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Influence of Timber Moisture Content on the Ultrasonic Wave Velocity Measurement of *Tectona grandis* L.F. and *Cupressus lusitanica* M. from Costa Rica

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Abstract: Ultrasound is a reliable non-destructive method commonly used to evaluate the state of a piece of wood. The effect of the moisture content (*MC*) on the timber wave velocity, which is different depending on the wood species, must be considered. *MC* adjustment factors are important if accurate and comparable results are to be achieved. Thus, the goal of this study is to define a model that allows obtaining the adjustment factor to predict the standard velocity (12% of *MC* (V_{12}) from velocity obtained at different *MC* for two Costa Rican commercial species: *Tectona grandis* L.F (teak) and *Cupressus lusitanica* M. (cypress). This effect was studied on small clean specimens during the desorption stages, from the fiber saturation point to the oven-dry state, controlling the specimen's mass and *MC* on 62 specimens. With this data, the rate of change in ultrasound velocity per *MC* was modeled. Thus, the applicability of already published moisture adjustment models for conifers and hardwood tropical species was proved. The results showed that the proposed model coefficients adjust better than the ones obtained from the wood science literature, which makes them suitable to describe ultrasound velocity in different moisture conditions (V_H).

Keywords: cypress; teak; dynamic modulus of elasticity; moisture content; ultrasonic velocity

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1. Introduction

Ultrasonic testing is one of the preferred non-destructive testing (*NDT*) methods for estimating the anisotropic elastic properties of wood materials, like young's modulus, which is one of the most important variables for wood. This *NDT* is a suitable tool to analyze the wood's mechanical behavior due to lower costs of equipment and staff, combining speed, ease, and accuracy in the results acquired [1]. This method estimates the dynamic modulus of elasticity (MOE_{dyn}) using the measurement of wave velocity and bulk density (ρ) of wood pieces [2]. Therefore, considering that MOE_{dyn} exhibits a nearly perfect linear relationship with the static modulus (MOE_{app}) [3], ultrasound testing represents a valuable alternative for wood testing. It is used effectively to predict lumber grade and strength properties, assess heritage structural elements, detect delamination, and monitor the in-use performance of timber during service life [4–10]. Additionally, it could be used to determine outdoor degradation or to evaluate wood structures subject to the constant action of weathering and high humidity, such as outdoor decks and other structures [1].

Empirical correction factors have been developed to predict standard velocity (12% of *MC* (V_{12})) from the obtained velocity at different *MC* (V_H) [11,12]. For these models, it must be considered that the V_H is influenced when timber contains only bound water, below the *FSP*, or when it also contains free water, above *FSP* [13]. This author estimated that MC influence is 8 times stronger below the FSP. Hence, the relation V_H and MC can be represented using a bilinear model with a change of the slope at the FSP [10,13].

The pattern of V_H vs. average MC during desorption varies within species [14,15]. Consequently, several researchers have performed corresponding adjustment factors for different species and moisture levels [16–20] tested three different tropical hardwoods, obtaining three different slopes (45, 55, and 66) ms^{-1}.

In general, most of the studies on timber ultrasound wave velocity that are available in the literature are focused on softwood species, although hardwood species have been studied and incorporated into Brazilian standards [21]. There is no evidence of the existence of a higher influence of MC and the ultrasound velocity comparing hardwoods and softwood species. While [22] observed that hardwoods presented a lower slope when moisture decreased, other authors have compared the slope of the ultrasound velocity with changes in the MC, obtaining almost the same slope for softwood and hardwoods. [23] found almost the same variation of ultrasound velocity with MC, 25 m s^{-1} for softwood and 24 ms^{-1} for hardwood. Similar values were obtained by [24], respectively, (33 and 31) ms^{-1}. However, ref. [25] reported higher differences among three hardwoods from (24 to 60) ms^{-1} than among three softwoods from (36 to 42) ms^{-1}.

In Costa Rica, many efforts have been made to increase structural wood consumption, which is promoted by the country's commitments to be carbon-neutral. Different studies have focused on characterizing native species of timber proceeding from local plantations [26]. Wood degradation in tropical environments and acid atmospheres from volcanic emanations have also been studied. The widespread use of wood in this environment is critical for the expansion of commercial utilization of these species in volcanic areas. The detailed methodology proposed for the evaluation of this degradation in tropical areas has been analyzed [27]. Considering that the ultrasound method allows determining the timber degradation in the same piece over time, the MC variations must be considered to adjust V_H to compare field data to continue that investigation.

