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Prediction of Maritime Pine Boards Modulus of Elasticity by Means of Sonic Testing on Green Timber

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Abstract: Timber buildings are experiencing a rapid diffusion due to their good performance and their sustainability; however, some steps of structural timber production process, such as drying, are energy-intensive and environmentally impactful, and many wood species are also affected by low yield. Therefore, it would be important to determine the quality of the green material, that is, in wet condition, before undergoing the most impactful and expensive production steps. This paper describes a research aimed at quantifying the variation of the dynamic modulus of elasticity MoE_{dyn}, which is commonly used for structural timber mechanical grading, from wet to dry condition in Sardinian maritime pine boards to be used for the production of laminated timber, and to examine the relationship between wet and dry MoE_{dyn}. The MoE_{dyn} was determined from measurements of the velocity of sonic waves propagating through the boards. The results show that the dry MoE_{dyn} can be estimated starting from boards sonic testing in the wet condition, so providing a basis for implementing Sardinian maritime pine pre-grading in order to obtain the reduction of manufacturing costs, the abatement of environmental impact, and the increase of structural grade yield.

Keywords: structural timber; green timber grading; nondestructive sonic testing; dynamic modulus of elasticity; sustainability

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1. Introduction

Timber is generally acknowledged as one of the most effective building materials in terms of environmental sustainability because of its inherent eco-compatibility, mechanical and building physic performance, and ease to install [1–3]. In the literature, there are numerous studies aimed at evaluating, through Life Cycle Assessment (LCA) approaches, the environmental impact of timber constructions in relation to other materials, especially concrete and steel, with reference to the consumption of raw materials and primary energy, the production of carbon dioxide, and in general the emission of greenhouse gases (GHG) in all phases of the useful life of the material [4–15]. The general result is the lower level of environmental impact of timber, especially considering wood carbon storage capacity. Therefore, the use of timber in construction has recently undergone a great boost, also favored by the development of highly technological construction systems such as laminated timber. If solid timber may have some limitations of use related to the maximum dimensions of the elements, depending on the tree from which they come, and to the presence of natural defects (knots, clusters of knots, resin pockets, etc.), the use of laminated timber overcomes these limitations thanks to the production process. The production process of laminated timber includes the quality control of the boards for the removal of the elements or portions that have defects higher than the thresholds defined in specific standards, and allows to obtain final structural elements with desired length, thickness, and shape via the phases of butt jointing of the boards, gluing of overlapping boards, and possible curvature. It is therefore an industrial product that entirely overcomes the limitations of solid timber thanks to the technological manufacturing.

Like solid timber, laminated timber must be graded to determine its strength and stiffness profile for structural purposes. Generally, grading of component dry boards is performed first, then the performance profile of the composite laminated element is defined according to boards properties. Boards grading can be carried out through the non-invasive determination of some indicating properties related to the mechanical ones (machine grading): strength, stiffness, and density [16–18].

In general, the production process of a laminated element consists of many phases: cutting, reduction into boards, drying, grading, jointing and gluing, and finishing processes (trimming, planing, cutting, etc.). Considering the energy required for the various processes that make up the structural timber supply chain, from the forest to the end user, and the related emissions, it is immediately evident that their optimization is important to keep the use of this material sustainable. Given that drying is the most environment-impactful phase of the entire process [19–22], due to the high energy required to remove moisture from the wood and the possible emission of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) [23], the advantage that would be obtained in drying only the material of proper quality is evident. Discarding wood with inferior properties prior to drying can result in significant cost savings in the drying process. In addition to this, the production of boards for laminated timber is affected by percentages of rejects that can be very high, which, depending on the wood species, can lead to low yields that affect the sustainability of the production. These aspects of the manufacturing process lead to the opportunity of carrying out a pre-grading of the material still in the wet condition, in order to bring to drying only the material suitable for structural uses and to reduce production costs related to low yields at the same time. In fact, measurements made on logs and standing trees in the forest can segregate the timber resource, diverting the higher quality material to construction timber and the poorer material to other markets, and reducing wastage [24].

In the literature, there is a certain number of researches aimed at pre-grading timber starting from the standing trees or the logs. In particular, papers aimed at timber pre-grading starting from logs [25–27] or from wet boards or specimens [27–38] have provided interesting results, showing good correlations between timber physical-mechanical parameters in the wet condition and those in the dry one, and highlighting the possibility of evaluating dry timber quality starting from the measurement of its characteristics in the wet condition. The parameter generally used in these studies for timber pre-grading is the dynamic modulus of elasticity $\mathrm{MoE_{dyn}}$, which nowadays is the most used feature in timber grading, evaluated through the measurement of the parameters associated with the propagation of acoustic waves in the material (velocity, frequency).

As reported in [39], wood has a structured hierarchy, dominated by a cellular and layered structure, and is composed of three constituents: lignin, hemicellulose, and cellulose. Cellulose and hemicellulose are hydrophilic, whereas lignin is less hydrophilic than hemicellulose. Cellulose crystalline regions and hemicellulose structure are responsible for the elastic behavior of wood under tension, and the presence of both hydrophobic and hydrophilic molecules explains why the mechanical properties of wood are strongly dependent on its water content. This behavior highlights the importance of understanding the mechanical properties of wood also in the wet condition.

This paper illustrates an experimental investigation aimed at determining the $\mathrm{MoE_{dyn}}$ in the wet and dry condition of Sardinian maritime pine boards. The $\mathrm{MoE_{dyn}}$ was determined by measuring the velocity of propagation of acoustic waves in the boards before and after the drying process.

Sardinian maritime pine is a wood species very common in Sardinia, currently under study as regards its possible structural use as glue-laminated timber (GLT) and cross-laminated timber (CLT). It is generally characterized by medium-low quality due to the presence of defects (knots, clusters of knots, resin pockets, grain deviation, etc.). Previous research about its yield for structural use showed that about 50% of the boards had to be rejected due to their defects [40–42], so that the possibility of defining the structural quality of the boards already in the wet state is a fundamental step to ensure the sustainability of the entire production process. In fact, the ability to provide a pre-grading on wet boards could significantly increase the profitability by saving the cost of drying and subsequent processing for non-structural grade boards sold at the same price whether wet or dry. This may lead to increased efficiency, energy savings, and lower costs.

