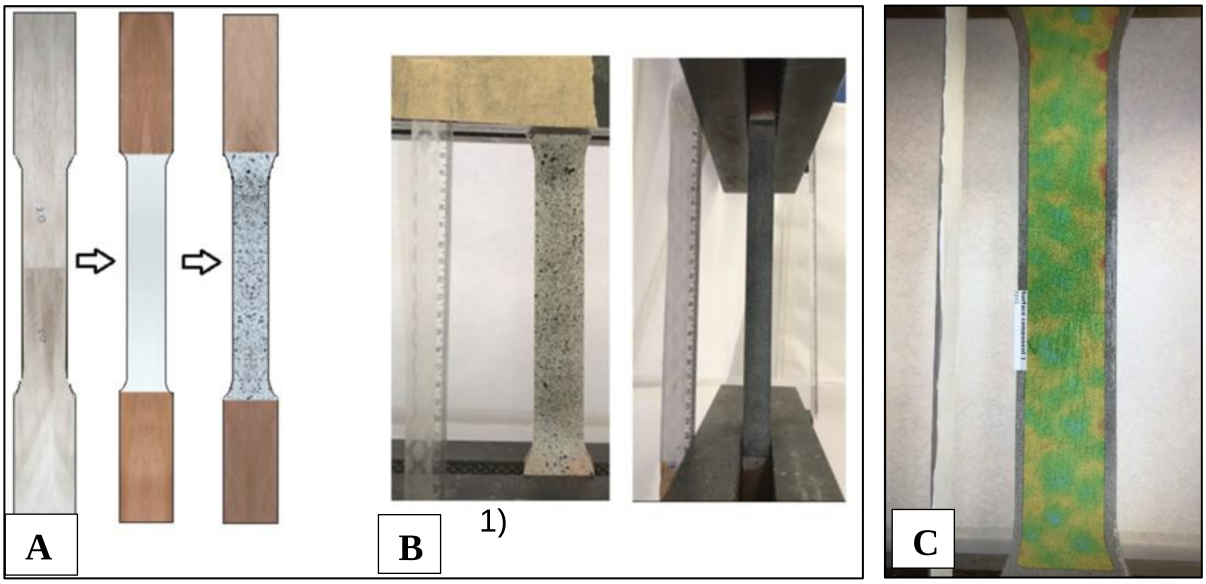


Figure 3. Preparation of the specimens for the tensile parallel to the fibers test to obtain displacement images. a) Area pattern to be analyzed; b) Image capturing: 1) width; 2) thickness; c) Displacement points assessed by the software.
Figura 3. Preparação de amostra de tração paralela às fibras para obtenção de imagens de deslocamento. a) Padronização da área a ser analisada; b) Captura das imagens: 1) largura; 2) espessura; c) Pontos de deslocamento aferidos no software.

To analyze the correlation between the stress and the strain of each sample, specimens were sprayed with black paint on a white base (Figure 3a) to obtain the displacements by DIC (Digital Image Correlation) from obtained video images and use them in data analysis and correlation software. Gom Correlate® software was used, which digitally correlates images from the fragmentation of videos into images. Each filmed second had 30 frames, that is, 30 images per second. Once the scale and surface to be analyzed were defined, the displacement of the samples in the x and y directions was obtained, enabling the calculation of Poisson's coefficients, the strain of each sample, and the longitudinal modulus of elasticity.

The strain was obtained by the ratio between the elongation of the pieces and their respective initial length.

$$\varepsilon = \frac{\delta}{L} \quad (1)$$

Where:
Ɛ = strain,
δ = elongation (final length) (mm),
L = initial length (mm).

Finally, the Modulus of Elasticity was determined from the acting stresses and the strain of the samples:

$$E = \frac{\sigma}{\varepsilon} \quad (2)$$

Wherein:
E = Modulus of Elasticity (MPa),
σ = tension (MPa),
Ɛ = strain.

RESULTS

The results of the physical and mechanical properties are shown in Table 2.