The species of interest *Tectona grandis* L.F (teak) and *Cupressus lusitanica* M. (cypress), two representative species commonly used in construction in Costa Rica, proceed from local forest plantations.

As a hardwood, young teak is the most commercialized in Costa Rica and the one that has been exported for the longest time, whereas cypress is the most widespread coniferous plant in Costa Rica [28]. The use of these wood species as structural material raises the need for standard parameters to determine the degradation of the wood over time and in different moisture scenarios.

Regarding teak, studies of its MOE_{dyn} are available [1,3,29–31] but no evidence has been found on the correlation factors between V_H and MC, nor have they been found for cypress.

The goal of this study is to determine appropriate moisture adjustment functions that allow comparing mechanical properties considering those obtained at different MCs for these two Costa Rican commercial species. This research contributes to the expansion of their commercial use and the increase of the knowledge of best practices databases in the country.

2. Materials and Methods

The symbols in the present paper are listed in Table 1.

Table 1. Symbols in the present paper.

MC	Moisture content (%)
FSP	Fiber saturation point (at 28% MC)
V_H	Ultrasound velocity at certain moisture conditions (ms^{-1})
V_H/V_{12}	The ratio of ultrasound velocity at certain MC (V_H) to ultrasound velocity at 12% MC (V_{12}) change rate
V_{12}	Ultrasound velocity at 12% MC (ms^{-1})
V_{fsp}	Ultrasound velocity at FSP 28% MC (ms^{-1})
ΔU	Moisture content variation
ρ	Density (kgm^{-3})
k_u	Adjustment factors for each timber specie
ToF	Time of flight
MOE_{dyn}	Dynamic modulus of elasticity (GPa)
ρV^2	MOE_{dyn} by calculation of V_H and density (GPa)
NDT	Non-destructive testing

2.1. Wood Material

This investigation was carried out with 62 small clean specimens (30 teak, 32 cypress). The samples were supplied in green condition (freshly cut), as solid wood from plantations obtained from local sawmills located in La Rita, Guápiles, Limón, (teak) and Paso Llano, San José de la Montaña, Heredia (cypress). The plantation's ages were 14 (teak) and 40 years (cypress), respectively, due to the maturity representation at which they are traded locally. The specimens dimensions were 1 × 1 × 16 (25(b) × 25(h) × 410(l) mm), according to [32].

2.2. General Procedure

The specimens were taken to the laboratory with a *MC* greater than *FSP*. Then, they were gently dried, and the initial ultrasonic wave velocity (considered the first valid measurement) was taken when the species reached 28% ± 1% *MC* ≈ the *FSP*. In literature, values between 28% and 32% as the FSP have been used by [13,33]. In this study, the *FSP* was considered as recommended by [18] at 28% for ultrasonic runtime measurement, and not 32%, which is recommended for the natural frequency measurement method.

Specimens were subjected to systematic monitoring during the desorption stages from *FSP* to 5% of *MC*. They were kiln-dried at a dry-bulb temperature of 103 °C and measurements of *ToF*, weight, and dimensions were taken every hour until they reached 5% of moisture, with at least 6 measurements for each specimen. Temperature control was considered, which means cooling the specimens after coming out of the oven in order not to affect the mass measurement. The bulk density ρ was calculated from weight and volume. The longitudinal wave propagation velocity of each specimen was measured repeatedly, three times, and, then averaged, as recommended by [10]. To avoid errors in the readings due to the pressure in the transducers, the recommendations by [34] were considered.

The *MC* was obtained according to the secondary oven drying [35]. From each specimen, a 5-cm sample was removed. The sample piece's mass measured wet and dried allows obtaining the moisture content of the test specimen at various test stages (%) by applying Equation (1).

$$MC = [(m_u - m_0)/m_0] \times 100 \quad (1)$$

where MC = moisture content of the test specimen at various test stages (%); m_u = test specimen mass at various test stages (kg), and m_0 = the oven-dried mass of the specimen (kg). Bulk density (kgm^{-3}) was determined.