The primary objectives of this study are to investigate the influence of moisture content on the MoE_{dyn} of Sardinian maritime pine, to quantify the variation of MoE_{dyn} from wet to dry condition and to examine the relationship between wet and dry MoE_{dyn} in Sardinian maritime pine, and to verify the feasibility of wet pre-grading of Sardinian maritime pine by means of the MoE_{dyn} determination from the velocity of propagation of acoustic waves in wet boards.

2. Materials

The wood analyzed in this study belongs to the maritime pine species (*Pinus pinaster*), coming from the forest in the internal area of Sardinia. The maritime pine is a heliophilous, moderately thermophilic species, which grows mainly in coastal and hilly areas where it finds optimal conditions of life around 800 meters above sea level. It grows in various soils, preferring in any case tendentially acid soils. Colonist par excellence, it propagates only by seed, dominating the vegetation and the land where it settles thanks to its rapid growth and its enormous dissemination capacity [43]. It is a very versatile species, and in Sardinia it has been widely used in forestry interventions as it has acclimatized on a much wider range than the original one. As it is not a particularly valuable species, the wood obtained from the pine forests is mainly used as fuel. However, maritime pine is successfully used for structural uses in other Italian and foreign regions and is present in the European standard EN 1912 [44] as a species graded for structural use. In recent years, a research has been started to evaluate the possibility of using Sardinian maritime pine as a structural material for laminated timber elements. This research addressed several aspects [40,41,45–51] including physical-mechanical performance and grading problems, and revealed that the material has not particularly high mechanical characteristics, but it can be used profitably in construction systems such as CLT, which allows to mitigate the medium-low quality of the material thanks to the lamination and the cross arrangement of the layers. The basic physical-mechanical properties of Sardinian maritime pine, as they result from the research already carried out [40], are the following: average density at 12% moisture content = 466 kg/m^3, average modulus of rupture (MoR) = 26,3 N/mm^2, and average static modulus of elasticity (MoE) = 7160 N/mm^2.

The experimental study described in the present paper was carried out on 91 boards of Sardinian maritime pine (Figure 1) whose average dimensions are reported in Table 1.

Figure 1. Sardinian maritime pine boards.

Table 1. Average dimensions of the boards.

Width [mm]	Thickness [mm]	Length [mm]
106.0 ± 3.0	42.6 ± 1.4	2799 ± 1.6

3. Methods

The boards underwent a first test session in wet conditions and a second test session after the natural drying process, when the moisture content reached an average value of about 12%. The natural drying process was carried out in a ventilated environment with a temperature of 25 °C and air relative humidity less than 65%, and had a variable duration depending on the initial moisture content of the boards. In both test sessions, weighing, acoustic velocity acquisition, and moisture content measurement, monitored daily during the drying process, were carried out. Each measurement was repeated three time, and the mean value was considered. The analyzed featured were mass m, moisture content U, density ρ, and propagation velocity V. Test sessions were run at temperature of 20 °C and air relative humidity less than 65%.

3.1. Measurement of Moisture Content

The saturation moisture of the cellular walls Us [%] indicates the moisture content level of the wood for which all cellular walls are completely saturated with water. If wood moisture is above the saturation point (U > Us), the water is in the liquid state in the lumen of the cells as the so-called free water or imbibition water. Variations of moisture above Us have very little influence on the physical-mechanical characteristics of the wood [52,53]. When the wood moisture is below the saturation point (U < Us), diffusion of water vapor in the lumens and bound water in the cell walls takes place. These two phases are not necessarily in local equilibrium and can be coupled via the sorption rate [54]. In this interval, the stored water has a decisive influence on the physical-mechanical characteristics of the wood [34,52]. Saturation moisture depends on the wood species and for most of them it is in the range $24\% \leq \text{Us} \leq 32\%$. Wood moisture can be measured or estimated. Direct methods provide for the measurement of the mass of water contained in the sample and the mass of the same in the anhydrous state, while indirect methods exploit the correlations existing between the moisture content of the wood and other physical quantities.

Among the indirect methods, the electrical resistance method [55] is generally applied. Wood is a very bad conductor of electricity and its resistivity decreases as moisture increases, and vice versa, following by and large an exponential law up to the saturation point, and then continues to decrease less markedly and regularly. This relationship is exploited to estimate the moisture content of the material starting from a measure of its resistivity. The most popular measurement method is based on the use of the hygrometer, an instrument that detects resistivity by means of metal electrodes embedded in the material. When using this equipment, two conditions must be considered: (1) the possible presence of a gradient between the various positions where the electrodes are fixed and (2) the measuring range. Practical experience shows that truly reliable results can only be obtained in the moisture range between a minimum of about 7% and a maximum of about 30% [55]. The wood directly in contact with the electrodes is what affects the measurement of resistivity, which depends on the wood species and the temperature; therefore, the instrument must be suitably calibrated according to the wood species on which the measurements are being made [55]. While direct measurements provide an average moisture value of the entire element, indirect methods return a local average value, and in order to obtain an average measurement it is suggested to repeat the measure at least in three points and at different depths, excluding the extremities and the areas with defects or anomalies (knots, etc.).

The instrument used for the tests is a Tramex PTM 6005 hygrometer which does not allow pre-calibration but allows the correction of the values according to the wood species, in this case maritime pine, through a conversion table supplied by the producer.

3.2. Measurement of Sonic Velocity

3.2.1. Theoretical

Various types of elastic waves can be produced in the matter, depending on the mode of excitation used. In the analysis of any type of wave, the material consisting of particles at rest, i.e., in a state of equilibrium, is considered. The average distances between the particles are on average constant, representing a condition of equilibrium between attractive and repulsive forces at the atomic or molecular level. If for some reason the particles are subject to moving away, the attractive forces prevail, so when the cause ceases, they return to their initial position; if they are subject to moving closer, repulsive forces prevail. Therefore, it can be said that, following the stresses, the particles undergo a shift from their position of equilibrium, and because of the elastic reaction of the material they tend to return to their primitive position. This applies if the stresses are contained within the elastic limits of the material.

