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ORIGINAL

Wood density estimation using the sclerometric method

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Abstract The density of wood is an important property that is required when developing timber designs. Wood density is conventionally determined in laboratory using the relationship between the mass and volume of standard specimens. Techniques that produce small perforations in the tested samples have been developed to determine this physical property. In the field of non-destructive testing using the ultrasonic techniques, the density is also required to generate the stiffness matrix, in addition to wave propagation velocity. This study proposes using the non-destructive sclerometric method to estimate the density of wood. Three tropical wood species with different densities were selected to establish constitutive relationships between density and the sclerometric indexes: cedar (*Cedrela* spp), garapa (*Apuleia leiocarpa*) and cumaru (*Dipteryx odorata*). For the sclerometric analysis, 0.08 m × 0.20 m × 0.30 m prismatic specimens were used. Using statistical analysis, the sclerometric indexes for all three anatomical directions of the wood were determined. The correlations indicate that sclerometry has great potential as a non-destructive method to estimate wood density.

1 Introduction

Wood density is an important property for several applications, such as timber design, paper and furniture industries, and wood transportation. Density is also important for determining the elastic constants of wood, which are related to the wave propagation velocity of ultrasonic waves and to density by the Christoffel equations (Bucur 2006, *apud* Bucur 1988).

Wood density is conventionally determined using the relationship between the mass and volume of standard specimens. This procedure has been adopted by the Brazilian Standard NBR 7190 (ABNT NBR 7190 1997) to obtain the basic and apparent densities of wood. According to the Wood Handbook (Forest Products Laboratory 2010), wood density depends on the width of the walls of the fibres and on the portion of voids that are occupied by vessels and parenchyma. Unlike other structural materials such as steel or concrete, the density of wood is not constant due to the considerable variety of wood species.

Several alternative techniques have been developed to determine wood density without the need to extract specimens. These techniques relate density to the resistance of wood to penetration or drilling. Moura and Santiago (1991), Louzada et al. (2005) and Shijun et al. (2012) determined wood density by means of the pylodin. Wu et al. (2010) used pylodin to evaluate the density of eucalyptus clones and affirmed that the equipment is efficient to estimate wood properties but not accurate enough for measuring properties. Resistographs were used by Isik and Li (2003) to determine the density along the radii of living trees as well as by Gouvêa et al. (2011) and Couto et al. (2013) to determine the basic wood density. Isik and Li (2003) and Gouvêa et al. (2011) concluded that the resistograph is more appropriate for estimating wood density than the pilodyn method. Although they are considered to be non-destructive, these techniques form small perforations in the tested samples.

Sclerometry is a non-destructive test method that is used when inspecting concrete structures. By using a rebound

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hammer a coefficient is measured that represents the elastic and damping characteristics of the concrete (Szilágyi et al. 2011). By means of this rebound coefficient correlations can be established to estimate the compressive strength of the concrete that is dependent on the characteristics inherent in the material. The technique utilises the relationship between the energy applied by a spring-mass device and the recovered energy (ABNT NBR 7584 2012).

Soriano et al. (2011a) used the sclerometric method on specimens sawn from a single log of *Eucalyptus saligna* to evaluate the correlation between the sclerometric index and the compression normal and parallel to the fibres. In a different study on sawn specimens from three different *E. saligna* logs, Soriano et al. (2011b) evaluated the sclerometric impact results with respect to the anatomical directions of the wood and concluded that the properties in the directions longitudinal and normal to the fibres (radial and tangential) can be distinguished when working with a single species. However, the radial and tangential directions were not distinguished.

The objective of this study was to demonstrate that the sclerometric technique can be used to estimate wood density based on the correlations between the density and the sclerometric indexes for three species of tropical wood.

2 Materials and methods

2.1 Materials

Three species of hardwood with different densities were selected for testing. All three are commonly used as structural elements in civil construction. Based on Brazilian Wood data at 15 % moisture content (IPT 1989), the species cumaru (*Dipteryx odorata*), garapa (*Apuleia leiocarpa*) and cedar (*Cedrela odorata*) were selected having densities of 1090, 830 and 530 kg m^{-3}, respectively.