2.3. Wave Velocity Measurement Procedure

Wave propagation time measurements were performed each hour following the described method. Ultrasonic velocity V_H was measured with a portable ultrasound device (Sylvatest duo-Lausanne, Switzerland), and based on the determination of the time of flight (*ToF*) of the ultrasonic wave between transmitter and receiver, which is generated by piezoelectric transducers with a frequency of about 54 kHz. Measurements were obtained in a direct contact position with the transducers placed facing each other on opposite edges of specimens at the center of the section in the longitudinal direction (Figure 1) since this is the most consistent parameter for the global evaluation of structural members. Three consecutive measurements were taken to verify each value, using the average. The ultrasound velocity was estimated from Equation (2).

$$V_H = L/ToF \quad (2)$$

where V_H = ultrasound velocity (ms^{-1}), L = specimen's length (m), *ToF* = time of flight (s).

The final consideration is the constant temperature (room temperature 20 °C) in the functional range of the model since according to [36], the frequency spectrum of the transmitted signal is lightly affected by temperature. This is also supported by [37], who found a dominant effect of *MC* over temperature on wave propagation by studying the differences in the trends of V_H across the moisture range, along with the higher decreasing rates per unit moisture.

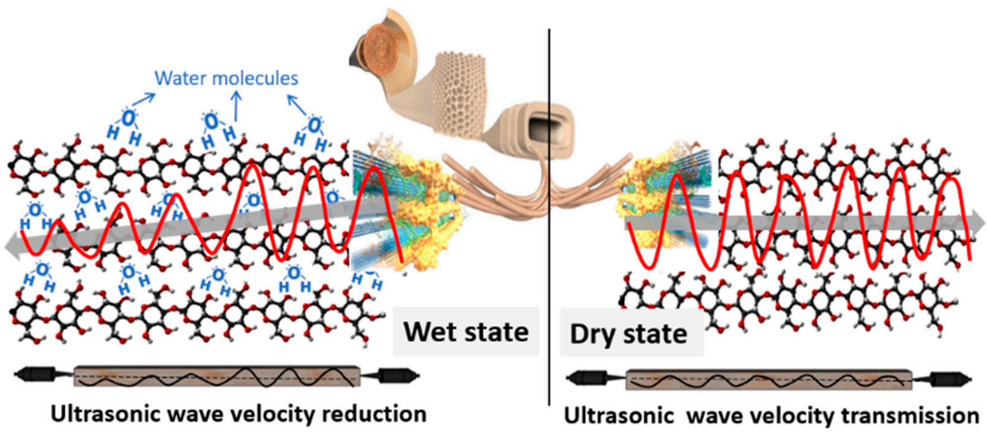

Figure 1. Representation of ultrasound velocity TOF measurement in the longitudinal direction and explaining wood structure in different scales to visualize the phenomenon of wave propagation and the affectation by water molecules. Central figure adapted from [38].

The percentage of the velocity variation for every 1% MC variation, V_H from the V_{12} relation is presented in Equation (3) [13,18,20,33,39]

$$V_H/V_{12} = 1 + k_u\,(MC - 12) \quad (3)$$

where V_{12} = velocity at 12% *MC*, V_H = velocity obtained in wood with *MC* below *FSP*, k_u = adjustment factors for each timber species.

2.4. Statistical Analysis

The V_H/V_{12} ratio was obtained for each of the measurements made. A Strubb analysis was performed at $p = 0.05$, 95% confidence intervals. All the data were studied using a non-linear regression analysis for each specie and the mean squared error and coefficient of determination were obtained. A nonlinear regression (nlinfit) was performed using Matlab® software.

3. Results and Discussion

The set of all determined properties is shown in Table 2. It must be considered that teak specimens come from the thinning of forest plantations, as is common in the Costa Rican internal market, since the wood from the final felling is exported. On the other hand, the cypress consumed in this country usually comes from older plantations. Therefore, it should be considered that in this study, teak is mainly sapwood, and for cypress, even though the percentage of heartwood is considerable (because of its age), it is difficult to visually determine the percentage because it does not show a noticeable color change between sapwood and heartwood. This explains the fact that both species tested in this studio have very similar densities, although teak has higher V_{12} than cypress, related with a higher modulus of elasticity (Table 2). Costa Rican teak timber increases in density with age, as reflected in literature, from values of 580 kgm^{-3} (17 years) to 610 kgm^{-3} (28 years) [40]. The average density for mature teak wood is 800 kgm^{-3} and 600 kgm^{-3} for cypress [26]. Considering the aforementioned characteristics, the obtained values are in the expected range with a relative variation of less than 10% among each species replication.

Table 2. Set of all determining properties at 12% *MC* (ρ, V_{fsp}, V_{12}) for cypress and teak.

