Influence of Physical and Chemical Components on the Physical-Mechanical Properties of Ten Brazilian Wood Species

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Wood offers a good combination of high strength and low density, but its complete characterization takes a long time. This study aimed to correlate apparent density, chemical component and porosity parameters with the physical and mechanical properties of the wood as an alternative route to reduce the time spent proposing equations to estimate each mechanical property. Ten tropical wood species were characterized in accordance with Brazilian Standards and chemical components were determined by the Klason method, and the porosity using mercury intrusion. Multivariate regression models were applied to the results of each species to find the relationships. Good results were obtained, such as the coefficient of determination and the analysis of variance, which indicated that the equations for 10 out of the 16 properties are significant. Therefore, the apparent density, chemical component and porosity parameters used reduce the time intervals much lower than the time test stipulated by the standard.

Keywords: Physical and mechanical properties, density, porosity, cellulose, hemicellulose, lignin, ash.

1. Introduction

Found in everyday life, mainly in civil, rural and housing construction, in paper, furniture, packaging and musical instrument industries, among other sectors, wood is the most well-known and used biological/organic material, which consists of a large quantity of substances that are used as raw materials in almost all fields of technology. Wood combines high strength, low density and low costs and due to this is widely used for structural applications. In North America (USA and Canada), wood is found in most residential houses and commercial buildings. Even though they are built out of brick or stone walls, they have elements with wooden structures. As a result, housing construction consumes (about) a third of the wood-based products in the USA. In the European market, wood has been more widely used recently in construction, and other areas, due to increasing availability of knowledge, as well as public policies that support the use of wood products, resulting in lower energy consumption and reduced CO₂ emissions compared to other materials (concrete, brick or steel).

In Brazil, wood is one of the most traditional materials used in construction. It is used for building components, such as roofing structures, floors, window frames, and in walkways and bridges. According to the National Forest Information System (NFIS), in 2014 the total production of sawn lumber in Brazil was approximately 11 million m³. Wood consumption and wood products have grown gradually in recent years in Brazil, mainly due to financing from governmental institutions (SI NAT Directive N005/2011). The Brazilian standard - NBR 7190 is the main guiding principle for projects and studies on wood, which establishes the general conditions that must be followed in the design, execution, and control of current wooden structures, such as bridges, pontoons, roofs, floors and structures. This standard presents six properties required for dimensioning structural elements for 43 species of hardwood (dicotyledonous angiosperms) and softwood (gymnosperms or conifers).

It is estimated that in the Amazon Forest, there are approximately 12,655 species, many of which are being cataloged and characterized, which greatly restricts their potential for applications. Thus, it is very important to characterize new species.

Wood extracted in Brazil can be used in several sectors, but often it has been sold under generic names and, thus, without any characterization, which can negatively influence its performance in service.

Although it is important to know the physical and mechanical properties of wood, they are obtained from running a long series of tests and using various kinds of equipment, available only in large research centers, which makes it difficult to determine them. According to Ter Steege et al., it would take at least 300 years to catalog and characterize all the tree species in the Amazon. For each species to be studied, 14 mechanical tests are performed, described in the Brazilian standard, which requires 12 specimens for each test, totaling 168 specimens.
In addition, the time required to perform the tests is approximately three weeks for each species. It should also be taken into account that in order to prepare the specimens, there is a need to remove a batch containing several logs and send it to the research center where tests will be carried out. On the other hand, in order to know the chemical composition of a wood species, analysis requires approximately 15g of ground or particulate material from the wood. The estimated time is three days to carry out the analysis. Mechanical tests need a larger amount of material to be removed, making transportation more difficult and costly, in addition to needing more time for its performance.

The Brazilian standard\cite{1} shows relationships for estimating strength and stiffness from other wood properties, however there are no equations that associate the physical and mechanical properties of wood with its chemical components\cite{12,15}. For example, Dias et al.\cite{16} considered the results obtained for forty tropical wood species in Brazil and obtained equations from which dependence among apparent density (12% moisture content) and strength and stiffness properties can be observed. However, the results of the regression models in property estimation did not provide good adjustments as the values for the coefficient of determination ($R^2$) were, in most cases, below 0.80. The authors recommend inserting new parameters to improve the mechanical property estimates.

Fujimoto et. al.\cite{17} evaluated the possibility of estimating mechanical properties using Near Infrared (NIR) spectroscopy. From samples of wood native to northern Japan (Larix gmelinii var. japonica and Larix kaempferi), the authors carried out mechanical and physical tests to determine the modulus of elasticity, modulus of rupture, compression strength parallel to the grain, dynamic modulus of elasticity of the air-dried wood and density following the Japanese standard JIS Z 2101.

As previously mentioned, wood extracted in Brazil offers possibilities to be used in various different sectors, however it was often commercialized without any characterization, which shows there is a great need for this study. Thus, this study aimed to use Brazilian wood species that have not yet been fully characterized and are already being commercialized.

Considering the limitations inherent to the studies reported in the literature to date, this study aimed to correlate apparent density, chemical component and porosity parameters with physical and mechanical properties of wood, using multivariable regression models.

