NONDESTRUCTIVE EVALUATION OF HARDNESS IN TROPICAL WOOD

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DA SILVA F, HIGUCHI N, NASCIMENTO CC, MATOS JLM, DE PAULA EVCM & DOS SANTOS J. 2014. Nondestructive evaluation of hardness in tropical wood. Various nondestructive techniques have been developed to evaluate wood quality. However, these studies were conducted mainly for temperate species. The Central Amazonian forests have more than 300 tree species per ha (> 10 cm diameter at breast height) and few studies using nondestructive techniques were conducted on these species. This study aimed to test a nondestructive technique, with application of stress waves, for the evaluation of hardness of timber species in the Central Amazon. The study was conducted in Itacoatiara city, Brazil (43° 2'–3° 04' S and 58° 31'–58° 57' W). Three timber species, namely, *Nectandra cuspidata*, *Mezilaurus itauba* and *Ocotea guianensis* were evaluated for hardness using nondestructive and destructive methods. Models adjusted for valuation of properties based on the speed of propagation of stress waves ($r^2 = 0.54–0.59$) and wood density ($r^2 = 0.73–0.78$) allowed the prediction of hardness of the wood species. Thus, the tested nondestructive techniques showed sufficient performances to predict timber hardness and would improve efficiency of the process to evaluate timber quality.

Keywords: Amazonian forest, timber evaluation, stress wave, technological properties

DA SILVA F, HIGUCHI N, NASCIMENTO CC, MATOS JLM, DE PAULA EVCM & DOS SANTOS J. 2014. Penilaian tanpa musnah kekerasan kayu tropika. Pelbagai teknik tanpa musnah telah dibangunkan untuk menilai kualiti kayu. Bagaimanapun kebanyakan kajian ini dijalankan untuk spesies temperat. Hutan Amazon Tengah mempunyai lebih 300 spesies pokok setiap hektar (> 10 cm diameter pada aras dada) dan tidak banyak ujian tanpa musnah dijalankan untuk spesies ini. Kajian ini bertujuan untuk menguji teknik penilaian tanpa musnah menggunakan gelombang tegasan untuk menilai kekerasan spesies kayu di Amazon Tengah. Kajian dijalankan di bandar raya Itacoatiara, Brazil (43° 2'–3° 4' Selatan dan 58° 31'–58° 57' Barat). Kekerasan tiga spesies kayu iaitu *Nectandra cuspidata*, *Mezilaurus itauba* dan *Ocotea guianensis* dinilai menggunakan kaedah tanpa musnah dan juga kaedah musnah. Model yang diselaraskan untuk penilaian ciri-ciri berdasarkan kelajuan rambatan gelombang tegasan ($r^2 = 0.54–0.59$) dan ketumpatan kayu ($r^2 = 0.73–0.78$) membolehkan ramalan dibuat untuk kekerasan spesies kayu. Oleh itu, kaedah tanpa musnah yang diuji menunjukkan prestasi yang baik dalam meramalkan kekerasan kayu. Kaedah ini dapat menambah baik kecekapan proses untuk menilai kualiti kayu.

INTRODUCTION

The Amazon has one of the largest timber stocks in the world. Unfortunately, lumber manufacturing generates large amounts of waste and the quality of products is very low, affecting volume of sales. Quality of products can be improved if the wood used is also of high quality. Thus, there is a need to examine the properties of wood before the products are made. Destructive methods are commonly used for testing physical and mechanical properties of wood in the Amazon. These methods, however, are costly and alternative methods, including nondestructive techniques, should be tested to improve operational efficiency. Nondestructive methods allow rapid assessments and cost saving (Garcia et al. 2011).

Nondestructive techniques have been widely studied for evaluation of timber quality in temperate tree species but there is scarce information on tropical tree species in the

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Amazon except for several researches using stress wave emission technique (Del Menezzi et al. 2010). Surface hardness is the most important mechanical property in wood furniture and building industries (Colenci 2006). Surface hardness is determined by Janka hardness destructive test (ABNT 1997). Given that Janka hardness test method is destructive and considering the research gap related to tropical species, especially those belonging to the Amazonian biome, the objective of this study was to predict Janka hardness of three tropical timber species using nondestructive evaluation with the application of stress waves.

MATERIALS AND METHODS

Study area

The study area is located at Itacoatiara city, Brazil, between 43° 2' and 3° 4' S and 58° 31' and 58° 57' W. Annual rainfall in the study area is 2200 mm with rainy season occurring in February till April. Lower monthly volume of rain is recorded between August and October. Maximum temperature is 32 °C and minimum, 23 °C while the average relative humidity is 82%. Forest type in the study area is classified as canopy-closed lowland tropical forest. According to the Holdridge life zones, this study site is classified as tropical moist forest.