In solids, the particles can oscillate in the direction of propagation as longitudinal waves or perpendicular to the direction of propagation as transverse waves. Longitudinal waves are commonly used in the field of non-destructive diagnostics [56,57], and are also used to estimate the mechanical parameters of the material in the context of this study.

The general equation of a longitudinal wave that propagates along a bar of section small with respect to the wavelength, and with section, density, and modulus of elasticity that remain constant along the longitudinal development of the bar itself can be written as

$$\partial^2 u/\partial x^2 - \rho/E\,\partial^2 u/\partial t = 0 \tag{1}$$

where x is the axis of the bar, u(x,t) is the temporary displacement that particles undergo under the action of the wave, t is the generic time, ρ is the density of the material, and E is the longitudinal modulus of elasticity that binds the longitudinal deformation ε to the pressure p induced by the passage of the wave.

Assuming

$$\rho/E = 1/V^2, \tag{2}$$

with V wave propagation velocity in the longitudinal direction, equation 1 takes the form

$$\partial^2 u/\partial x^2 - 1/V^2\,\partial^2 u/\partial t = 0 \tag{3}$$

This equation defines the longitudinal motion u(x,t) of the considered bar. The differential equation has a general solution of the form

$$u(x,t) = f_1(x - Vt) + f_2(x + Vt), \tag{4}$$

where $f_1(x - Vt)$ is a wave that propagates in a positive direction with a velocity $V = \sqrt{\left(\frac{E}{\rho}\right)}$ and $f_2(x + Vt)$ is a wave that propagates in a negative direction with a velocity $V = -\sqrt{\left(\frac{E}{\rho}\right)}$.

Wood is an orthotropic material, which means that its properties vary according to three mutually orthogonal directions, conventionally assumed to coincide with the longitudinal, radial, and tangential axes of a cylindrical coordinate system in which the longitudinal direction coincides with the axis of the trunk and then with the direction of the fibers of the material. Therefore, the velocity of an acoustic impulse that propagates in the wood depends on the direction of propagation too. The velocity in the longitudinal direction is the highest, being about five times greater than in the radial one, whereas the one in the tangential direction is the lowest [53,58].

When estimating wood elastic properties and grading structural timber, it is assumed that the propagation of a longitudinal sonic wave in a long and thin board can be assimilated to the phenomenon of propagation of the longitudinal wave in a thin bar previously described, as the use of a wavelength greater than the size of the natural non-homogeneities present in the wood satisfies the homogeneity requirement [59,60] so as the relation V= $\sqrt{\left(\frac{E}{\rho}\right)}$ is assumed valid, with V propagation sonic velocity, and E and ρ, respectively, the longitudinal modulus of elasticity and density of the wood. Therefore, the $\mathrm{MoE_{dyn}}$ can be calculated by means of the inverse relation

$$\mathrm{MoE_{dyn}} = \mathrm{E} = \rho \mathrm{V}^2 \tag{5}$$

3.2.2. Experimental

The boards were tested to acquire the velocity of a longitudinal sonic wave that propagates in the board from one end to the other. The instrumentation used consists of the following system (Figure 2):

- an impact hammer with piezoceramic sensor for generating the signal,
- a piezoelectric transducer for receiving the signal,
- a Velleman Instruments digital oscilloscope for signal visualization and preliminary analysis, and
- a PC for data storage and signal processing.

Figure 2. Instrumental set.

In order to reduce the dissipation of the signal caused by the difference in acoustic impedance of the two materials in contact, a layer of mastic was applied to the surface of the receiver in contact with the board and used as coupling agent. The test schematic is shown in Figure 3.

The test detects the time t taken by the wave impressed by the hammer at one end of the board to reach the receiver transducer placed at the other end. Known the length l of the table, assumed as the space travelled by the wave, the propagation velocity is obtained as

$$\mathrm{V} = \mathrm{l}/\mathrm{t}. \tag{6}$$

Note that V represents an apparent velocity, as it is calculated as a function of the distance l between the emitter and the receiver and not as a function of the real, unknown path that the wave travels inside the material. This approximation is widely accepted in the context of sonic and ultrasonic non-destructive testing. For each board, the measurement was repeated three times and the average of the results was considered.

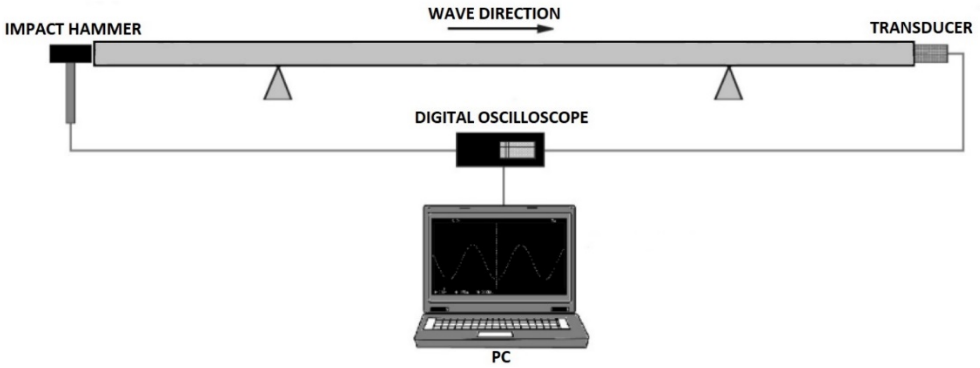

Figure 3. Test schematic.

4. Results and Discussion

Table 2 shows the variation of the quantities analyzed both in the wet and the dry conditions of the boards.

Table 2. Mean values of measured quantities in wet and dry conditions of the boards.

	U [%]	m [Kg]	ρ [Kg/m^3]	V [m/s]	MoE$_{dyn}$ [N/mm^2]
wet	22.5 ± 5.0	8.2 ± 1.4	646.2 ± 105.8	3477 ± 451	7743 ± 1595
dry	11.4 ± 0.7	6.3 ± 0.5	495.5 ± 34.8	4106 ± 330	8388 ± 1366

It can be noted that in the passage from the wet to the dry state, mass and density undergo an average reduction of 23%, whereas velocity shows an increase of 18%. There is also a reduction in the variability of the values, which in the dry state are less scattered. Figures 4 and 5 show the trend of density and velocity as functions of moisture content.