Table 2. Physical and mechanical properties of *Eucalyptus grandis* wood.
Tabela 2. Propriedades físicas e mecânicas da madeira de *Eucalyptus grandis.*

	Property (unit)	Average
Physical properties	Basic density (g/cm³)	0.497 (8.52%)
	Shrinkage	1.25
	Swelling	1.27
Mechanical properties	Compression parallel to the fibers (MPa)	53.06 (7.15%)
	Tensile parallel to the fibers (MPa)	118.50 (29.55%)
	Modulus of elasticity (MPa) - DIC	12,664.24 (10.67%)
	Modulus of elasticity (MPa) – stress wave	11,941.35 (14.79%)

Where: g/cm³ - grams per cubic centimeter; MPa – Mega Pascal; mm – millimeter; DIC – Digital Image Correlation. Subscript: coefficient of variation.

As for anisotropy, the shrinkage (1.25) and swelling (1.27) coefficients were close to 1. The average compressive strength parallel to the fibers found was 53.06 MPa, and the tensile parallel to the fibers was 118.50 MPa.

The Modulus of Elasticity (E) result of the stress wave timer (11.941,35 MPa) was similar to the one obtained by calculation from strain (12.664,24 MPa) provided by the Digital Image Correlation (*DIC*) method.

DISCUSSION

Density is a technological characteristic of wood quality and best expresses relationships with the other characteristics. It is also related to several factors such as tree age, site location, and proportion of late and early-aged wood, being used as a wood quality indicative parameter as it expresses the other characteristics. The result found (0,497 g/cm³) is similar to other studies, for instance, Lahr *et al*. (2018), Rosso *et al*. (2013), and NBR 7190 (1997), indicating that the wood is suitable for many uses, e.g., furniture and structures).

Anisotropy represents the stability of the material concerning dimensional changes due to variations in humidity. In the case of naturally anisotropic wood, the coefficient does not reach 1. However, similar results indicate few problems with warping, twisting, and other defects caused by the loss or gain of moisture. This wood is excellent for uses that do not permit high dimensional variations, such as windows, furniture, musical instruments, etc.

The compressive strength observed in this research was similar to that found by Iejavs *et al*. (2021) – 54.1 MPa – and Hein and Lima (2012) – 51.17 MPa –, and higher than that presented by the Brazilian Standard (1997) – 40.3 MPa, and Vega *et al*. (2020) - 38.2 MPa. The compressive strength parallel to the fibers is one of the most important results in the characterization of wood because it is used for classification in terms of strength class. As recommended by NBR 7190 (1997), the resistance classes aim at using wood with standardized properties, guiding the choice of material for the elaboration of structural projects. Therefore, the wood samples in this research can be classified as C40, which stands for uses where strength requirements do not exceed 40 MPa, such as in structures.

Although tensile strengths parallel to the fibers can range from 45 to 120 MPa (Green, 2001), this result (118.5 MPa) was higher than the one in most studies that assess this type of tension, as in Vega *et al*. (2020) – 55.1 MPa, and in the Brazilian Standard 7190 (1997) – 70.2 MPa. This behavior can be closely related to the orientation of the microfibril angle (MFA) of the S2 layer, which significantly influences tensile strength, stiffness, and shrinkage (Tabet and Aziz, 2013). Treacy *et al.* (2001) concluded that both longitudinal tensile strength and wood stiffness were shown to be markedly affected by MFA. According to them, the tensile strength and stiffness decrease rapidly as the MFA increases. Other factors, such as age, site location, and species, can affect the wood anatomy structure, including MFA and cell wall, interfering in wood behavior. Moreover, Boyd (1985) reports that the orientation of microfibrils in the S2 layer in angiosperms (including *Eucalyptus*) ranges from 5º to 20º. These aspects are also related to the test complexity, in which the rupture occurs by the sliding among the cells or by the rupture of cell walls, which also explains the coefficient of variation (29.55%). Furthermore, this performance indicated that the wood in this study is feasible for structural and furniture purposes, and other uses that require good tensile strength.

Moreover, other researchers noticed a similar Modulus of Elasticity (E) to the results in this study. For instance, Cademartori *et al*. (2014), based on the estimation of the *Eucalyptus grandis* modulus of elasticity through non-destructive ultrasound and stress wave techniques, concluded that both can be used to determine it. In addition, Del Menezzi *et al*. (2014), studying two non-destructive methods to estimate the mechanical properties of wood and the mass loss by heat treatments, indicated the great potential of the two techniques to evaluate material properties.

