

Investigation of the Fiber Saturation Point of Tropical Brazilian Wood Species

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The fiber saturation point (FSP) is an important parameter of wood material, related to dimensional stability and variations of mechanical performance. This paper investigated the FSP values of 15 tropical Brazilian wood species covering all strength classes of the Brazilian standard code. An additional goal was to estimate FSP value based on the wood's apparent density. The FSP values were determined by measuring the wood specimen dimensions during moisture content reduction from the saturated state. Wood densities at 0% and 12% moisture contents and basic density were determined according to the Brazilian standard code. The average FSP for all wood species was 21.6% moisture content. Among density values, good correlations were observed, and a multivariate regression model for FSP estimation based on wood densities presented a coefficient of determination equal to 13.07%. There was no correlation between FSP and wood densities, suggesting that this parameter is almost constant regardless of the wood species.

Keywords: FSP; Regression model; Tropical wood

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INTRODUCTION

There are many wood species grown in Brazil (Ter Steege *et al.* 2016; Almeida *et al.* 2017), and many such species can be used as raw material for several sectors such as the furniture industry and civil construction (Calil Junior *et al.* 2003; Passarini and Hernández 2016). For better use of wood resources, it is important to characterize the physical and mechanical properties of wood (Almeida *et al.* 2016). The Brazilian standard code ABNT NBR 7190/1997 “Design of Timber Structures” (ABNT 1997) prescribes the procedures for both structural design and characterization of wood properties, as well as strength classes of wood based on the strength in compression parallel to the grain.

The fiber saturation point (FSP) is a well-established moisture content value (Babiak and Kúdela 1995; Jankowska and Kozakiewicz 2016; Zelinka *et al.* 2016). Two other indirect methods use experimental sorption isotherms and the Nelson sorption isotherm model.

The FSP is the equilibrium moisture content at a given temperature when air relative humidity is equal to 1 (100%). Below the FSP there is an increase in strength and stiffness of wood as it undergoes a drying process (Passarini *et al.* 2014). In addition, shrinkage of wood samples can be observed with this drying, which can cause dimensional stability problems (Galvão and Jankowsky 1985; Ye *et al.* 2006; Almeida *et al.* 2017; Tarmian 2017). Above this value of moisture content, there are no more dimensional variations (the wood sample has already achieved the green volume), and mechanical properties remain the same (Kollmann and Côte 1968; Murata *et al.* 2013; Zauer *et al.* 2014).

There is no consensus regarding the FSP value (Berry and Roderick 2005). Still, this parameter is important for better use of wood materials without variation in mechanical properties and higher dimensional stability. For Kollmann and Côte (1968) and Durlo and Marchiori (1992), among other authors, the average FSP is 28% moisture content. For Cisternas (1994), this parameter is 30% moisture content. The Brazilian standard code prescribes that the FSP value is about 25% moisture content. This parameter is related to the anatomical characteristics of wood (Kokutse *et al.* 2010).

Density is one of the most important physical properties of wood. This property can be easily determined, being the ratio between the weight and volume of a wood sample. Wood is a hygroscopic material and its density varies with the moisture content. Therefore it is necessary to specify the moisture content of the wood sample whose density has been determined (Almeida *et al.* 2016, 2017).

Based on that dependence of wood density and the moisture content of the sample, the basic density is beneficial for comparisons, because its value is always the same for the same sample, regardless of the moisture content of the sample. Basic density is the ratio between the weight of a dried sample and the green volume of the same sample, resulting in the smallest possible value for the density of this wood sample (Almeida *et al.* 2016; Jankowska and Kozakiewicz 2016).

This research investigated the fiber saturation point of tropical Brazilian wood species covering the five strength classes of the Brazilian standard code, providing more accurate results and trying to estimate this parameter based on the wood density using regression models.