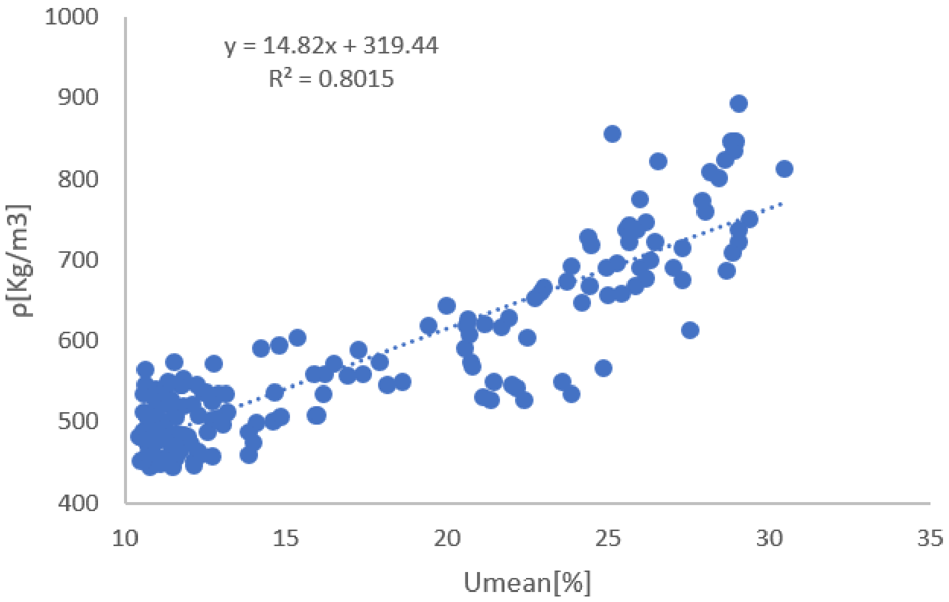

Figure 4. Density ρ as a function of moisture content U.

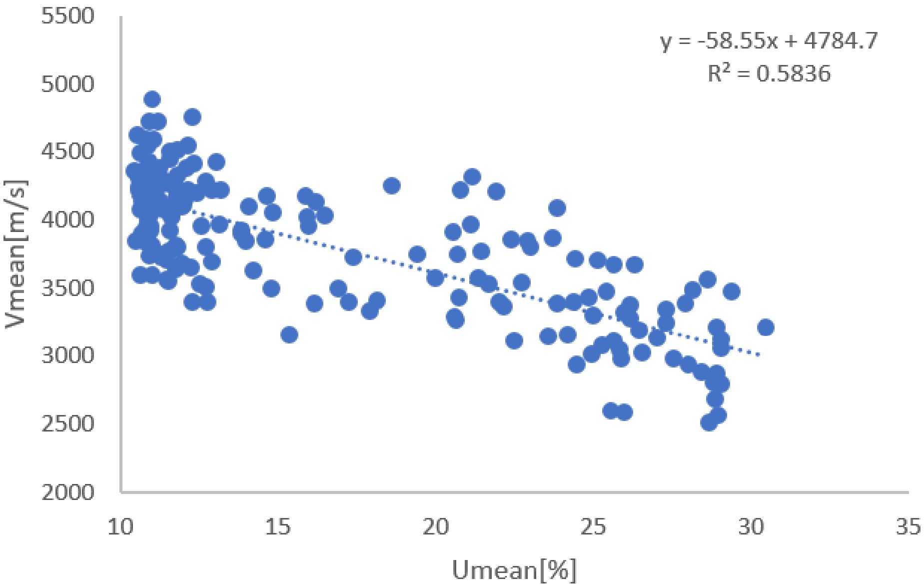

Figure 5. Velocity V as a function of moisture content U.

Density and velocity have an inverse relationship with moisture content with respect to each other. As the drying progresses and the moisture level decreases, a decrease in density is observed, as expected, resulting from the decrease in the water content inside the wood. On the contrary, the decrease in moisture content corresponds to an increase in the propagation velocity of the sonic wave, in accordance with the existing literature [61–63] on the relationship between wave velocity and moisture content, which presents different relationships depending on of the wood species. In most species, the increase in velocity from the wet state to the saturation point is not very significant, while from the saturation point to the dry state it is much greater; this is explained as follows [52]. For low water contents ($U < 18\%$), when water is present in the cell walls as bound water, the elastic wave is dispersed by the wood and the cell boundaries. The lateral units of OH or other radicals of the cellulosic material can reorient their position under the elastic stress. In this case, the attenuation mechanism related to the cellulosic cell wall material is probably the most important. With a higher moisture content but below the saturation point, scattering at the cell boundaries may be the most important loss mechanism. When the saturation point is exceeded and free water is present in the cell cavities, the porosity of the material takes over as a predominant factor in the dispersion of the elastic wave.

Starting from equation 5, the MoE_{dyn} value in the wet and dry conditions was calculated obtaining the average values shown in Table 3.

Table 3. MoE_{dyn} average values in wet and dry conditions.

	U [%]	**MoE_{dyn} [N/mm^2]**
wet	22.5 ± 5.0	7743 ± 1595
dry	11.4 ± 0.7	8388 ± 1366

In the transition from the wet to the dry condition, an increase in the average MoE_{dyn} of about 8% is observed. Figure 6 shows the variation of MoE_{dyn} with moisture content; an almost non-significant correlation is observed.