The procedure for the complete characterization of the physical and mechanical properties of wood according to the Brazilian standard NBR 7190 (ABNT NBR 7190 1997) requires a minimum number of 12 specimens. According to this recommendation, for each species 12 boards sawn from the mature wood portion of heartwood were selected. Each of the boards had a transverse section measuring 0.08 m × 0.20 m and was divided into two groups: non-stabilised (*NS*) and stabilised (*S*). To form group NS, 0.4 m was cut from the tip of each board, and a 0.3-m-long prismatic specimen was extracted. The moisture content was preserved. For group S, 0.3-m-long prismatic specimens were extracted from the parts of the boards that had already been stabilised by drying processes. The cumaru species, which had an initial moisture content of 12.4 % (which is below fibre saturation point), underwent natural drying in a ventilated and protected environment (room located in the laboratory).

The garapa and cedar boards, which had moisture contents of 47.5 and 78.8 %, respectively (above fibre saturation point), were stabilised using industrial drying processes. A drying program with moisture and temperature control was followed for the pieces having reached the moisture content close to 12 %, thus providing homogeneous moisture within each species. After the drying process, these pieces were maintained in a naturally ventilated building for 3 months, to provide the moisture equilibrium with the environment.

2.2 Sclerometric tests

The application points for the sclerometric impacts were marked on each surface of the prisms and were 25 mm apart. Nine points were marked on the central regions of each tangential surface, and five points were marked on the transverse and radial surfaces (Fig. 1). Therefore, 18 impacts were applied to the radial direction and 10 impacts were applied in the tangential and longitudinal directions on each prism.

The sclerometric impacts were applied using a digital instrument (Digital Silver Schmidt BN, PROCEQ, Switzerland) as shown in Fig. 2 that operates with impact energy of 2.207 J, a steel plunger diameter of 0.015 m and a spherical tip radius of 0.025 m. To prevent specimen movement during the sclerometric test, Soriano et al. (2011a) suggested holding the piece in a hydraulic press. For this purpose, the authors suggested a pressure calculated of 15 % of the compressive stress perpendicular to the grain, assuring the elastic behavior of the material.

The sclerometric indexes (SI) for each specimen were calculated as the average of all of the sclerometric impacts obtained in each anatomical direction of the wood. The

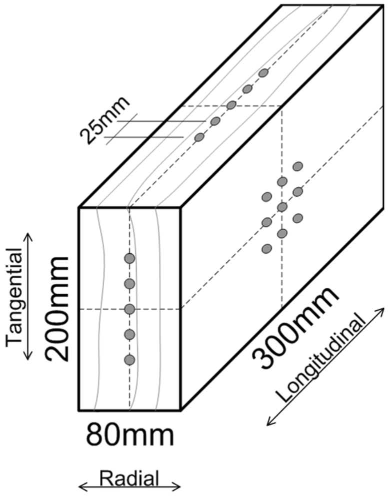

Fig. 1 Locations of points for the sclerometry tests according to the anatomical directions

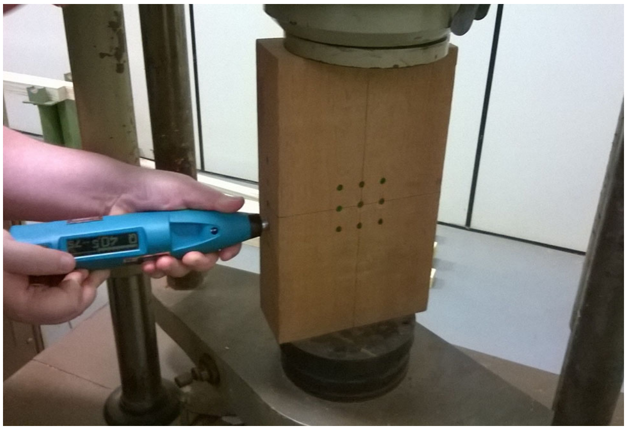

Fig. 2 Fixed prism of wood and application of sclerometric impacts

sclerometric impact value corresponds to the percentage of energy that is returned to the device, so it is a dimensionless value.

2.3 Determining density and moisture content

Density and moisture content were determined after completion of the sclerometric tests. To determine the moisture content, a 0.02 m × 0.03 m × 0.05 m specimen was extracted from each prism in compliance with the Brazilian standard NBR 7190 (ABNT NBR 7190 1997). The specimens were dried in a kiln at 103 ± 2 °C. The water mass was then obtained from the difference between the initial and oven dry mass.

3 Results and discussion

The average apparent density and moisture content of each species are shown in Table 1. The garapa and cedar specimens, which had initial moisture contents of 47.5 and 78.8 %, respectively, had significant decreases in density and moisture content upon stabilisation. In the condition of wood stabilised by the method described, the moisture content was uniform within each species.