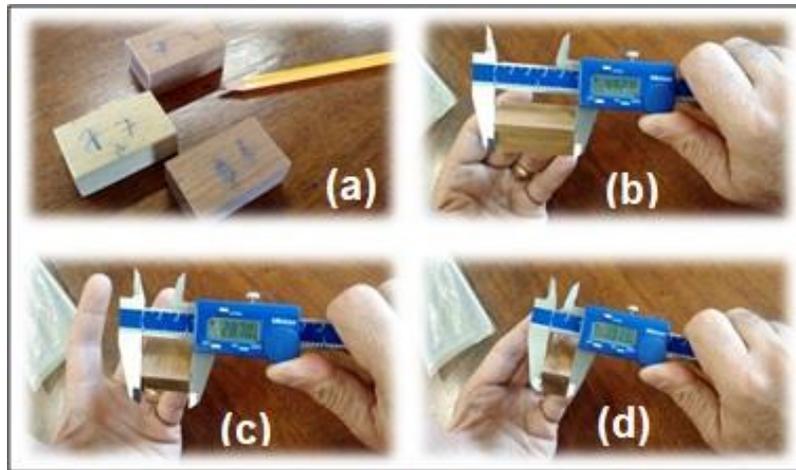
EXPERIMENTAL

The five strength classes of the Brazilian standard code were considered here for investigating the fiber saturation point of tropical Brazilian wood species. Three wood species were considered for each strength class. Table 1 presents the 15 wood species considered in this study.

According to Annex B of the Brazilian standard code “Determination of wood properties for design of structures,” (ABNT 1997), the following wood properties were determined: Densities at 0% and 12% moisture contents (d_0 and d_{12} , respectively) and basic density (d_{bas}). In addition, the FSP values were determined by measuring wood specimen dimensions during moisture content reduction from the saturated state (drying process). FSP is the moisture content value when the wood starts to shrink with the drying process. Figure 1 illustrates these measurements. Twelve repetitions were performed for each wood species considered totaling 180 determinations for each variable.

Table 1. Tropical Brazilian Wood Species Considered – ABNT NBR 7190/1997

Strength Class	Wood Species
D20	<i>Pachira quinata</i>
	<i>Cedrela</i> sp.
	<i>Erisma</i> sp.
D30	<i>Cassia ferruginea</i>
	<i>Calophyllum</i> sp.
	<i>Ocotea odorifera</i>
D40	<i>Vataieropsis araroba</i>
	<i>Goupia glabra</i>
	<i>Vatairea fusca</i>
D50	<i>Qualea albiflora</i>
	<i>Gossypiospermun praecox</i>
	<i>Bagassa guianensis</i>
D60	<i>Dinizia excelsa</i>
	<i>Dipteryx</i> sp.
	<i>Mezilaurus itauba</i>

**Fig. 1.** Process of specimen measurement – Specimens (a); Length measurement (b); Width measurement (c); Thickness measurement (d)

Statistical analysis was performed using R-version 3.5.1 software (R Core Team, Vienna, Austria). A summary of results in general and for the five strength classes was made. Boxplots of dry density (density at 0% moisture content) and FSP moisture content were built for evaluating the behavior of these results for different strength classes. Scatter plots of variables were observed trying to determine a relation between wood densities and FSP (as well as the Pearson correlation matrix). Linear regression models between wood densities were determined, and a multivariate regression model was fitted for FSP estimation based on the wood densities.

Analyses of variance was carried out to test the representativeness of these models at a 5% significance level. A P-value of less than 5% shows acceptable model representativeness. The coefficient of determination R^2 makes it possible to measure the interaction between dependent and independent variables.

RESULTS AND DISCUSSION

By performing the wood densities determinations as well as the FSP measurement for the 15 wood species (covering the five classes), it was possible to summarize these results. Tables 2 to 7 presents summaries of results for all wood species in general, and for each strength class of the Brazilian standard code, respectively. The coefficient of variation is denoted by CV.

Table 2. Summary of General Results

General	d_{12} (g/cm ³)	d_0 (g/cm ³)	d_{bas} (g/cm ³)	FSP (%)
Mean	0.83	0.81	0.64	21.60
CV (%)	23.12	24.70	23.50	16.70
Minimum	0.44	0.40	0.37	15.68
Maximum	1.25	1.24	0.98	36.04
Count	180.00	180.00	180.00	180.00

Table 3. Summary of D20 Strength Class Results

D20	d_{12} (g/cm ³)	d_0 (g/cm ³)	d_{bas} (g/cm ³)	FSP (%)
Mean	0.56	0.53	0.45	21.89
CV (%)	15.93	16.43	13.06	19.30
Minimum	0.44	0.40	0.37	15.68
Maximum	0.74	0.69	0.58	36.00
Count	36.00	36.00	36.00	36.00