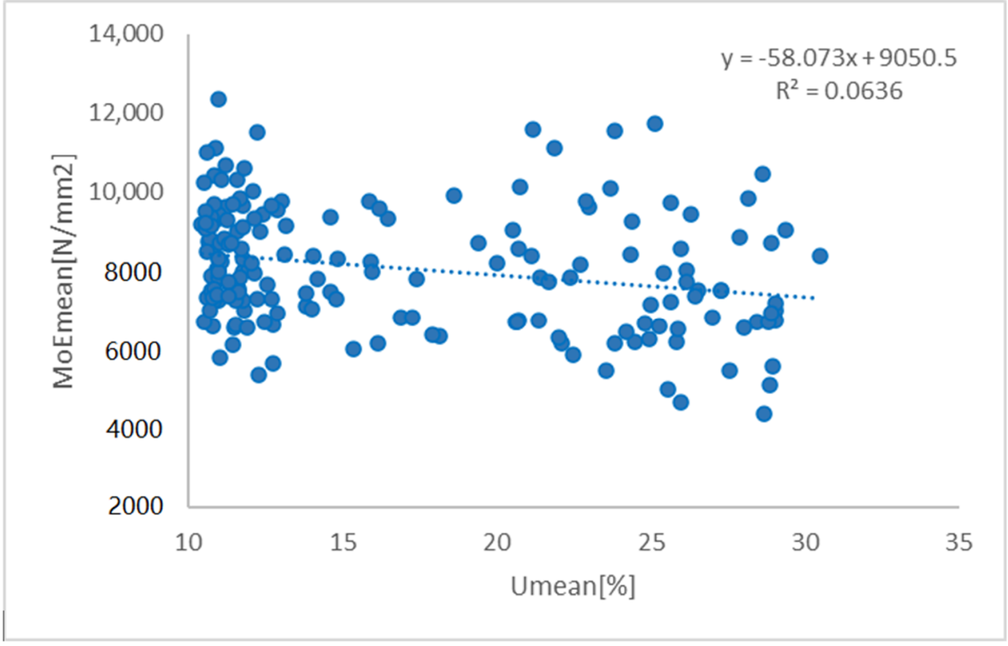

Figure 6. MoE_{dyn} variation with moisture content U.

Figures 7 and 8 show the relationship between MoE_{dyn} and, respectively, wood density and wave velocity in the wet condition, whereas Figures 9 and 10 show the same relationship in the dry condition. Figure 11 shows the trend with moisture of the ratio between density, velocity, MoE_{dyn}, and the respective mean values measured in dry condition.

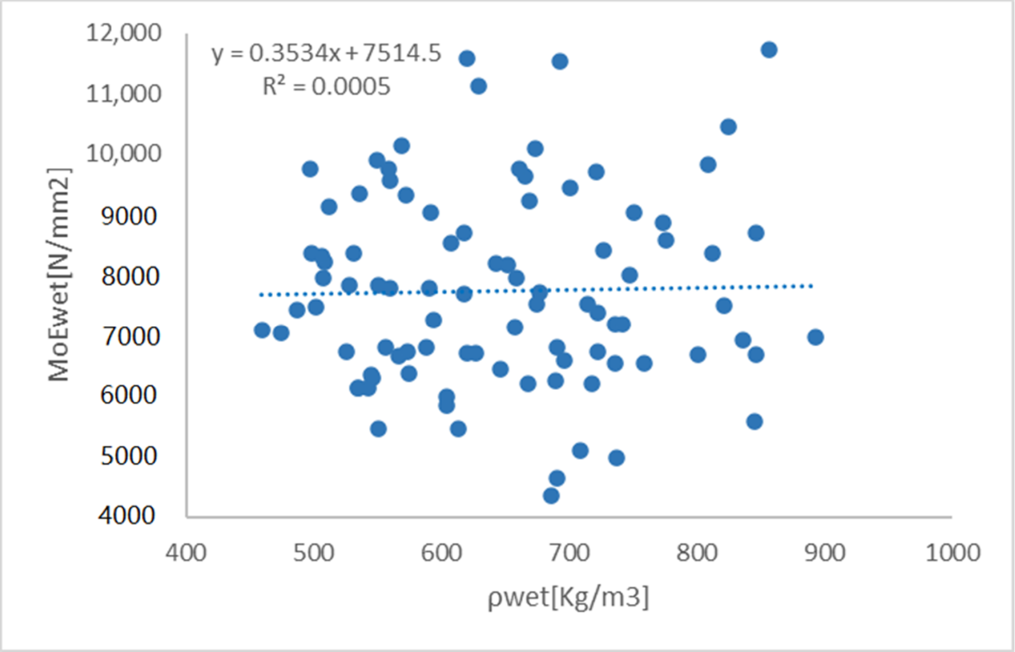

Figure 7. MoE_{dyn} vs. wood density ρ—Wet condition.

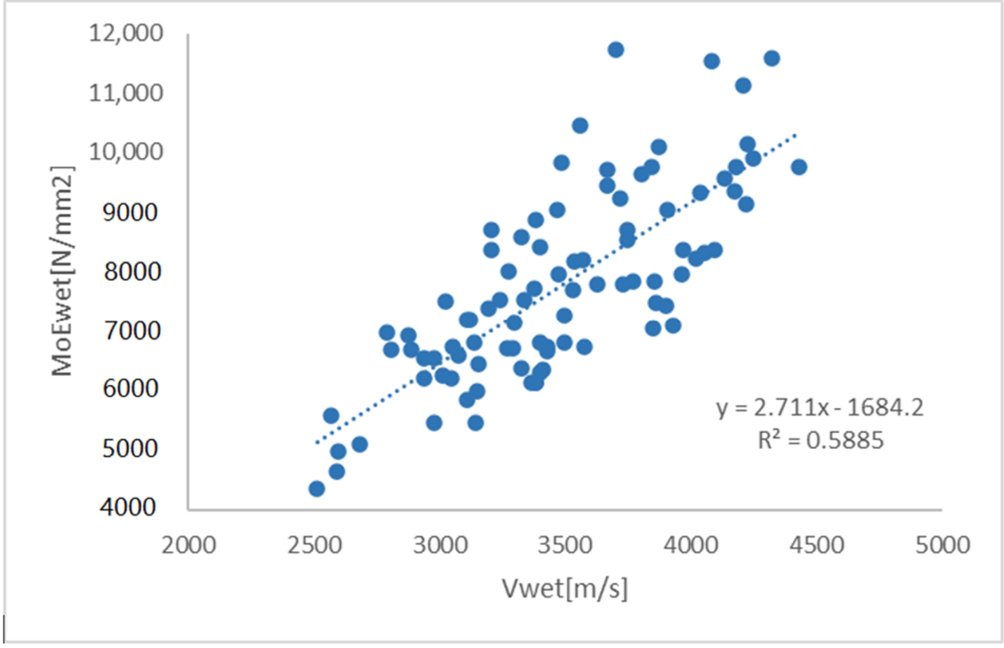

Figure 8. MoE_{dyn} vs. wave velocity V—Wet condition.