2. Materials and Methods

Table 1 shows the wood species studied with the respective images of the samples. The wood was collected from a company called Madeireira César Ind. e Com. Madeiras Nobres, located in Brotaç, São Paulo, Brazil. The specimens were cut, removing them from regions that were at least 30 cm away from the ends of the piece on each side.

It should be mentioned that 12 pieces of each species were needed for the tests. For this purpose, the company used 6 trees from each species to remove the pieces, two from Macajai, Roraima (RR), two from Cláudia, Mato Grosso (MT) and two from Maués, Amazonas (AM). Each tree was first cut above the diameter at breast height, approximately 1.3m from the base, and the second cut was made 3m from the first, therefore 2 pieces were removed from each tree, totaling 12 pieces. Sampling was performed from wood obtained from axial and radial cuts.

In order to ensure that the study was fully representative, species were chosen that are grouped into the five resistance classes indicated by the Brazilian standard\cite{1} for dicotyledons (two species for each class), that is, it covers a wide range of densities. Thus, there are two species that

| Common Name | Scientific name       | Sample Image |
|-------------|-----------------------|--------------|
| Tatajuba    | Bagasse guianensis    |              |
| Roxinho     | Peltogyne recifensis  |              |
| Cambará     | Erisma uncinatum      |              |
| Cedroarana  | Cedrelinga catenaformis |            |
| Cumaru      | Dipteryx odorata      |              |
| Cupíuba     | Goupia glaba          |              |
| Caixeta     | Simarouba versicolor  |              |
| Cedro       | Cedrela fissilis      |              |
| Sucupira    | Diplotropis purpúrea  |              |
| Cajueiro    | Anacardium sp.        |              |
would be within each of the five classes of dicotyledons (C20, C30, C40, C50 and C60).

According to Silva et al.\textsuperscript{18}, the wood strength and stiffness are influenced by moisture content under the fiber saturation point, and consequently the specimens were submitted to an air conditioning room to reach the equilibrium moisture content, 12%.

The physical and mechanical properties of the samples were evaluated using the Brazilian standard\textsuperscript{11}, respectively. Table 2 lists the name of 17 parameters and their initials, respectively, to make it easier to distinguish between the physical and mechanical properties of the wood. Twelve wood specimens were used for the study to obtain the physical and mechanical properties, resulting in 2040 samples for the experimental tests.

The chemical compositions evaluated consisted of cellulose, hemicellulose, lignin, extractives and ash contents. The sample preparation process followed the precepts of the TAPPI 264 CM-97 standard\textsuperscript{19}, and the entire chemical analysis was performed in duplicate.

First, a Willey SL-31 knife mill was used to grind the material that was sieved using a 30-mesh size, thus obtaining 15 grams of sample per species of wood evaluated. The samples were made using filter paper containing half the material of each sample (7.5g) to perform the duplicate, which were subjected to the extraction process using organo-soluble solvents in a Soxhlet extractor. There were two steps. The first one consisted of using 1:1 (v/v) parts of cyclohexane/ethanol, for 8 hours of using 1:1 (v/v) parts of cyclohexane/ethanol, for 8 hours to remove the organo-soluble extractives; and the second used boiling water for the same period. The materials were dried at 100 °C for 30 min in a kiln.

To determine the Lignin content of the material, the Klason method modified by NREL\textsuperscript{20} was used. This method was divided into two steps. The first step consisted of preparing the an initial dry mass of 0.8 g of ground material (42 mesh) with 12 ml of 72% sulfuric acid added to an autoclavable borosilicate tube of 500 ml, which reacted under constant agitation for a period of 2 hours. The second step consists of adding 450 ml of distilled water to the tube (3% sulfuric acid concentration), which was then closed and placed in the autoclave at a temperature of 120 °C at a pressure bar of 2.0.

After the autoclave was depressurized, the tubes were cooled using ice and water to room temperature (25 °C). From this method, a residual solid and a solution were obtained, which were then filtered through a sintered glass funnel of known mass, using the retained material to calculate the insoluble lignin and filtered liquid to determine the soluble lignin. The sum of both the insoluble lignin and soluble lignin consists of the total lignin value of the material.

The insoluble lignin was obtained from samples of the retained material from the filtration. The retained material was oven dried for 24 hours and transferred to a desiccator to produce a constant mass. This dry mass is the insoluble lignin content. After that, the insoluble lignin content is correct for inorganic content. It should be mentioned that the presence of insoluble lignin ash should be considered, determined from the calcination of the residue obtained from the Klason method. Calcination consisted of exposing the retained material to 525 °C for 4 hours with a heating ramp of 100 °C.h\textsuperscript{-1}. The insoluble lignin (IL-%) was calculated by the following Equation 1:

\[
IL = \frac{m_L - m_C}{m_S} \times 100
\]

where \(m_L\) is the lignin dry mass (g), \(m_C\) is the ash mass (g) and \(m_S\) is the dry sample mass (g).