Table 4. Summary of D30 Strength Class Results

D30	d_{12} (g/cm ³)	d_0 (g/cm ³)	d_{bas} (g/cm ³)	FSP (%)
Mean	0.91	0.90	0.66	20.91
CV (%)	14.62	15.65	7.88	13.64
Minimum	0.74	0.70	0.58	15.90
Maximum	1.15	1.15	0.78	25.87
Count	36.00	36.00	36.00	36.00

Table 5. Summary of D40 Strength Class Results

D40	d_{12} (g/cm ³)	d_0 (g/cm ³)	d_{bas} (g/cm ³)	FSP (%)
Mean	0.77	0.75	0.57	19.86
CV (%)	10.15	11.12	15.06	15.08
Minimum	0.60	0.56	0.41	15.94
Maximum	0.88	0.87	0.75	27.51
Count	36.00	36.00	36.00	36.00

Table 6. Summary of D50 Strength Class Results

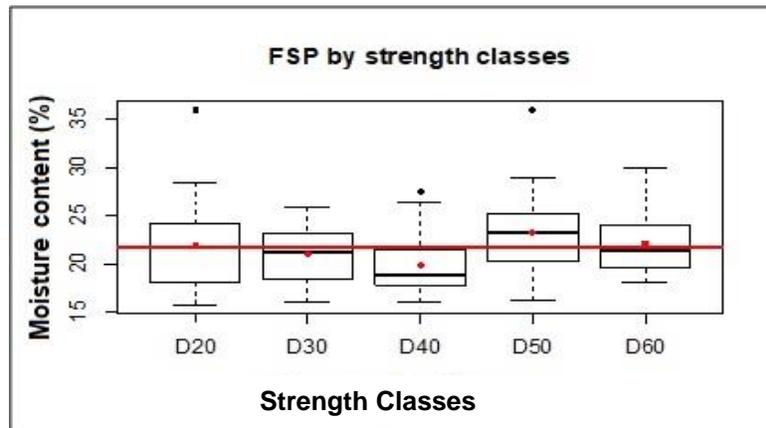
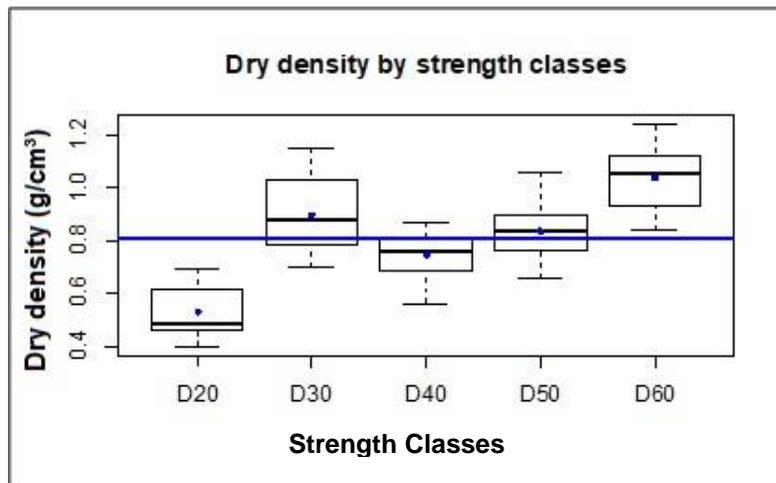
D50	d_{12} (g/cm ³)	d_0 (g/cm ³)	d_{bas} (g/cm ³)	FSP (%)
Mean	0.86	0.83	0.67	23.25
CV (%)	10.27	11.46	8.24	16.88
Minimum	0.69	0.66	0.56	16.03
Maximum	1.06	1.06	0.77	36.04
Count	36.00	36.00	36.00	36.00

Table 7. Summary of D60 Strength Class Results

D60	d_{12} (g/cm ³)	d_b (g/cm ³)	d_{bas} (g/cm ³)	FSP (%)
Mean	1.04	1.03	0.86	22.10
CV (%)	11.23	11.62	8.54	13.91
Minimum	0.86	0.84	0.74	17.91
Maximum	1.25	1.24	0.98	29.84
Count	36.00	36.00	36.00	36.00

The highest values for wood densities were found for a D60 wood species. On the other hand, the smallest values of wood densities resulted from a D20 wood species. The highest FSP was 36.04% for a sample of the D50 wood species, and the lowest FSP value was 15.68% for an example of the D20 wood species.