The average values of the sclerometric indexes for each anatomical direction and the moisture contents are shown in Tables 2, 3 and 4. The results show that the sclerometric indexes increase with increasing density. More of the energy is absorbed in the lower density species, which leads to lower sclerometric index values.

For each of the three species, the tangential direction has the highest average sclerometric index, and longitudinal direction has the lowest index (Tables 2, 3 and 4). This result is consistent with a previous study on a single species of wood (Soriano et al. 2011a). As found by Holmberg (2000) in his evaluation of the influence of the fibre angles on the Brinell hardness, this behaviour can be explained by material densification due to flexure of the cell walls. Therefore, a higher energy response occurs when force is applied normal to the fibres. When force is applied parallel to the fibres, deformation occurs in the cell walls, which adjust themselves in the lumens and absorb more energy.

The data were organised by anatomical direction, and normality tests for statistical analyses using skewness and kurtosis were performed using the Minitab 16 Statistical Software. The least significant difference (LSD) Tukey test was used to determine the average values of the sclerometric indexes at a 95 % confidence level for each anatomical direction of the wood. These values are shown in Tables 2, 3 and 4.

The statistical results indicate that the sclerometric indexes of the three species were different. Except for the low density wood (cedar) in the longitudinal direction, the method did not detect variations in the moisture content of the samples (groups NS and S). This statistical difference observed only for the longitudinal direction of cedar is probably due to the effects caused by the high moisture content (NS group, with 78.8 %) on the impact damping, as well as the crushing of cell walls.

In general, the results shown in Tables 2, 3 and 4 indicate that sclerometry is not significantly affected by variations in moisture content. According to the Wood Handbook (Forest Products Laboratory 2010), some mechanical properties of wood, such as compression and tension parallel to the grain, are strongly affected by reduction of the moisture content below fiber saturation

Table 1 Densities and moisture contents of the three species

Species	Moisture condition	ρ (kg m^{-3})[a]	CV (%)[b]	MC (%)[c]	CV (%)[b]
Cumaru	Non-stabilised	1070	6.4	12.8	9.4
	Stabilised	1060	5.5	8.5	12.9
Garapa	Non-stabilised	1048	13.1	47.5	37.5
	Stabilised	828	3.8	17.0	20.7
Cedar	Non-stabilised	746	3.1	78.8	6.5
	Stabilised	534	4.8	24.9	7.5

[a] Apparent density

[b] Coefficient of variation

[c] Moisture content

point. On the other hand, the resistance to compression and tension perpendicular to the grain are less intensely affected by variations in moisture content.

Table 2 Average values of sclerometric indexes (SI), corresponding to 120 impacts in the longitudinal direction

Species	Moisture condition	NI[a]	SI[b] (mean)	CV (%)[c]	Tukey[d]
Cumaru	Stabilised	120	37.8	6.54	A
Cumaru	Non-stabilised	120	35.3	14.34	A
Garapa	Non-stabilised	120	30.5	7.72	B
Garapa	Stabilised	120	28.5	7.10	B
Cedar	Stabilised	120	17.0	17.58	C
Cedar	Non-stabilised	120	11.2	15.74	D

[a] Number of impacts applied to 12 prismatic specimen

[b] Sclerometer indexes that represent the average of sclerometric impacts

[c] Coefficient of variation (%)

[d] Based on the LSD Tukey test with a 5.0 % margin of error, there is no statistically significant difference between the values denoted by the same letter

Because the sclerometric method cannot distinguish between the moisture contents, the effects of the different moisture contents were ignored, and the data from both groups (NS and S) were combined to generate the correlations. Thus, 24 sclerometric index values were assumed per species for each anatomical direction. However, for the results of the cedar in the longitudinal direction, in which the groups (NS and S) were differentiated, only the values of the stabilised group were considered. During data normality analysis, the garapa species had an *outlier* in the radial direction, which was excluded to ensure data normality. The statistical analysis by skewness and kurtosis (Table 5) shows that all of the $Z_{skewness}$ and $Z_{kurtosis}$ values are between ±1.96, which ensures data normality with a maximum error of 5 %.