The soluble lignin (SL) was obtained from liquid samples (7.5 ml) that were filtered and analyzed by Ultraviolet - UV-Vis Spectrophotometric method modified by NREL\textsuperscript{20} using a quartz cell of 10mm optical path, due to the lignin strongly absorbing the ultraviolet light characteristic by the aromatic characteristic. Spectrophotometry measurements were carried out in the region of 280 nm and 215 nm wavelengths, corresponding to ultraviolet light. A dilution factor of 5 was used, that is, 1 ml of the filtrate was diluted 4 times in the sulfuric acid solution in the same proportions. The soluble lignin is calculated by the following Equation 2:

\[
SL = \frac{(4.53 \times A_{215} - A_{280}) \times \nu f \times DF}{3 \times m_b}
\]

where \(A_{215}\) is the absorbance at 215nm, \(A_{280}\) is the absorbance at 280nm, \(\nu f\) is the measured volume of the acid solution (Klason reaction), DF is the dilution factor (dilution of the solution in which the spectrum was recorded) and \(m_b\) is the biomass dry mass used for the Klason reaction.

The cellulose and hemicelluloses contents were obtained by high performance liquid chromatography from the quantification of the sugars (and derivatives) contained in the hydrolyzate resulting from the determination of Lignin Klason. The quantified sugars and derivatives were:
cellulose, glucose, xylose, arabinose, acetic acid, furfural and hydroxymethylfurufural. In the chromatographic analyses (SHIMADZU–CR 7A), the chromatographic analysis of furfural and hydroxymethylfurufural is performed first.

The solution containing the hydrolysate obtained (Klason method) was filtered using a 0.45 μm membrane. The resulting solution was injected into a Hewlett-Packard RP18 (C18) column with a 1:8 (v:v) acetonitrile/water solution eluent, containing 1% acetic acid and a flow set at 0.8 mL min⁻¹ at room temperature, using a UV–254nm detector (SPD-10A-modified). Then, the hydrolysate solution was filtered in membrane (SEP PAK C18 - Waters) to retain the soluble lignin and other degradation products. The second part is the chromatographic analysis for sugar determination, that the same solution containing the hydrolysate was filtered with a membrane of 0.45μm. The resulting solution was injected into the chromatograph through an Aminex HPX-87H column (300 × 7.8nm BIO-RAD) with an eluent 0.005 M H₂SO₄ and flow set at 0.6 mL/min and temperature at 45 °C, using a refractive index detector (SHIMADZU R10-6A).

In accordance with Marabezi², using this methodology converts the masses of glucose, cellulbiose and hydroxymethylfurufural into cellulose, through corresponding calibration lines and applying the respective conversion factors: 0.90, 0.5 and 1.7; and the masses of xylose, arabinose and furfural and acetyl groups in hemicelluloses through the same procedure, with a factor of 0.88 for xylose and arabinose, 1.29 for furfural and 0.72 for conversion of acetic acid to acetyl.

The ash content of the wood species was determined by the residue content resulting from the complete burning of the samples, that is, the percentage of inorganic material in the sample, according to the TAPPI T211 om-02 standard (modified). The crushed and dried sample (1g) is added to a porcelain crucible of known mass. This sample was maintained under 525 °C/4 h in a muffle furnace.

The porosity was determined by mercury intrusion in double tests for each wood species, in the Micromeritics Poresizer (model 9320) with 200 MPa pressure, mercury with a surface tension of 0.494 g cm⁻², density of 13.533 g/ml, contact angle of advance and retreat of 130° and equilibrium time between low and high pressure of 10 seconds. The properties analyzed were the total pore area (TPA), apparent density (AD) and average pore diameter (APD). First, specimens with nominal dimensions of a 2 cm high prism and 1 cm² base were prepared, and then they were placed in a furnace with air circulation at 50 °C for a period of 24 hours for the drying process.

The statistical analysis for the estimation of the physical (TRR, TTR) and mechanical (f₁₀₀, f₉₀, f₆₀, f₄₅, f₃₃, E₀₀, E₉₀, E₆₀, E₄₅, E₃₃, f₁₀₀, f₉₀, f₆₀, f₄₅, W, f₉₀, E₆₀, E₄₅, E₃₃) properties (Table 2) as a function of wood constituents (He, Cel, IL, SL, Ash, Ext), porosity (Por) and apparent density (ρap) for all 10 wood species were obtained with the regression models (Equation 5) based on analysis of variance (ANOVA) F test (p < 0.05), using Minitab® version 16 software.

\[
Y = \alpha_0 + \alpha_1 \cdot \text{He} + \alpha_2 \cdot \text{Cel} + \alpha_3 \cdot \text{IL} + \alpha_4 \cdot \text{SL} + \\
\alpha_5 \cdot \text{Ash} + \alpha_6 \cdot \text{Ext} + \alpha_7 \cdot \text{Por} + \alpha_8 \cdot \rho_{ap}
\]

where Y denotes the estimated physical and mechanical properties and α are the coefficients adjusted by the least squares method. The quality of the adjustments was obtained according to the coefficient of determination (R²). From the ANOVA assumptions of the regression models, p-value below the significance level (p-value < 0.05) implies that the model or its terms are considered significant in the property estimation, and not significant otherwise (p-value>0.05).