Although the Modulus of Elasticity does not inform the wood behavior, it can be inferred that higher E indicates higher strength and lower strain. Also, the lower the E, the worse the qualities for structural purposes. Comparable results were found in other studies with *Eucalyptus grandis*, as in Cadermatori *et al*. (2014) and Juizo *et al*. (2018).

The stress wave timer and DIC results and considerations observed in the literature suggest that both tools efficiently obtained the dynamic modulus of elasticity and strain, respectively. So far, DIC usually requires surface preparation with a layer of paint or powder fixed on the surface. It needs careful optimization for the specific application and optical access to the specimen (Palanca *et al*., 2016). However, the DIC technique enables the capture of full-field shape, displacement, and strain. One can measure strains across an entire surface, whereas other methods, such as strain gauge positioning, are limited by the surface available for gluing the gauge (Begonia *et al*., 2015). Also, the DIC allows strain and displacement determination in any direction and at any point, being non-contact, with high precision, wide measurement range, and good measurement stability (Zhou *et al*., 2013).

CONCLUSIONS

- As for the physical properties, the basic density was 0.497 g/cm³, and the anisotropy of shrinkage and swelling were 1.25 and 1.27, respectively, indicating good dimensional stability.
- Tensile strength presented a better behavior than that usually found in the literature. Nevertheless, in parallel compression, samples were similar to those observed in other studies.
- Regarding the parallel compression strength, the wood can be classified as C40 (NBR 7190-1997), which indicates uses where the parallel compression strength requirement is up to 40 MPa.
- All results demonstrate reliability for solid uses of the wood, such as furniture and structures.
- The Modulus of Elasticity calculated from the strain obtained by the DIC method (12,664.24 MPa) was similar to that calculated from the wave velocity of the stress wave timer (11,941.35 MPa). These results demonstrate the technical feasibility of the two methods, Digital Image Correlation and Stress Wave Timer, for obtaining displacement, strain, and modulus of elasticity data.

ACKNOWLEDGMENT

We gratefully thank UNIEDU (FUMDES) Postgraduate Program from Santa Catarina State Government.

REFERENCES

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. **NBR 7190**: Projeto de estruturas de madeira. Rio de Janeiro, 1997.

AMERICAN SOCIETY FOR TESTING AND MATERIALS **D 2395**: Standard Test Method for Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials. ASTM International, West Conshohocken, PA. 2017.

AMERICAN SOCIETY FOR TESTING AND MATERIALS **D 4761**: Standard Test Method for Mechanical Properties of Lumber and Wood-Based Structural Materials. ASTM International, West Conshohocken, PA. 2019.

BEGONIA, M. T.; DALLAS, M.; VIZCARRA, B.; JOHNSON, M. L.; THIAGARAJAN, G. Non-Contact strain measurement in the mouse forearm loading model using Digital Image Correlation (DIC). **Bone**, Australia, v. 81, p. 593–601, 2015.

Boyd, J. D. Biophysical control of microfibril orientation in plant cell walls: aquatic and terrestrial plants including trees. **Springer**, Netherlands, 210 p., 1985.

BRUNO, L. Mechanical characterization of composite materials by optical techniques: A review. **Optics and Lasers in Engineering**, United Kingdom, v. 104, p. 192-203, 2018.

CADEMARTORI, P. H. G. DE, MISSIO, A. L., GATTO, D. A., & BELTRAME, R. Prediction of the modulus of elasticity of *Eucalyptus grandis* through two nondestructive techniques. **Floresta e Ambiente**, Seropédica, v. 21, n. 3, p. 369-375, 2014.

DEL MENEZZI, C. H. S.; AMORIM, M. R. S.; COSTA, M. A.; GARCEZ, L. R. O. Evaluation of Thermally Modified Wood by Means of Stress Wave and Ultrasound Nondestructive Methods. **Materials Science**, Belarus, v. 20, n. 1, 2014.

FLORÊNCIO, G. W. L; MARTINS, F. B.; FAGUNDES, F. F. A. Climate change on Eucalyptus plantations and adaptive measures for sustainable forestry development across Brazil. **Industrial Crops and Products**, Netherlands, v. 188, Part A, 2022.