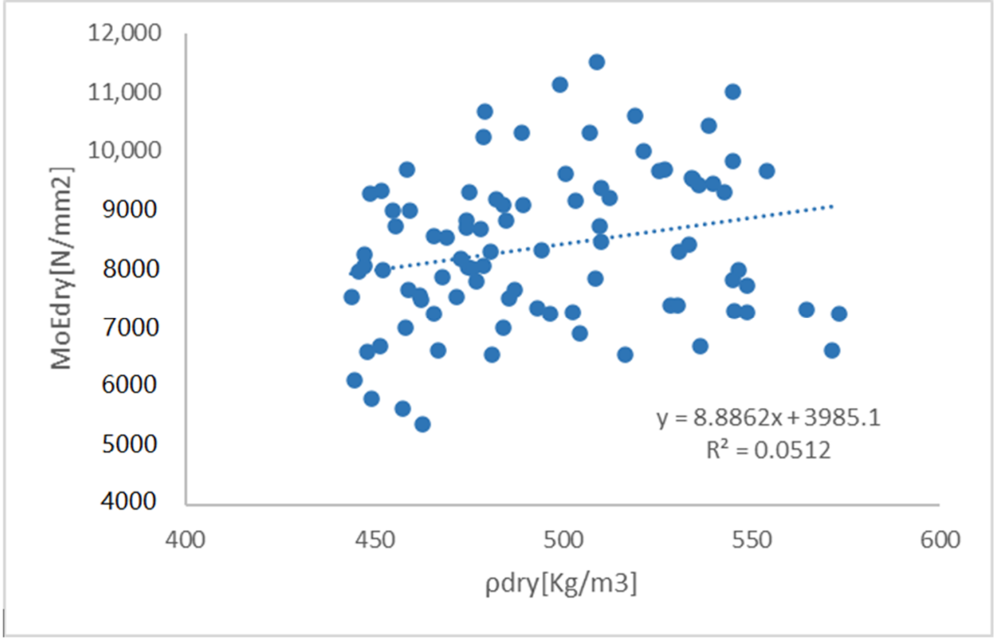

Figure 9. MoE_{dyn} vs. wood density ρ—Dry condition.

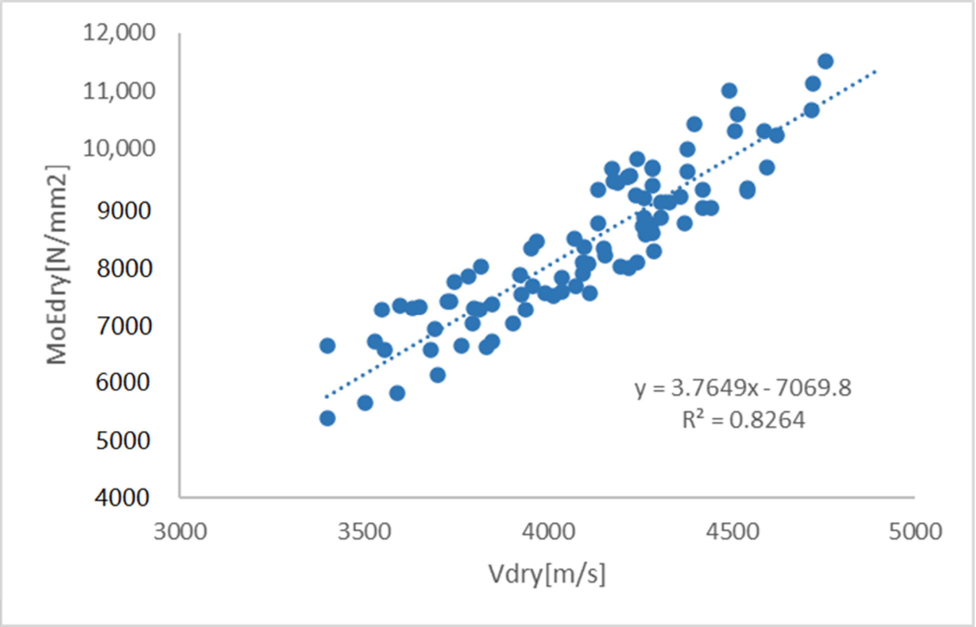

Figure 10. MoE_{dyn} vs. wave velocity V—Dry condition.