Having obtained 12 values of the physical and mechanical properties for each of the ten-wood species, six samples were randomly selected and the average of each group was calculated, resulting in two average values per property and wood species, which were associated with the two sample values of the chemical components and porosity values.

3. Results

Figure 1 shows the results of the three groups for porosity: the highest values (cedroarana, caixeta, cedro and cajetauro), the medim values (cambara, sucupira, cupiúba and cumaru) and the low ones (tatajuba and roxinho); for apparent density: cumaru, tatajuba, roxinho and cupiúba are in the highest values group, sucupira and cambara in the medium one and the lowest are cedroarana, cedro, cajetauro and caixeta.

Total radial retraction (TRR) can also be divided into three groups: 5% to 6% – caixeta, cambara and sucupira; 4% to 5% – cajetauro, cumaru, cupiúba and tatajuba; 3% to 4% – cedroarana, cedro and roxinho. As with the results for TTR, they can be divided into the following groups: more than 8% – caixeta and sucupira; between 8% and 6% – cajetauro, cambara, cupiúba and roxinho; less than 6% – cedroarana, cedro, cumaru and tatajuba.

Therefore, the ρap values obtained were coherent with values of annexe E of the Brazilian standard¹¹, thus the tatajuba and roxinho wood species present the highest density and

![Figure 1](image-url)
lowest porosity. The cedro, cedroarana, caixeta and cajueiro wood species present the lower density and higher porosity. Regarding the TRR both in the radial and tangential directions, the cedro and cedroarana wood presented lower values (high stability) than the cambará, sucupira and caixeta wood with lower dimensional stability.

It can be seen that the $f_{\text{c90}}$ values (Figure 2) can be almost classified into pairs: cumaru and tatajuba (more than 80 MPa), roxinho and sucupira (60 – 70 MPa), cupiúba, cedroarana, cajueiro and cambara (40 – 50 MPa) and caixeta and cedro (30 – 40 MPa). There are four groups for $f_{\text{c90}}$: cumaru and roxinho (100 – 120 MPa), cajueiro and tatajuba (80 – 100 MPa), cedro, cupiúba and sucupira (60 – 80 MPa) and cedroarana, caixeta and cambara (40 – 60 MPa).

Figure 2c shows that the wood can be classified by: near 4 MPa – roxinho and tatajuba; near 3 MPa – cedroarana, cedro, cupiúba, sucupira and cumaru; near 2 MPa – caixeta, cajueiro and cambara. On the order hand, Figure 2d seems to have a division in the middle: the different types of wood on the right (cumaru, cupiúba, roxinho, sucupira and tatajuba) have values between 15 and 20 MPa and the woods from on the left (cedroarana, caixeta, cajueiro, cambara and cedro) have values between 5 and 10 MPa.

The coefficient of variation values are similar to the values obtained by other authors. As can be observed, the $f_{\text{c90}}$, $f_{\text{c90}}$, $f_{\text{c90}}$ and $f_{\text{c90}}$ values obtained were coherent with the values in Annex E of the Brazilian standard for cedro, cumaru, cupiúba, sucupira and tatajuba. The $f_{\text{c90}}$ value was significant for the 85 MPa tatajuba wood, as it is very close to 79.5 MPa of annex E of the Brazilian standard. The slight differences are common concerning different batches of the species, according to other studies.

Roxinho wood stands out among the three species as it has a higher resistance for the four properties in Figure 2. Moreover, the denser woods, such as tatajuba and cumaru also showed higher strengths. This is associated to the fact that the density has a strong influence on mechanical properties, as confirmed by other authors.

The variation of the mean values of $f_{\text{c90}}$ (Figure 3) is a property in which the results were diffused, therefore the ascending order for the results is caixeta, cambara, cajueiro, cedroarana, cedro, cupiúba, sucupira, cumaru, roxinho and tatajuba.

On the other hand, Figure 3b shows that the $f_{\text{t90}}$ values are mainly between 60 and 80 MPa (cajueiro, cambara, cedro, and cupiúba), but the wood from cedroarana and caixeta have values between 40 and 60 MPa. Furthermore, the $f_{\text{c90}}$ values for sucupira, tatajuba, roxinho and cumaru are near 90, 110, 140 and 160 MPa, respectively.

The strength in perpendicular compression to the fiber ($f_{\text{c90}}$), shown in Figure 3c, looks like the values for $f_{\text{c90}}$ because of the heterogeneity. Therefore, the ascending order for the results is caixeta, cajueiro, cedro, cedroarana, cambara, sucupira, cupiúba, tatajuba, roxinho and cumaru.

For the $f_{\text{c90}}$ and $f_{\text{t90}}$, the results are similar as cumaru, roxinho and tatajuba have the highest values, cupiúba and sucupira are in the middle and cedroarana, cedro, caixeta, cajueiro and cambara are the lowest values. Moreover, there is a density relationship that influences these properties (Figure 3) due to the species with the highest resistance values which were the most dense, similarly obtained in other studies.