After confirming data normality, linear regression equations were developed from the apparent densities *versus* sclerometric indexes shown in Fig. 3a–c, where the sclerometric index values represent the averages of the impacts applied to each sample in each anatomical direction. Due to the results confirming that the rebound coefficients are associated with the elastic properties of wood,

Table 3 Average values of sclerometric indexes (SI), corresponding to 216 impacts in the radial direction

Species	Moisture condition	NI[a]	SI[b] (mean)	CV (%)[c]	Tukey[d]
Cumaru	Non-stabilised	216	39.1	9.69	A
Cumaru	Stabilised	216	37.7	10.07	A
Garapa	Non-stabilised	216	33.4	10.79	B
Garapa	Stabilised	216	32.6	6.83	B
Cedar	Non-stabilised	216	27.2	10.01	C
Cedar	Stabilised	216	23.9	12.25	C

[a] Number of impacts applied to 12 prismatic specimen

[b] Sclerometer indexes that represent the average of sclerometric impacts

[c] Coefficient of variation (%)

[d] Based on the LSD Tukey test with a 5.0 % margin of error, there is no statistically significant difference between the values denoted by the same letter

Table 4 Average values of sclerometric indexes (SI), corresponding to 120 impacts in the tangential direction

Species	Moisture condition	NI[a]	SI[b] (mean)	CV (%)[c]	Tukey[d]
Cumaru	Stabilised	120	42.9	10.93	A
Cumaru	Non-stabilised	120	42.5	8.14	A
Garapa	Non-stabilised	120	36.4	6.78	B
Garapa	Stabilised	120	36.1	4.50	B
Cedar	Non-stabilised	120	29.5	11.35	C
Cedar	Stabilised	120	27.6	12.20	C

[a] Number of impacts applied to 12 prismatic specimen

[b] Sclerometer indexes that represent the average of sclerometric impacts

[c] Coefficient of variation (%)

[d] Based on the LSD Tukey test with a 5.0 % margin of error, there is no statistically significant difference between the values denoted by the same letter

Table 5 Average sclerometric index (SI) values for the three species and data normality in the longitudinal (L), radial (R) and tangential (T) directions

Species	Cumaru			Garapa			Cedar		
Direction	L	R	T	L	R	T	L	R	T
NPS[a]	24	24	24	24	23[b]	24	12[c]	24	24
SI (mean)	36.5	38.4	42.7	29.5	32.5	36.2	17.0	25.6	28.5
SD	4.1	3.8	4.0	2.4	2.8	2.1	3.0	3.2	3.4
$Z_{skewness}$	0.61	0.15	1.02	0.73	1.42	−0.51	−0.23	−0.12	1.31
$Z_{kurtosis}$	0.03	−1.04	−0.82	−0.49	0.85	0.23	−0.05	−0.46	0.26
p value	0.667	0.512	0.145	0.753	0.201	0.628	0.930	0.966	0.700