Species/Age	Density ρ (kgm^{-3})	V_{fsp} (ms^{-1})	V_{12} (ms^{-1})
Cypress/40 years	533.37 ± 52.73	3860.76 ± 397.38	4655.16 ± 400.27
Teak/14 years	531.30 ± 49.22	4463.80 ± 360.69	5152.39 ± 371.37

Figures 2 and 3 show the relation between *MC* and ultrasound velocity from *FSP* to oven dry conditions for teak and cypress, respectively. These scatter plots found that ultrasound velocity increases as *MC* decreases, showing an inverse relationship with a linear tendency. Then, a linear adjustment function describes the correlation between the variables below *FSP*, which was calculated considering the overall values presented by specimens (Table 2).

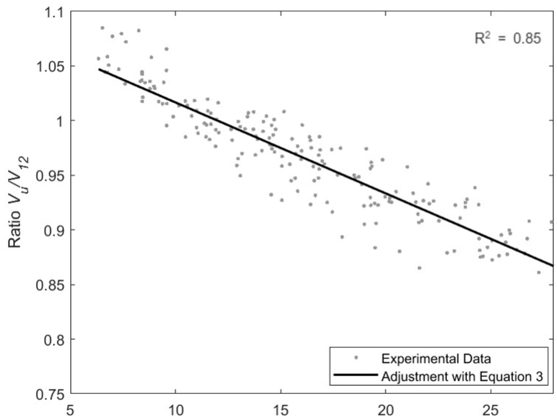

Figure 2. Correlation between *MC* and relative ultrasound velocity measurement (5%–28%) trend line for Teak.

The different slope k_u were determined for both species. Using Equation (3), the correction factors for some *NDT* results to a standard 12% *MC* were calculated. The proposed model for teak is presented in Equations (4) and (5) describes the proposed cypress model.

$$V_H/V_{12} = 1 - 0.0083 \cdot (MC - 12) \quad (4)$$

$$V_H/V_{12} = 1 - 0.0106 \cdot (MC - 12) \quad (5)$$

The experimental adjustment parameters are shown in Equations (4) and (5). These were found using the nlinfit tool, where the factors were obtained using least squares with a 95% confidence interval, considering that the k_u parameter was $k_1 = 1$.

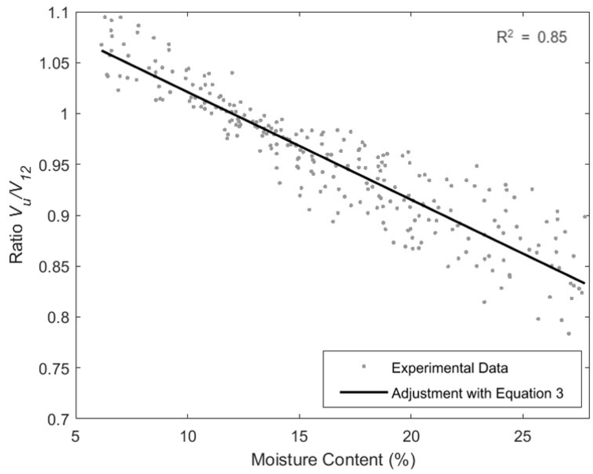

Figure 3. Correlation between *MC* and relative ultrasound (5%–28%) trend line for Cypress.

The performance of the model found was evaluated with two statistical parameters: the mean squared error (*MSE*) and the coefficient of determination (R^2). In the case of the model for the cypress, it presented an R^2 of 0.8480 and an *MSE* of 6.33×10^{-4}, while for teak it showed an R^2 of 0.8486 and an *MSE* of 4.15×10^{-4}. Therefore, the results of the relationship between ultrasound velocity and *MC* confirm the reliability of the coefficients for prediction purposes following the literature on the subject [13,18,20,41,42].

A Matlab routine was programmed for testing the performance of available models in the literature and the developed models with the experimental datasets obtained in this study. Models for hardwoods were tested with the teak dataset, while the cypress dataset was used to test softwood models.

Table 3 shows the statistical performance of the different models for the experimental data, distinguishing models for hardwoods and softwoods. In Figures 4 and 5, the adjustment according to the different parameters can be observed graphically applied to the experimental data for teak and cypress.

Table 3. Adjustment (R^2 and *MSE*) of the proposed models versus literature models tested with the experimental teak and cypress data for the estimation of references velocity at 12% *MC* (V_{12}) from velocity (V_H) with different moisture content.