The graph shown in Figure 4a indicates that this property has dispersed values for the wood, therefore the ascending order for the results is caixeta, cedro, cedroarana, cajueiro, cupiúba, cambara, sucupira, tatajuba, roxinho and cumaru. The $E_{\text{c90}}$ property of the woods from cedroarana, caixeta, cajueiro, cambara and cedro are between 400 and 600 MPa, the wood from cupiúba, roxinho, sucupira and tatajuba are
between 800 and 1000 MPa. The only one that is more than 1200 MPa is cumaru.

The longitudinal modulus of elasticity values in $E_{\text{c0}}$ were coherent with the values according to Annex E of the Brazilian standard. For example, tatajuba has a value of 19,583 MPa according to the standard and, in the present study present a 19,761 MPa was obtained. Such variations are compatible with the values determined by Komariah et al.

The wood from cedroarana, cajueiro, cambara, cupiuba and sucupira have almost the same value for $E_{\text{c0}}$ which is about 12,500 MPa. However, caixeta and cedro have values for this property under 10,000 MPa and roxinho, tatajuba and cumaru are near 20,000 MPa. This was a similar case in Figure 4d; the only difference is that the value for EM to cumaru is almost 25,000 MPa.

Regarding the chemistry components of these different types of wood (Figure 5), it can be observed that the ascending orders for the results of each component are: cellulose – cambara, sucupira, cupiuba, tatajuba, cedro, cumaru, roxinho, cedroarana, caixeta and cajueiro; hemicellulose – cedro, cupiuba, caixeta, cedroarana, cumaru, cambara, tatajuba, sucupira, roxinho and cajueiro; insoluble lignin – cajueiro, caixeta, cedroarana, cedro, roxinho, tatajuba, cupiuba, cambara, cumaru and sucupira; soluble lignin – cedro, tatajuba, caixeta, cambara, cumaru, sucupira, roxinho, cedroarana and cajueiro; ash – cupiuba, sucupira, tatajuba, cumaru, caixeta, roxinho, cajueiro, cedroarana, cedro and cambara; extractives – tatajuba, caixeta, cedroarana, cajueiro, cedro, cumara, roxinho, sucupira, cumaru and cupiuba.

The amounts of chemical constituents are in accordance with the values obtained for the 40% to 50% of cellulose; 20% to 30% of hemicellulose; 10% to 36% of total lignin; 2% to 15% of extractives; and 0.1% to 5.0% of ash. The highest concentrations of cellulose and hemicellulose were found in cajueiro wood, which, consequently, presented smaller amounts of total lignin. This fact can be related to the wood aspects, because the cajueiro wood has some similarity with the Pinus sp. with regard to density, workability and susceptibility to microorganism attacks.

The opposite occurred with sucupira, which had the highest concentrations of total lignin and the lowest concentrations of cellulose and hemicellulose. As lignin promotes stiffness, protection against microorganism attacks and sustainability of fibers and vases, it appears that the wood has high natural durability.

Although some studies presented in the literature address the topic of tropical wood extractives, such as those by Santana & Okino allows some comparisons with the results obtained here. It is noteworthy that the types of wood that presented the highest percentages of extractives were Cumaru (approximately 13%) and Cupiuba (approximately 12%), possibly related to the fact that they are the wood species that present the most striking odors among those studied. Immediately after that was Sucupira, with about 10%, which although had no noticeable taste or odor or more intense color, had good durability and resistance to fungi and termites, probably due to the action of the substances contained in the extractives together with the highest concentration of lignin.

Zau et al. show that the chemical, physical and mechanical properties of agglomerated panels produced with cumaru residue, resulted in 18.32% ± 1.24 of organic extractive content. On the other hand, Santana and Okino found a higher ash content for Cumaru, approximately 13% and Cupiuba (approximately 12%), possibly related to the fact that they are the wood species that present the most striking odors among those studied. Immediately after that was Sucupira, with about 10%, which although had no noticeable taste or odor or more intense color, had good durability and resistance to fungi and termites, probably due to the action of the substances contained in the extractives together with the highest concentration of lignin.

Using the same TAPPI T211 standard om-02, Zau et al. found a higher ash content for Cumaru, 1.72% ± 0.15. On the other hand, Silva et al. used the ASTM 1102-56 standard and the ash content value was 0.3%. They point out that the extractive and ash contents may vary due to some factors, such as soil characteristics.