[a] Number of prismatic specimen

[b] this outlier was excluded

[c] Prismatic specimen of group S

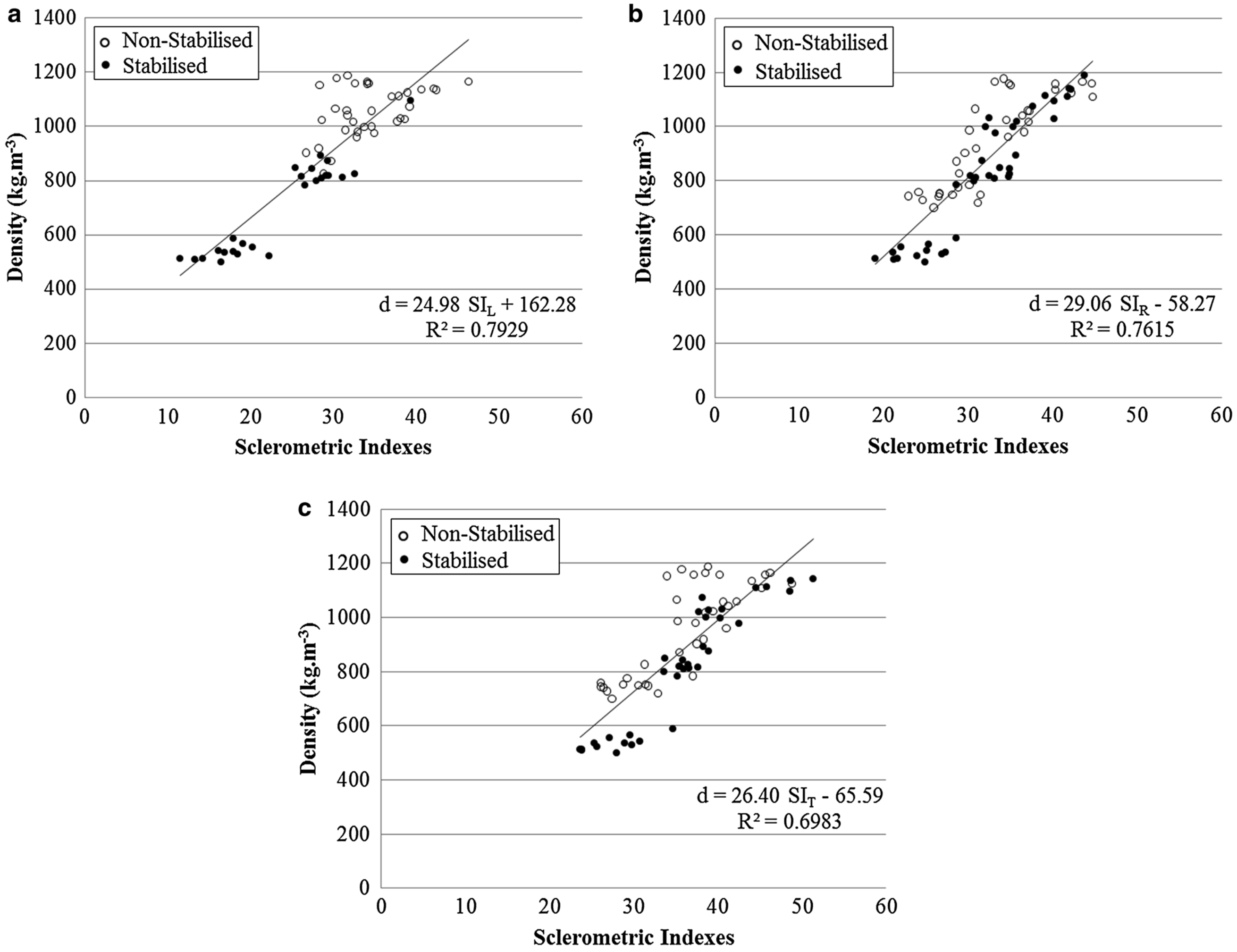

Fig. 3 Density as a function of the sclerometric indexes: **a** longitudinal direction, **b** radial direction and **c** tangential direction. *d* density, *SI* sclerometric index, *L* longitudinal directions, *R* radial directions, *T* tangential directions

being, therefore, different for each orthotropic direction, the regressions were fitted separately for the longitudinal, radial and tangential directions, with 60, 71 and 72 points, respectively (Fig. 3a–c).

The best regression ($R^2 = 79.29\ \%$) was found for the longitudinal direction, which can be explained by the sclerometric indexes. The lowest determination coefficient was obtained for the tangential direction ($R^2 = 69.83\ \%$).

However, the determination coefficients obtained for all three directions were higher than those found in other studies that estimated wood density using penetration and perforation tests. Moura and Santiago (1991) calculated a determination coefficient of 64 % when using pilodyn tests in Pinus trees. Louzada et al. (2005) and Shijun et al. (2012) used the same method in eucalyptus trees and found R^2 values of 27 and 35–41 %, respectively. Couto et al. (2013) used a resistograph in eucalyptus trees and calculated R^2 values between 54 and 67 %.

The results of this research preliminarily indicate that the wood density can be estimated by applying sclerometry parallel and normal to the fibres by using the linear relationships presented in Fig. 3a–c. In a future research, these equations should be improved by considering a larger number of species and also by conditioning the pieces at equilibrium moisture content of 12 %.

Whereas the conventional method to determine the density of wood requires the confection of test specimens, with measuring and monitoring of the drying in the laboratory, the sclerometric NDT allows to quickly estimate the density of wood in the field. Compared with the other techniques described, the sclerometric method benefits from being non-destructive, and by not requiring holes to be made in the sample, the physical integrity of the specimen is maintained.

4 Conclusion

This study proposed using the non-destructive sclerometric method to estimate wood density and applied the method to three hardwood species. The results of the study are as follows:

- The rebound coefficient is different for each anatomical direction, requiring the fit of three models to predict the wood density.
- The linear relationships between density and the sclerometric indexes have correlation coefficients greater than 0.84. The coefficients in the radial and tangential directions were 0.87 and 0.84, respectively.
- For each species, in normal direction to the fibres, the sclerometric indexes were not significantly different for different moisture contents.
- The sclerometric indexes were stronger in the anatomical direction tangential to the fibres than parallel to the fibres.

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