In Figs. 2 and 3, boxplots of FSP and dry density values are shown for all strength classes. The horizontal lines represent the overall average value (covering all fifteen wood species), and the average value by strength class is represented by solid points (red and blue for FSP and dry density, respectively).

**Fig. 2.** Boxplots of FSP results for each strength class**Fig. 3.** Boxplots of Dry density values for each strength class

Figures 2 and 3 make it possible to observe a tendency of increase of wood density with the increasing of the strength class (that is based on the strength in compression parallel to grain), but FSP values seem not to change so much with strength class variation. It is important to highlight that the D30 wood species presented high-density values (Fig. 3), which seems to be related to anatomical characteristics of wood (grain direction, for example).

Scatterplots and Pearson correlation were carried out to investigate the interaction among the variables. Figure 4 shows the scatterplots for densities and FSP in pairs, and Table 8 presents the Pearson correlation coefficients for each pair that has been plotted.

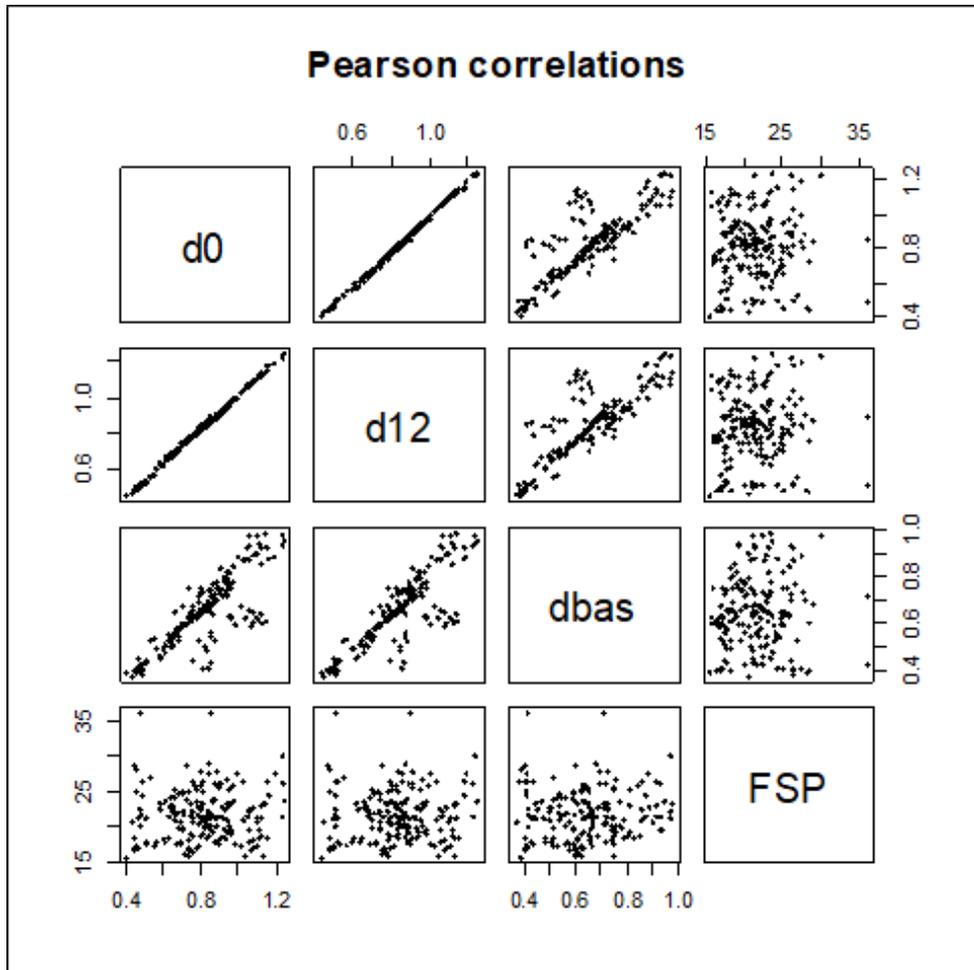


Fig. 4. Scatterplots of dry density values for each strength class

Table 8. Matrix of Pearson Correlation

Variables	d_0	d_{12}	d_{bas}	FSP
d_0	1	0.9986	0.8347	0.0155
d_{12}	0.9986	1	0.8354	0.0245
d_{bas}	0.8347	0.8354	1	0.0862
FSP	0.0155	0.0245	0.0862	1