Table 3 shows the regression models and the respective coefficient of determination in the estimation of wood properties, and Table 4 shows the numerical intervals of the independent variables of the obtained adjustments. Moreover, in Table 3, the terms of the models considered significant by ANOVA were duly underlined. The significance of the models was designated as SM, and the models can be significant (S) or not (NS).
Intervals of confidence

Table 3. Results of multivariable regression models applied for the ten wood species.

| TRR = a_0 + a_1 Por + a_2 He + a_3 Cel + a_4 IL + a_5 SL + a_6 Ash + a_7 Ext + a_8 Por + a_9, p_m | R² (%) | F |
|---------------------------------------------------------------|--------|---|
| 1.00423 – 0.0598497 He + 0.161199 Cel + 0.211325 IL + 0.219873 SL + 0.54172 Ash + 0.0585386 Ext – 10.3552 Por – 7.89255 p_m | 55.70 | NS |
| 13.8972 – 0.17602 He + 0.57368 Cel + 0.489992 IL + 1.0962 SL + 0.434925 Ash + 0.178019 Ext – 19.693 Por – 16.0401 p_m | 86.64 | NS |
| \( f_1 = -151.933 + 1.24366 He + 1.66847 Cel + 1.42686 IL - 4.5862 SL - 3.30513 Ash - 2.15895 Ext + 25.1747 Por + 105.625 p_m \) | 99.69 | S |
| \( f_2 = -120.557 + 7.80428 He + 0.653931 Cel + 3.2484 IL - 25.9725 SL + 4.64536 Ash + 2.29757 Ext + 103.628 Por + 155.129 p_m \) | 91.94 | S |
| \( f_3 = 14.3938 + 0.0987351 He - 0.200044 Cel + 0.14628 IL + 0.61742 SL - 2.80478 Ash - 0.154106 Ext + 3.02166 Por + 3.68662 p_m \) | 70.31 | NS |
| \( f_4 = 45.0526 + 0.603093 Cel - 0.946233 IL - 0.658137 SL - 10.977 Ash + 0.398132 Ext + 21.459 Por + 30.3891 p_m \) | 96.97 | S |
| \( f_5 = 0.0270621 + 0.0205575 Cel - 0.00059906 SL - 0.139357 SL - 0.394968 Ash - 0.0264954 Ext + 0.200725 Por + 1.08872 p_m \) | 87.99 | S |
| \( f_6 = -674.814 + 1.34682 Cel + 6.38663 IL - 25.2675 SL + 70.657 Ash + 4.15845 Ext - 174.338 Por + 42.228 p_m \) | 98.99 | S |
| \( E_1 = -4513.1 + 787.744 He + 431.099 Cel + 205.938 SL - 1500.98 SL + 6479.37 Ash - 103.257 Ext + 296.523 Por + 26237.9 p_m \) | 99.28 | S |
| \( E_2 = -29114.8 + 299.478 He + 365.822 Cel + 72.7035 SL - 1222.82 SL + 3475.32 Ash - 210.424 Ext + 5030.14 Por + 3.68662 p_m \) | 99.75 | S |
| \( E_3 = -4888.63 + 83.9516 Cel + 781.078 SL + 225.201 IL - 1100.24 SL + 6694.12 Ash + 0.149.961 Ext - 2691.52 Por + 24469.8 p_m \) | 99.52 | S |
| \( f_7 = -105.501 + 0.289965 Cel + 3.02692 Cel + 1.14436 IL - 8.96208 SL - 18.4164 Ash + 0.104555 Ext + 71.7444 Por + 107.667 p_m \) | 95.22 | NS |
| \( f_8 = -472.083 - 1.25237 He + 9.12182 Cel + 4.57334 SL - 17.4205 SL + 30.7517 Ash + 2.20399 Ext + 140.338 Por + 71.3795 p_m \) | 97.85 | NS |
| \( W = -126.674 + 4.894 He - 0.254245 Cel + 1.89813 IL - 5.37704 SL - 20.5034 Ash + 0.855499 Ext + 36.6718 Por - 10.2846 p_m \) | 99.89 | NS |
| \( f_9 = -4.48889 - 0.490513 He + 0.0743078 Cel - 0.172129 IL + 0.112121 SL + 2.21648 Ash + 0.0408142 Ext - 3.29173 Por + 23.712 p_m \) | 97.87 | S |
| \( E_{10} = -1424.82 + 14.22 He + 12.4742 Cel + 6.53891 IL - 72.6691 SL - 107.596 Ash + 10.8421 Ext + 468.118 Por + 1345.81 p_m \) | 99.89 | S |

Table 4. Intervals of the values in the independent variables utilized in the regression models.

| Properties | Intervals of confidence |
|------------|------------------------|
| He (%)     | [12.54; 18.14]         |
| Cel (%)    | [38.85; 50.82]         |
| IL (%)     | [31.63; 43.63]         |
| SL (%)     | [0.24; 1.85]           |
| Ci (%)     | [0.24; 0.86]           |
| Ext (%)    | [6.17; 13.04]          |
| Por        | [0.30; 0.73]           |
| \( p_m (g/cm^3) \) | [0.41; 1.10] |

It can be observed for the obtained equations, as results, that it presents a good coefficient of determination \( R^2 > 90\% \), except in the three cases, as justified: the first and second cases are the TRR and TTR. As a justification, it should be noted that the variability of these properties is directly related to anatomical aspects of the wood, such as the arrangement of fibers, vessels and medullar rays. In addition, the presence of stalks in the connections between vessel elements may affect the rates of fluid percolation inside the wood, directly interfering with the retraction phenomenon. These aspects are not captured in the statistical analysis because they are not controllable factors, and such effects are not considered. The conclusions of other authors corroborate with this argument\[13,47,48\].