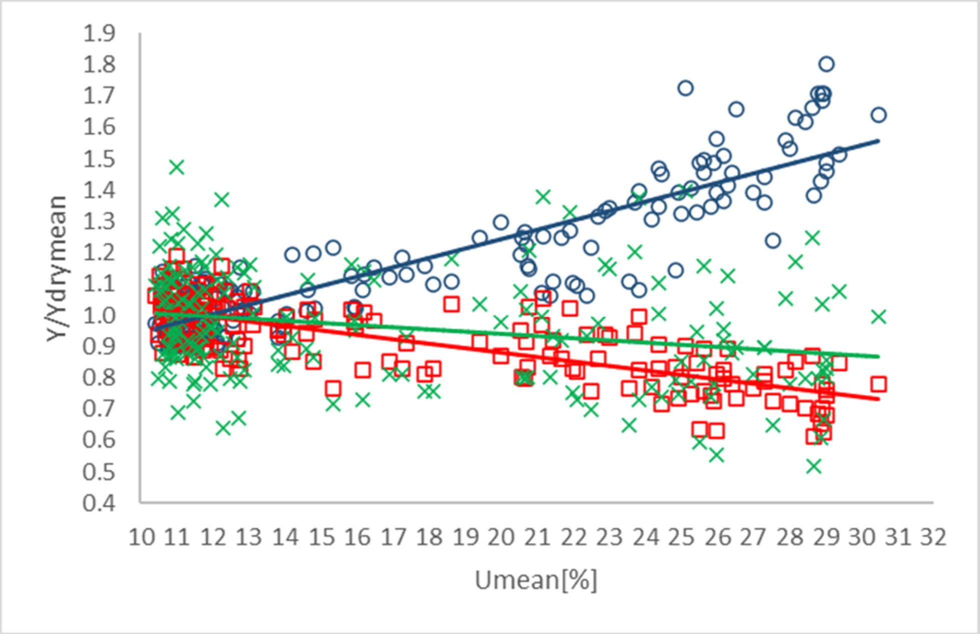

Figure 11. Ratio between feature (ρ, V, MoE_{dyn}) and mean feature measured in dry conditions ($\rho_{\text{dry,mean}}$, $V_{\text{dry,mean}}$, $\text{Mo}_{\text{Edry,mean}}$) vs. moisture content U. ○ is ρ / $\rho_{\text{dry,mean}}$; □ is $V/V_{\text{dry,mean}}$; × is $\text{MoE}_{\text{dyn}}/\text{MoE}_{\text{dry,mean}}$.

It can be observed that the limited increase in MoE_{dyn} in the passage from the wet to the dry condition and the poor correlation with moisture content (Figure 6) are due to the inverse proportionality that density and velocity have with MoE_{dyn}. As MoE_{dyn} is proportional to V^2, the greater weight of velocity with respect to density in the determination of MoE_{dyn}, also shown by the better degree of correlation (see R^2 in Figures 7–10), means that as the moisture content decreases, the MoE_{dyn} increases as the velocity, but to a lesser extent, because it is counterbalanced by the decrease in density (Figure 11). This trend of MoE_{dyn} is in line with literature [29,30,36].

Figure 12 shows the relationship between MoE_{dyn} in the wet and in the dry conditions. A determination coefficient R^2 of about 0.8 can be observed, indicating the good level of correlation between the two parameters. By following the simple linear regression analysis, and taking into account that the coefficient R^2 indicates the portion of the total variance of a quantity attributable to the predictor parameter, a relationship can be introduced to estimate the value of MoE_{dyn} in the dry condition starting from the values measured in the wet one:

$$MoE_{dry} = 0.7614MoE_{wet} + 2492.3. \quad (7)$$

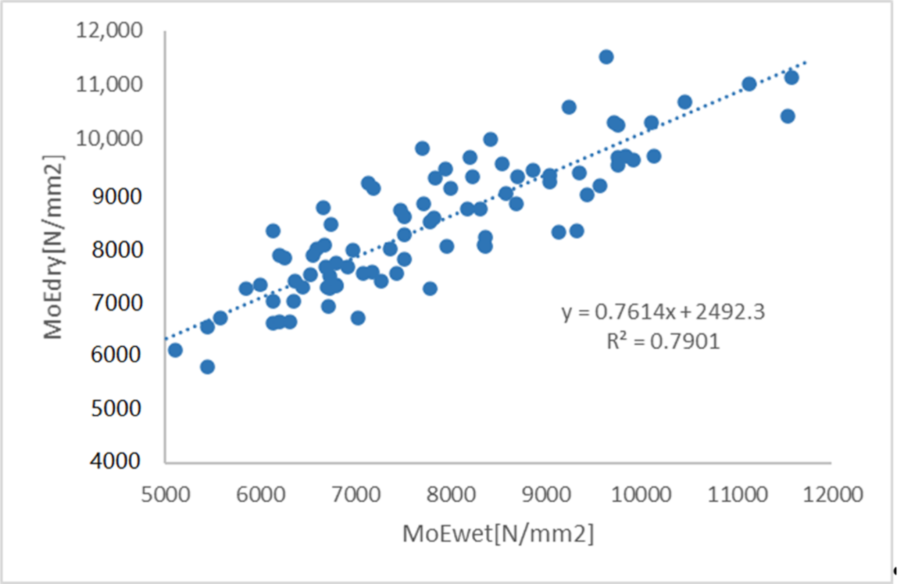

Figure 12. MoE_{wet} vs. MoE_{dry}.

Again, for predictive purposes, it is useful to highlight the relationship between MoE_{dyn} in the dry condition and density and wave velocity measured in the wet condition, that is, the two parameters directly measured on wet boards. Figures 13 and 14 show these relationships.

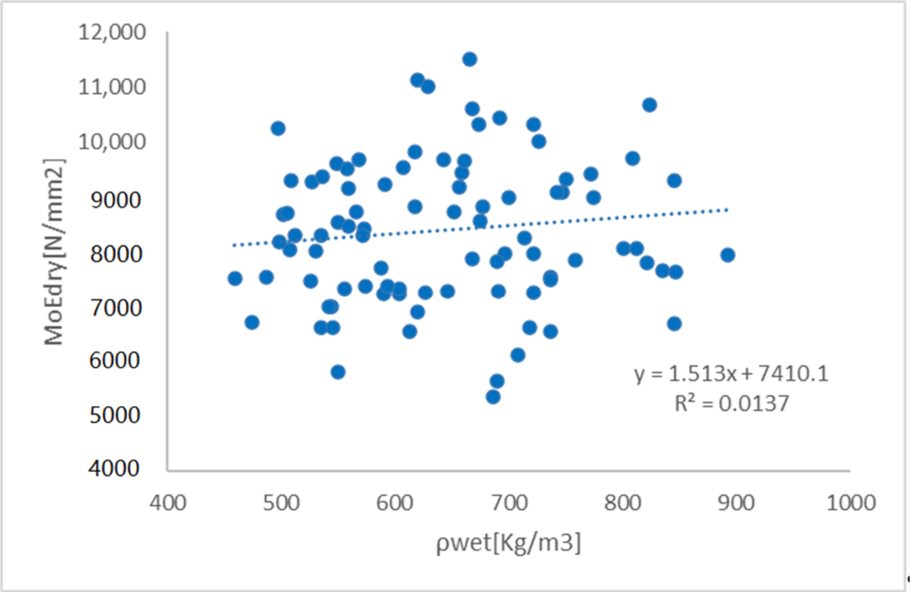

Figure 13. MoE_{dry} vs. density in wet condition.