Based on Fig. 4 and the Pearson correlation coefficients shown in Table 8, it is possible to observe that there was no correlation between FSP values and wood densities

($r \leq 0.0862$). On the other hand, a high correlation between wood density values was observed, and Table 9 presents linear regression models fitted by the ordinary least square method and tested by Analysis of Variance (ANOVA).

Table 9. Matrix of Pearson Correlation

Independent	Dependent	Intercept	Slope	R ²	P-value
d_{12}	d_0	-0.0539	1.0396	0.9971	0.0000
d_{bas}	d_{12}	0.14769	1.06224	0.6962	0.0000
d_{bas}	d_0	0.09916	1.10499	0.6951	0.0000

As shown in Table 9, all three linear models were significant (P-value < 0.05). The linear regression model for d_{12} and d_0 variables presented the highest P-value being R² 99.71%. The lowest coefficient of determination was 69.51% for d_{bas} and d_0 variables.

A multivariate regression model was performed to find a relation between wood densities and FSP, making it easier for its determination. This model had the following independent variables: d_{12} , d_0 , d_{bas} , $d_{12} \times d_0$, $d_{12} \times d_{bas}$, $d_0 \times d_{bas}$, and $d_{12} \times d_0 \times d_{bas}$. Table 10 shows the estimated coefficients for this model.

Table 10. Multivariate Regression Model for FSP Determination Based on Wood Density Values

Coefficients	Estimated value	P-value	Model's P-value	R ² (Adj.)
Intercept	26.7400	0.1196	0.0000	0.1307
d_{12}	-139.4300	0.2205		
d_0	206.4800	0.0644		
d_{bas}	-79.2900	0.0576		
$d_{12} \times d_0$	-75.9300	<u>0.0023</u>		
$d_{12} \times d_{bas}$	401.6100	<u>0.0301</u>		
$d_0 \times d_{bas}$	-349.9300	<u>0.0424</u>		
$d_{12} \times d_0 \times d_{bas}$	30.6200	0.4365		

ANOVA at a 5% significance level was performed for investigating the representativeness of the multivariate regression model resulting P-value less than 0.05, which leads us to accept the model representativeness. But, on the other hand, the coefficient of determination was 13.07%, and only $d_{12} \times d_0$, $d_{12} \times d_{bas}$, and $d_0 \times d_{bas}$ were the significative independent variables of the model (underlined P-values).

The results of the Pearson correlation matrix and the multivariate regression model suggest that the FSP does not depend on the wood density, being a constant parameter related to the anatomical characteristics of wood. The average value and the coefficient of variation of FSP for the fifteen tropical Brazilian wood species considered were 21.6% and 16.70%, respectively, being lower than the moisture content value provided for the literature.

CONCLUSIONS

1. The values of fiber saturation point do not vary with different strength classes of wood in compliance with the Brazilian standard code; In addition, the average fiber saturation point for fifteen tropical Brazilian wood species was at 21.6% moisture.

2. There is no correlation between fiber saturation point and wood densities; the highest coefficient of correlation was 0.0862 for FSP ~ d_{bas} (fiber saturation point as a function of basic density).
3. The investigation of the Pearson correlation between densities at 0% and 12% moisture and basic density provided coefficients of correlation greater than 0.80, the highest value being between densities at 0% and 12% moisture.
4. Linear regression models among wood densities were significant, resulting in coefficients of determination equal to 99.71%, 69.62%, and 69.51%, for $d_0 \sim d_{12}$, $d_{12} \sim d_{bas}$, and $d_0 \sim d_{bas}$, respectively.
5. The multivariate regression model for FSP estimation by the wood densities was significant; the coefficient of determination was equal to 13.07%, but only the independent variables $d_{12} \times d_0$, $d_{12} \times d_{bas}$, and $d_0 \times d_{bas}$ were significant.
6. The FSP is not well correlated with wood densities, as well as the strength classes of wood, leading us to conclude that this parameter is almost constant regardless of the physical properties of wood.

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