The third case is the resistance of the wood to the normal traction to the fibers. As a justification, it should be noted that this property is strongly influenced by the anatomical characteristics of the wood, in particular, the percentage of amorphous zones at the microfibrillar level and small localized imperfections that, leading to fragile discontinuities, accentuate the character of the typical rupture in this type of request.

It can be observed according to the NBR ABNT 7190/97, in its article 7.2.3, the safety of structural wooden parts in relation to the limit states must not depend on the normal tensile strength to the fibers, for the reasons stated. Moreover, the mentioned normative document determines that when the normal tensile stresses to the fibers reach significant values in structural situations, devices (generally metallic) must be used that behave as restrictions to the consequences of these stresses. It is clear that these aspects are not captured in the statistical analysis, only with the parameters addressed here. The conclusions of other studies corroborate this argument\[13,47,47\].
Notice that six properties \( (E_{\text{c0}}, W_{\text{c0}}, E_{\text{t0}}, E_{\text{c90}}, E_{\text{t90}}, f_{\text{c90}}}) \) (see Table 3) have a coefficient of determination \( (R^2) \) above 99%, which indicates a high level of reliability. The compression strength to parallel fiber \( (f_{\text{c90}}) \) presents a higher adjustment of \( R^2 \) = 99.69%. It is very interesting that this property is the reference, according to the Brazilian standard\(^1\), for the classification of many species not known in the five classes of resistances recommended in this document.

From the analysis of variance, Table 3 shows that the estimation models for the TTR, TTR, \( f_{\text{c0}}, f_{\text{c90}}, f_{\text{t0}}, f_{\text{t90}} \) and \( W \) properties, even with \( R^2 \) values ranging from 57.70 to 99.89%, were still considered non-significant, and this implies that variations in the dependent variables are not able to explain the variations in the estimated properties, which reveals the small accuracy of the models in the estimation of these properties.

For the ten other properties, the regression models were considered significant by ANOVA, and in all these adjustments, only the apparent density \( (\rho_{\text{ap}}) \) and porosity \( (\text{Por}) \) were considered significant, implying that variations in \( \text{He}, \text{Cel}, \text{IL}, \text{SL}, \text{Ci} \) and \( \text{Ext} \) properties do not explain the variations in \( f_{\text{c0}}, f_{\text{c90}}, f_{\text{t0}}, f_{\text{t90}}, E_{\text{c0}}, E_{\text{c90}}, E_{\text{t0}}, E_{\text{t90}}, \text{Por}, \text{and} \ E_{\text{c0}} \) which enables us to conclude that the accuracy of the models \( (R^2) \) is mostly explained by the apparent density and porosity.

Observing that caixeta, tatajuba and roxinho have the highest apparent density values \( (\rho_{\text{ap}} > 0.90 \text{ g/cm}^3) \), and that 83% of the native forest types of wood have density values lower than 0.90 g/cm\(^3\), such specimens were excluded for the analysis of \( f_{\text{c0}} \) via the regression model as \( f_{\text{c90}} \) is the reference property considered by the Brazilian standard\(^1\) of wood structures. Combining the two types of lignin \( (\text{IL} + \text{SL}; \text{total lignin}) \) and excluding the three species with the highest apparent density values, the regression model for \( f_{\text{c0}} \) estimation resulted in: \( f_{\text{c0}} = 29 + 1.65 \cdot \text{Cel} - 0.87 \cdot \text{He} - 19.7 \cdot \text{Ci} - 3.500 \cdot \text{Ext} + 24.2 \cdot \text{Por} + 88.7 \cdot \text{ap} + 0.01 \cdot (\text{IL} + \text{SL}), \) with \( R^2 = 97.22\% \).

It should be noted that under these conditions, besides porosity and apparent density, the sum of lignins was also considered significant by ANOVA, indicating that the consideration of specific ranges of apparent density may result in different conclusions from the regression models obtained, and that should be the focus of new research.

It is important to note that the time to obtain the parameters used in the regression models for the wood species is approximately two days, and if such parameters are known, the equations allow the rapid estimation of the various physical and mechanical properties evaluated. This time interval is much lower than that required to promote the complete characterization of the species (destructive testing in the laboratory), usually around three weeks per species, as argued by other authors\(^{32,54}\).

### 4. Discussion

Several authors from different areas of wood engineering observed that the apparent density is a physical property of wood correlated to a strong influence on mechanical properties. For example: as demonstrated by Burdzik and Nkwera\(^2\) in the study on transverse vibration tests to predict stiffness and strength properties of full size \( \text{Eucalyptus grandis} \), Logsdon et al.\(^8\) in the characterization of cambara’s wood; Icimoto et al.\(^9\) researched the influence of lamellar thickness on strength and stiffness of glued laminated timber beams of \( \text{Pinus oocarpa} \); Rocco Lahr et al.\(^3\) tried to discover the influence of moisture on the strength and stiffness properties of the wood and carried out the complete characterization of the \( \text{Vatairea} \) sp. wood species.