Sampling

Trees for sampling were chosen based on their wood and harvest date. Wood can influence speed of propagation waves and mechanical properties (Kollmann & Coté 1968). Trees chosen were split into planks and radial samples were removed. From the planks, samples (150 mm × 50 mm × 50 mm) were taken for determination of hardness according to COPANT Standards (COPANT 1972a). Analyses were performed for 20 *Nectandra cuspidata*, 15 *Mezilaurus itauba* and 12 *Ocotea guianensis* samples.

Stress wave nondestructive testing

A stress wave timer was used to measure the propagation velocity of stress waves. Samples were dried for 45 days until moisture content of 12.5% was achieved. A stress wave timer was used for measuring stress wave transit time over a distance of 80 cm. Six replications were performed on each sample in the longitudinal direction of the wood fibres.

Sample hardness and physical properties

Before the nondestructive test, samples of each species (150 mm × 50 mm × 50 mm) were evaluated for physical properties (COPANT 1972b). Wood density and tangential, radial and volumetric contractions were measured. Moisture contents of samples ranged from 9 to 13%. Janka hardness test was used to measure hardness of samples (Janka 1906). The hardness tests were performed using electromechanical Universal testing machine based on resistance to penetration by a 1-cm^2 steel ball. Measurement was replicated twice in each axial direction (parallel and perpendicular).

Statistical analyses

Statistical analyses using R software (www.r-project.org) were conducted to examine differences in average propagation velocity of stress waves and specific gravity between the species. Linear regression analysis was performed to determine relationships between studied variables, namely, hardness, basic density and propagation velocity of stress waves.

RESULTS AND DISCUSSION

Results of this study are tabulated in Table 1. Density values obtained in this study were consistent with those reported by IPT (1985), i.e. 0.60, 0.8 and 0.70 g cm^{-3} for *N. cuspidata*, *M. itauba* and *O. guianensis* respectively. However, a lower value (0.40 g cm^{-3}) was reported for the density of *N. cuspidata* in Juruá-Solimões Rivers, Amazonas State (LPF 1988). Density values ranged from 0.68 to 0.70 g cm^{-3} for *M. itauba* from Belém, Pará State and Santarem in Amazonas State (LPF 1988).

Variations in density are due to differences in cellular structures, hereditary tendencies, physiological and mechanical influences as well as environmental factors (Kollmann & Côté 1968). According to these authors, the presence of extractives can also influence the density of wood. However, there is no knowledge about the interrelationship between these two properties. Denser wood has higher amount of extractives but this characteristic is not directly related to

Table 1 Density (g cm^{-3}), perpendicular and parallel hardness (N mm^{-2}) and wave propagation velocity (m s^{-1}) for the species studied

Species	Variable	N	Mean ± SD	Vel ± SD
Nectandra cuspidata	Density	80	0.610 ± 0.032	3319.05 ± 319.30
	f H_0	20	390.48 ± 73.17	
	f H_{90}	20	420.45 ± 39.22	
Mezilaurus itauba	Density	27	0.792 ± 0.032	4074.95 ± 305.21
	f H_0	15	502.81 ± 57.17	
	f H_{90}	15	505.44 ± 60.04	
Ocotea guianensis	Density	20	0.698 ± 0.027	3963.27 ± 335.29
	f H_0	12	413.58 ± 24.27	
	f H_{90}	12	467.12 ± 32.18	

f H_0 = hardness parallel to fibre, f H_{90} = hardness perpendicular to grain, SD = standard deviation, Vel = velocity of wave propagation, N = number of samples

density. Variation in density values between the species studied could be explained by genetic characteristics associated with the allometry, growth pattern and tree architecture specific to species (Meinzer 2003, Wright et al. 2003, Sterck et al. 2006).

Nondestructive tests were performed parallel to fibre because size of samples can influence propagation velocity of stress waves when tests are performed in the transverse and diagonal directions (Puehringer 2002). Associating results of nondestructive tests with density, we observed that species with higher density showed higher velocity values (Figure 1). Media with higher density values have less resistance to wave propagation. Air causes greater resistance to wave propagation, thus, in species with higher density, waves propagate more easily.

Parallel hardness ranged from 390 to 505 N mm^{-2} while perpendicular hardness, 420 to 505 N mm^{-2} (Table 1). Both hardness values were positively correlated ($r^2 = 0.734$ and $r^2 = 0.780$ respectively, $p > 0.0001$) with density (Table 1). The present results supported findings of Kolmann and Côté (1968) which reported that hardness was proportional to density. On the other hand, the same Amazonian wood species having similar densities as the species in the current study had different hardness values (Bessa et al. 1990).