Equation	Specie	Author	k_u	R^2	MSE
Hardwood models/Dataset teak (14 years)					
T	*Teak*	(Proposed model)	0.0083	0.8486	4.14×10^{-4}
H1	*Eucalyptus grandis*	[20]	0.0066	0.7893	5.78×10^{-4}
H2	*Corymbia citridora*	[20]	0.0083	0.8485	4.16×10^{-4}
H3	*Eucalyptus pellita*	[20]	0.0067	0.7893	5.78×10^{-4}
Softwood models/Dataset cypress (40 years)					
C	*Cypress*	(Proposed model)	0.0106	0.8479	6.34×10^{-4}
C1	-	[42]	0.0100	0.8449	6.47×10^{-4}
C2	*Fir and Spruce*	[13,41]	0.0053	0.5052	0.0021
C3	*Spruce and Scots pine*	[18]	0.0060	0.5914	0.0017

k_u = adjustment factors for each timber species. Note: all Equations are for 5% < *MC* < 28% except C1 for 5% < *MC* < 30% and C2 ≤ 32%).

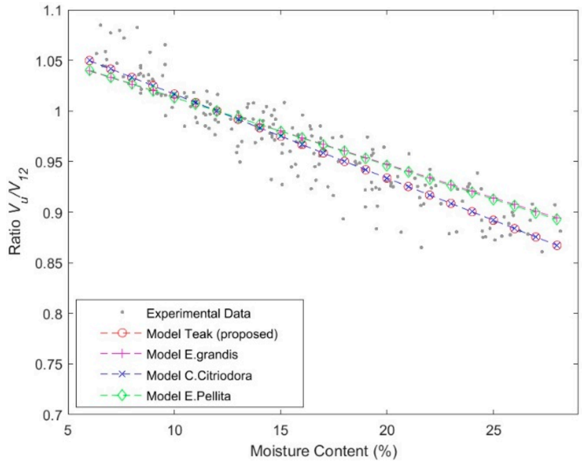

Figure 4. Comparison of adjustment equations to obtain longitudinal references velocity at 12% *MC* (V_{12}) for hardwood with the experimental data teak.

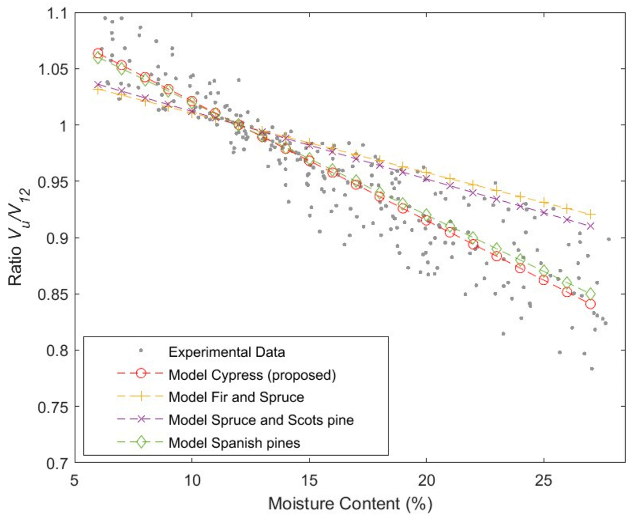

Figure 5. Comparison of adjustment equations to obtain longitudinal references velocity at 12% *MC* (V_{12}) for softwood with the experimental data cypress.

In the equations proposed by different authors to infer V_{12} from a V_H estimated in *MC* below *FSP*, the k_u varied from 0.53% to 1%. In this research, values of k_u were 0.83% for teak (Equations (4) and (T) in Table 3), 1.06% for cypress (Equations (5) and (C) also in Table 3). These values are within the interval obtained by the authors cited in Table 3, using a V_H derived for *MC* below *FSP*.

The obtained results show a suitable fit in the models using the developed parameters, with high determination coefficients and low mean square errors, which means a good statistical fit in the order of other studies in the literature, taking into account that they were fitted with small clear specimens. It should be considered that *MC* influence is not totally independent of dimensions. According to [22] dimensions can also influence the measurement of *MC* during drying studies. The *MC* inside small clear specimens is more homogenous than it is in structural sizes, where a *MC* gradient can exist from the inside to the outside, and slenderness (length/width) may also affect low-frequency ultrasound devices (from 23 to 54 kHz) [22].