Cavalheiro et al.\(^4\) tried to find a relationship between apparent density and basic density, as estimators of other physical properties of wood (longitudinal, radial, tangential, volumetric retraction and anisotropy coefficient). To do this, they used coniferous species \( (\text{Pinus sp. and Pinus oocarpa}) \) and dicotyledons \( (\text{Paricá (Schizolobium amazonicum)}, \text{Jatobá (Hymenaea sp.) and Lyptus}^6) \) and the linear, exponential, logarithmic and geometric regression models. Lyptus\(^8\) wood is extracted from renewable forests from planted trees developed with the crossing of species.

After tests using analysis of variance (ANOVA) of the regression models, considered at the confidence level \( (\alpha) \) 5%, it was concluded that it was impossible to establish significant relationships to allow the adoption of density as an estimator of other physical properties of wood, due to the fact that they did not find a pattern of behavior both between density and retractions, as well as density and anisotropy coefficient.

In the same research area, Christoforo et al.\(^6\) proposed to correlate the apparent density with physical properties of retraction (radial, longitudinal and volumetric) and coefficient of anisotropy. They used the linear, quadratic, cubic and exponential models, and a species of each of the resistance class established in accordance with the Brazilian standard\(^1\) for the Cedro Doce – \( \text{Cedrela sp} \) (resistance class C20), Canafistula – \( \text{Peltophorum dubium}. \) (C30), \( \text{Angelim Araroba – Vataireopsis araroba} \) (C40), \( \text{Mandioqueira – Qualea sp} \) (C50) and \( \text{Angelim Vermelho – Dinizia excelsa} \) (C60). They obtained a value below 0.70 \( (R^2) \) and indicated that more studies are needed with more species to obtain a value above 0.70 \( (R^2) \).

Almeida et al.\(^3\) evaluated the correlation between apparent density and compressive strength parallel to the fiber \( (f_{\text{c0}}) \), establishing an important base for the classification of wood strength as a parameter included in the Brazilian standard\(^1\). Therefore, wood species such as canafistula \( (\text{Cassia farruginea}) \) \( \text{Angelim araroba (Vataireopsis araroba)} \) and Castle \( (\text{Gossypiospermum sp}) \) were utilized, adopting the regression models adopted with no linear, exponential, logarithmic and geometric parameters. However, the regression models produced by Almeida et al.\(^3\) did not provide good estimates for the compressive strength parallel to the fibers, since the best coefficient of determination \( (R^2) \) was obtained for Canafistula, \( \text{Angelim araroba} \) and Castle at 48.57%, 14.89% and 52.84%, respectively. Moreover, considering the three species together provided a coefficient of determination of 17.88% (as best estimate).

In this study, in addition to the apparent density property, the porosity parameter and chemical components were used together, which made it possible to obtain more accurate statistical models to correlate with physical and mechanical properties, resulting in the coefficient of determination values \( (R^2) \) above 95%.

Furthermore, it is known that \( R^2 \) is not sufficient to judge the significance of the model. The significance
of the model can be assessed by analysis of variance. The progressive inclusion of terms in the models implied proportional increases in the value of the coefficient of determination of all models, implying the significance of each term. However, the analysis of variance by ANOVA was performed, in which 10 properties have significant estimates \( f_{c0}, f_{c90}, f_{v0}, f_{v90}, E_{c0}, E_{c90}, E_{v0}, E_{v90} \) and only the properties of density and porosity influence significantly in the properties.

Unfortunately, the lack of information in the literature also momentarily impedes the testing of the obtained equations as the values of the chemical properties of the species in the literature differ from the range of values of the results of this study with extrapolation. Therefore, further analysis of the accuracy and validation of the equations may be the subject of future studies.

In addition, due to the limitations inherent in the studies reported in the literature to date, which have a correlation between density, porosity and chemical components, the pioneering nature of this study offers the possibility of continuing research on this topic. In this case, ten wood species were studied, but the number of species can be increased to enhance the reliability of the proposed equations. Moreover, the mechanical properties were observed for the wood presenting moisture content of 12%. This approach can be used to relate the percentages of chemical constituents of the wood with the physical-mechanical properties determined in the condition of moisture equal to or higher than the saturation point of the fibers.

5. Conclusions

From the results of the study it can be concluded that:

1. It is possible to establish reliable equations, from the variables: apparent density, porosity, percentage of cellulose, hemicellulose, insoluble lignin, soluble lignin, extractives and ash of tropical Brazilian wood species, to estimate the set of physical and mechanical properties studied in this research. Therefore, further analysis of the accuracy and validation of equations might be necessary.

2. The accuracy of the estimates provided by the equations was observed by the high values of the coefficient of determination \( R^2 \) indicating that the equations for 10 out of the 16 properties are significant.

3. The parameters to estimate the set of properties studied in this research (of the order of two days per species) can be obtained in time intervals much lower than those necessary to promote the complete characterization of the species through the tests stipulated by the Brazilian standard (usually around three weeks per species).

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