Density is linked mainly to cell wall thickness. There is higher proportion of cell wall per unit distance in the direction perpendicular to the fibres. Therefore, mechanical strength is greatest in this direction. All species in this study are classified as medium hardness (LPF 1997) (Table 2).

The classification by LPF (1997) was made to facilitate the assessment of price and commercialisation of timbers by means of grouping of species with similar characteristics due to the large variability of tropical species. However, by grouping species into classes, other features such as natural durability characterised by the presence of extractives are disregarded. Accurate and expedient methods to estimate hardness of wood are necessary in view of its wide practical applicability. Hardness is an important indicator to determine the most appropriate uses for tropical timber such as hardwood floors and integral parts of transport vehicles (Grobério & Rocco-Lahr 2002). Wooden bridges with density values exceeding 0.8 g cm^{-3} were more protected against degradation than those with density below 0.8 g cm^{-3} (Xavier & Chahud 2006). Thus, this work is important to establish relationship between density, parallel:perpendicular hardness and velocity of propagation wave (Figure 1). It is possible to establish a quick, simple and low-cost

Table 2 Grading of wood hardness according to LPF (1997)

Hardness	N mm^{-2}
Low	< 360
Average	360–802
High	> 802

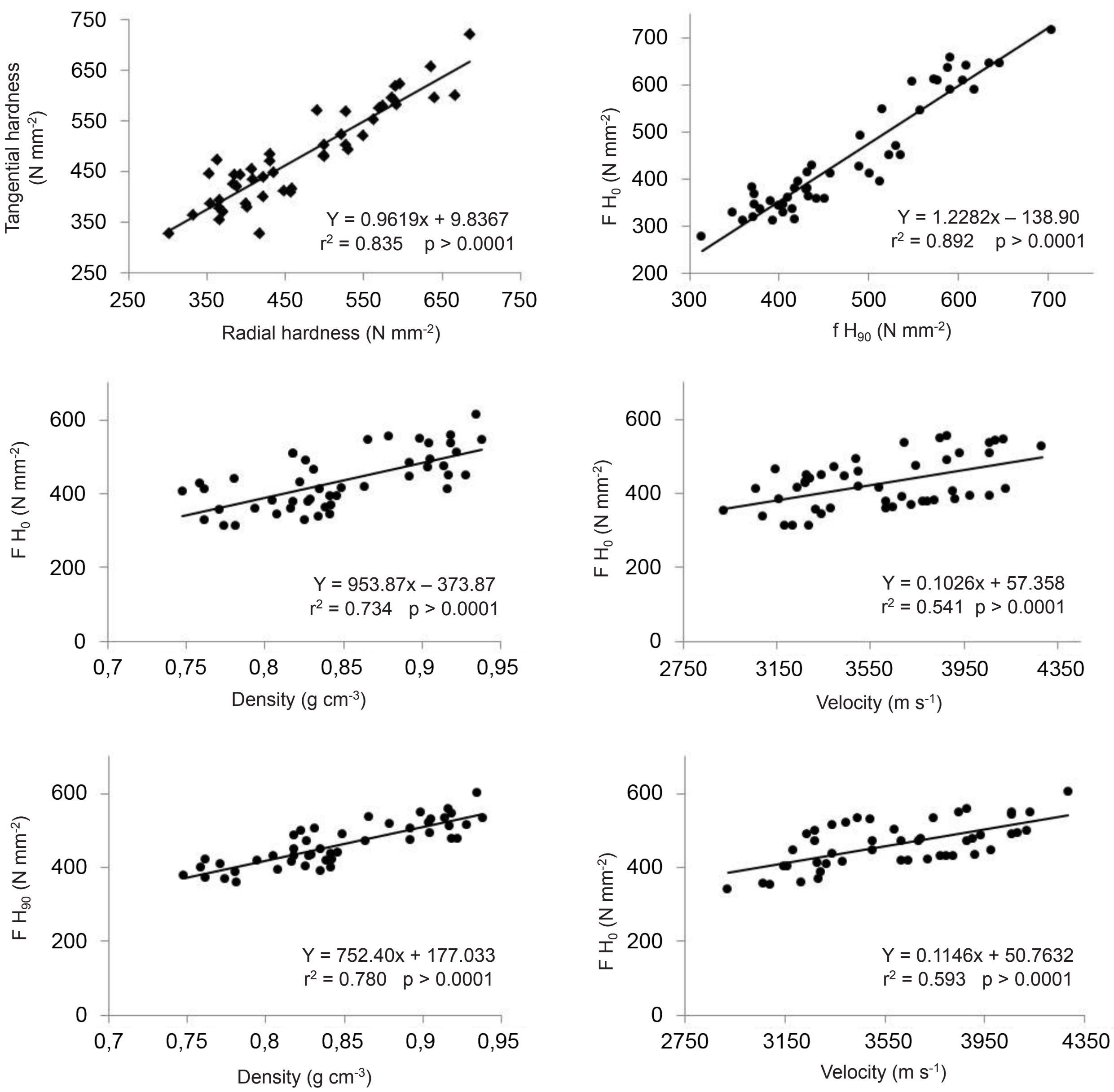

Figure 1 Relationship between density, propagation wave velocity and hardness of *Nectandra cuspidata*, *Mezilaurus itauba* and *Ocotea guianensis;* f H_0 = hardness parallel to fibre, f H_{90} = hardness perpendicular to grain

assessment for hardness using nondestructive method.

In the relationship between parallel and tangential hardness, and the relationship between perpendicular and radial hardness, the coefficient of determination r^2 obtained were 0.83 and 0.89 respectively. These values were close to 0.80 obtained by Caixeta et al. (2003) who worked on species with density range of 0.602–0.817 g cm^{-3}. It has been reported that coefficient of determination for perpendicular and parallel hardness values of Lauraceae and Vochysiaceae were close to 1 (Pogetto et al. 2006); this value was similar to our finding (r^2 = 0.94). The relationship between hardness indicates equivalence between resistance regardless of the direction of load application. Relationship between perpendicular and parallel hardness depends on density of the wood, and hardness increases with density (Colenci 2002).

In general, long fibres with thicker cell walls or wood with higher density have higher propagation velocity of stress waves (Oliveira & Sales 2000, Bucur 2002). However, in a nondestructive evaluation of species with high density, it was found that propagation velocity values of stress waves ranged from 4514 to 4279 m s^{-1} for *Goupia glabra* (density 0.83 g cm^{-3})