GREEN, D. W. Wood: Strength and Stiffness. **Encyclopedia of Materials: Science and Technology**. Elsevier Science Ltd.: Amsterdam, The Netherlands. p 9732-9736, 2001.

HEIN, P. R. G.; LIMA, J. T. Relationships between microfibril angle, modulus of elasticity and compressive strength in *Eucalyptus* wood. **Maderas. Ciencia y Tecnologia**, Chile, v. 14, n. 3, p. 267-274, 2012.

IEJAVS, J.; PODNIEKS, M.; UZULS, A. Some physical and mechanical properties of wood of fast-growing tree species eucalyptus (*Eucalyptus grandis*) and radiata pine (*Pinus radiata* D.Don). **Agronomy Research**, Estonia, v. 19, n. 2, p. 434-443, 2021.

JUIZO, C. G. F.; ZEN, L. R.; KLITZKE, W.; FRANÇA, M. C.; CREMONEZ, V. G.; KLITZKE, R. J. Propriedades tecnológicas da madeira de eucalipto submetida ao tratamento térmico. **Nativa**, Brazil, v. 6, n. 5, p. 537-542, 2018.

LAHR, F. A.; NOGUEIRA, M. C. J. A.; ARAUJO, V. A.; VASCONCELOS, J. S.; CHRISTOFORO, A. L. Wood utilization of *Eucalyptus grandis* in structural elements: densities and mechanical properties. **Engenharia Agrícola**, Brazil, v. 38, n. 5, p. 642-647, 2018.

LEE, S. H.; LUM, W. C.; ANTOV, P.; KRISTAK, L. Engineering wood products from *Eucalyptus* spp.: A review. **Advances in Materials Science and Engineering**, USA, v. 2022, p.1-14, 2022.

MOLLAND, A. F.; TURNOCK, S. R. Chapter 6 - Rudder experimental data. In: Marine Rudders, Hydrofoils and Control Surfaces. Book. Ed. **Butterworth-Heinemann**, United Kingdom, p. 105-296, 2022.

MYBURG, A.; GRATTAPAGLIA, D.; TUSKAN, G. *et al.* The genome of *Eucalyptus grandis*. **Nature**, United Kingdom, v. 510, p. 356–362, 2014.

PALANCA, M.; TOZZI, G.; CRISTOFOLINI, L. The use of digital image corelation in the biomechanical area: a reviw. **International Biomechanics**, London, v. 3, n. 1, p. 1-21, 2016.

ROSSO, S.; MUNIZ, G. I. B.; MATOS, J. L. M.; HASELEIN, C. R.; HEIN, P. R. G.; LOPES, M. C. Estimate of the density of *Eucalyptus grandis* W. Hill ex Maiden using near infrared spectroscopy. **Cerne**, Brazil, v. 19, n. 4, 2013.

TABET, A.; AZIZ, F. A. Cellulose microfibril angle in wood and its dynamic mechanical significance. In: VAN DE VEN, T. G. M. **Cellulose - Fundamental Aspects**. InTechOpen, London, 2013, 378 p.

TREACY, M.; DHUBHA´IN, A.N.; EVERTSEN, J. The influence of microfibril angle on modulus of elasticity and modulus of rupture in four provenances of Irish grown sitka spruce (*Picea sitchensis* (Bong.) Carr). **Journal of the Institute of Wood Science**, London, v. 15, p. 211-220, 2001.

VEGA, A.; BAÑO, V.; CARDOSO, A. Experimental and numerical evaluation of the structural performance of Uruguayan *Eucalyptus grandis* finger joint. **European Journal of Wood and Wood Products**, Germany, v. 78, p. 923-932, 2020.

WASHINGTON, P. **Digital Image Correlation**. Available in: https://slideplayer.com/slide/7008770/. 2015.

ZHANG, Y.; WANG, X. Geographical spatial distribution and productivity dynamic change of eucalyptus plantations in China. **Science Rep**, United Kingdom, v. 11, p. 19764, 2021.

ZHOU, J. W.; LIU, D. H.; SHAO, L. Y.; WANG, Z. L. Application of Digital Image Correlation to measurement of packaging material mechanical properties. **Hindawi Publishing Corporation**, London, v. 2013, p. 1-8, 2013.