Assuming the previous considerations, the studied teak shows coefficients in the order of those obtained for larger pieces (metric scale) of *Corymbia citriodora*, being different from those of *Eucalyptus grandis* and *Eucalyptus pellita*. As is summarized in Table 3, teak experimental data were evaluated with the models for these three hardwoods species (H1), (H2), and (H3) developed by [20]. It must be considered that these species presented greater average densities (*E. grandis* (508 kg m^{-3}), *E. pellita* (737 kg m^{-3}), *C. citriodora* (813 kg m^{-3})) than teak (531 kg m^{-3}).

Thus, it should be considered that *E. grandis* and *E. pellita*, although different in density, present similar behavior related to velocity variation as a function of *MC*, whereas *C. citriodora* presents a greater variation, with a slope similar to the tested teak (Figure 4). Therefore, it should be considered that variation in ultrasound velocity by moisture influence is intrinsic to the species.

Similar behavior is observed when the experimental data for cypress were analyzed with softwood models (C1), (C2), and (C3), with densities around 450 kgm^{-3}, which are lower than the 533 kgm^{-3} obtained for cypress. It was observed that the cypress proposed model (C) is similar to (C1) proposed by [42], which was used for four Spanish (radiata, scots, salzmann, and maritime) pines [22]. It is interesting to have found similarities only with one of the three models, as is shown in Table 3.

To understand the cause of this, additional research is required. Considering the specie's anatomical and chemical characteristics. Such as porosity, the geometry of its tracheids or vessels (arrangement, size, frequency, contents), other factors associated with the composition of its fibers (cellulose, hemicellulose, and lignin) and hence its hydration potential, and climatic factors influencing variations in the species characteristics should also be considered [43].

For the two species studied, the ultrasound velocity increased as the *MC* decreased. Using the relation 1% of *MC* decrease, the V_H increased 43.9 ms^{-1} for teak and 50.5 ms^{-1} for cypress. These data contrast with what was obtained in the study carried out by [22], where it was determined that the ultrasound velocity was influenced by the *MC* more in hardwoods than in softwoods.

It must be considered that cypress has ranges of velocity variation (*ToF*) of 1466.45 ms^{-1} and moisture content variation (ΔU) of 23.69%, whereas teak has ranges of 1464.98 ms^{-1} and 24.46%, respectively.

The species tested, teak (531.30 kgm^{-3}), and cypress (533.37 kgm^{-3}), although possessing similar densities, presented a different behavior related to the ultrasound velocity variation as a function of *MC*, with cypress showing a greater variation (slope), which is attributable to the higher percentage of the heartwood due to its age. Thus, further research can deepen in the relationship between volumetric contractions (shrinkage and swelling) and the anatomy of wood cells and their relationships with bound water movement.

The contribution of this work lies in highlighting the need to evaluate with experimental data the models available in the literature. As shown in this research, the variation between models is substantial, and it is the reason why some models fit better than others. Therefore, empirical models and comparisons are necessary.

4. Conclusions

The present research provides adjustment functions to obtain the velocity at 12% MC of Costa Rican young teak (14 years) and mature cypress (40 years) timber at different *MCs* employing ultrasound measurements. The coefficient between the velocities obtained at different *MC* and the reference velocity (V_{12}) shows a linear relationship with *MC*, with a determination coefficient above 85% for both species studied.

During *FSP* desorption at the oven-dry condition, the ultrasound velocity in the longitudinal direction can be corrected, for every 1% in *MC* by 43.9 ms^{-1} for teak and 50.5 ms^{-1} for cypress. The influence of *MC* on the ultrasound velocity can be considered slightly higher for cypress (conifer) than for teak (hardwood).

Experimental data on teak and cypress have been used to test proposed models, along with those previously published by researchers for coniferous and hardwood species. Teak model presents similar adjustment factors to the hardwood model for Brazilian *Corymbia citrodora* and the cypress model showed agreement with the model of Spanish pines wood.

These models can be applied to moisture correction in *NDT* for teak and cypress in Costa Rica. Obtained results open the way for monitoring the in-use performance of these timber over its lifespan and determining outdoor degradation, as it is being done in extreme acid environments. It will contribute to the expansion of their commercial use and knowledge of best practice databases in the country.

Author Contributions: The individual contributions by the authors were as follows: conceptualization, V.P., C.T. and B.G.-R.; methodology, V.P., C.T. and B.G.-R.; validation, C.T. and J.C.; formal analysis, C.T, V.P., J.C. and B.G.-R.; original draft preparation, V.P. and J.C.; writing, V.P., B.G.-R. and C.T.; review and editing, V.P., C.T. and B.G.-R.; supervision, C.T. All authors have read and agreed to the published version of the manuscript.

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