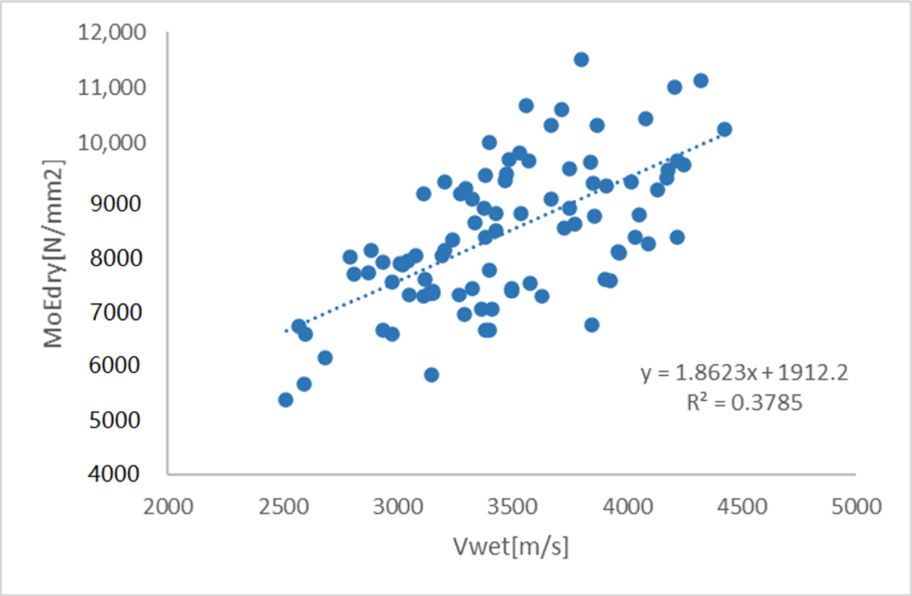

Figure 14. MoE_{dry} vs. wave velocity in wet condition.

It can be noted a little significant correlation with density and a more significant one with propagation velocity, even if R^2 is lower than that between MoE_{dry} and MoE_{wet}. This is because MoE_{dyn} is in any case determined by the relation $V = \sqrt{\left(\frac{E}{\rho}\right)}$ and therefore influenced by both V and ρ.

It is interesting to note that if a two-variable regression analysis is implemented, assuming ρ_{wet} and V_{wet} as predictive parameters and MoE_{dry} as the predicted feature, a clear improvement of the coefficient of determination, being in that case $R^2 = 0.7653$, and therefore of the degree of correlation between the parameters is obtained. This leads to an improvement of the MoE_{dry} estimate compared to the case of linear regressions with a single variable (ρ_{wet} or V_{wet}). The statistical parameters of the two-variable linear regression are the following: intercepting point = −9823.7, ρ_{wet} coefficient = 10.2, and V_{wet} coefficient = 3.3.

Based on this result, a straightforward relationship can be introduced to estimate MoE_{dyn} in the dry condition starting from density and propagation velocity measured directly on wet boards, bypassing MoE_{dyn} computing in the wet condition:

$$MoE_{dry} = 10.2\rho_{wet} + 3.3V_{wet} - 9823.7. \tag{8}$$

It is worth highlighting that the obtained relations can be considered valid only for the sample of board examined in this study. To extend the validity to the wood species under study, an experimental campaign on a larger sample suitably representative of the same species is necessary.

The results just presented point out the good correlation between the dynamic modulus of elasticity measured in dry condition and the same feature measured in wet condition, leading to the possibility of estimating MoE_{dry} from MoE_{wet}. The potential of getting MoE_{dry} prediction with a two-variable linear regression model that considers board density and sonic velocity as predictive features—without the need to calculate MoE_{wet}—is also assessed. Existing studies on Sardinian maritime pine [41,45] show a high correlation between the dynamic modulus of elasticity derived from sonic measurements in dry conditions and the main static mechanical characteristics of the material, such as strength and stiffness, which define the performance profile of the material itself and allow its sorting in strength classes according to standards. Therefore, the dynamic MoE_{wet} derived from sonic velocity measurements on wet boards can be considered indicative of the mechanical quality of dry boards. Future studies on Sardinian maritime pine will be aimed at the analysis of the direct correlation between the dynamic MoE_{wet} and the main characteristics that contribute to the attribution of a strength class to the board, that is, static strength and stiffness, and material defects, in order to perform an out-and-out classification of the tables since in the wet state.

5. Conclusions

An experimental investigation aimed at investigating the relationship between wet and dry dynamic modulus of elasticity MoE_{dyn} in Sardinian maritime pine has been carried. MoE_{dyn} of Sardinian maritime pine boards both in the wet and dry conditions has been determined from measurements of the velocity of sonic waves propagating from one end of the boards to the other. The correlations between the parameters involved have been studied.

The following conclusions can be drawn.

- In the passage from the wet to the dry state, mass and density undergo an average reduction of 23%, whereas sonic velocity and MoE_{dyn} show an increase of about 18% and 8%, respectively.
- The inverse dependence of MoE_{dyn} with respect to density and sonic velocity and the greater weight of velocity in the variation of MoE_{dyn} from wet to dry state are highlighted.
- The linear regression analysis for predicting MoE_{dry} from MoE_{wet} points out the good level of correlation between the two parameters, being the determination coefficient R^2 about 0.8, and allows to implement a relationship to estimate MoE_{dyn} in the dry condition starting from MoE_{dyn} measured in wet condition.
- A two-variable regression model, assuming ρ_{wet} and V_{wet} as predictive parameters and MoE_{dry} as the predicted feature, gives a determination coefficient R^2 of about 0.76, and allows to implement a straightforward relationship to estimate MoE_{dyn} in the dry condition starting from density and propagation velocity measured directly on wet boards, bypassing MoE_{dyn} computing in the wet condition.

Further research will exploit the relationship between the dynamic MoE_{wet} derived from sonic velocity measurements on wet boards and static strength, stiffness, and material defects, in order to verify the feasibility of Sardinian maritime pine grading since in the wet condition.

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