and *Hymenaea* sp. (1.15 g cm^{-3}) (Oliveira et al. 2002). These results showed that there is an inverse relationship between density and velocity of propagation. In a study of 55 timber species, including nine species of hardwood from South America and Africa, great variation was observed in density (0.097–0.855 g cm^{-3}) but very little in propagation speed (4.21–5.540 m s^{-1}) (Illic 2003).

Many researchers found positive correlation between propagation velocity of stress waves and density (Feeney et al. 1998, Oliveira & Sales 2000, Bucur 2002, Colenci 2002, 2003 Illic). On the other hand, Wegst (2006) found that high values of propagation velocity of stress waves were obtained from species with high and low densities such as *Caesalpinia echinata*, *Manilkara* sp., *Pinus sylvestris* and *Ochroma* sp. Longui (2005) found strong relationship between density and propagation velocity of stress waves in samples of *C. echinata*, *Tabebuia* sp. and *Manilkara* sp. Ravenshorst et al. (2008) who studied nine tropical species from South America and Africa reported that stiffness of wood can be predicted in high accuracy (r^2 = 0.63) using propagation velocity of stress waves. Strong relationship (r^2 = 0.83) between stiffness and propagation velocity of stress waves was reported for lumber species of *Sextonia rubra* whose density ranged from 0.53 to 0.85 g cm^{-3} (Teles 2009). Del Menezzi et al. (2010) used propagation velocity of stress waves to evaluate six Brazilian tropical species, namely, *Balfourodendron riedelianum*, *Cedrela fissilis*, *Cordia goeldiana*, *Bowdichia virgilioides*, *Dipteryx odorata* and *Tabebuia* sp. whose density ranged from 0.62 to 1.22 g cm^{-3} and maximum propagation velocity of stress waves was 4555 m s^{-1}. They obtained high coefficient of determination value (r^2 = 0.9, n = 120) in the relationship between dynamic modulus and flexural properties. Based on the cited works, we can highlight the importance of our results. Although in our work we used tropical wood, the result was similar to those found for temperate species such as pine. Results presented in this study confirmed results of other researches whereby nondestructive methods were efficient for estimation of mechanical properties. Nondestructive evaluation with application of stress waves was accurate, reliable, quick and cost effective for estimating hardness of the species studied.

CONCLUSIONS

This study presented new information on the use of stress waves as a nondestructive method. We conclude that stress wave method is good for determining hardness. Very strong relationship was found between stress wave velocity and hardness. Hardness increased as wood density increased. Similar positive relationship was observed between hardness and speed of propagation of stress waves. Linear relationships established showed that velocity of propagation stress waves and density allowed accurate prediction of hardness of timber. Nondestructive evaluation was also cheaper and faster. Thus, we recommend a larger study on the relationship between stress wave transmission and physical and mechanical properties of tropical timbers.

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