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Machine Grading of High-Density Hardwoods (Southern Blue Gum) from Tensile Testing

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Abstract: Hardwoods commonly have high mechanical properties, which makes them interesting for structural use, but softwoods dominate the structural timber market in Europe. Tensile strength classes are recommended for engineered wood products. However, current European standards do not provide tensile strength classes for hardwoods and the declaration of tensile properties from machine grading in the industry is not yet possible. The present paper aims to contribute to the revision of European standards through the technical group CEN/TC124/WG2/TG2: Tensile strength classes for hardwoods, of the European Standardisation Committee. An experimental campaign which involved machine grading and tensile testing of over 569 boards of Southern blue gum (*Eucalyptus globulus* Labill.) from Spain and Portugal was made. Six new tensile strength classes were defined, from ET24 ($f_{t,0,k}$ = 24 N/mm^2, $E_{t,0,m}$ = 18 kN/mm^2 and ρ_k = 590 kg/m^3) to ET42 ($f_{t,0,k}$ = 42 N/mm^2, $E_{t,0,m}$ = 23 kN/mm^2 and ρ_k = 640 kg/m^3). Machine grading made possible the definition of six strength class combinations. Four combinations resulted in 40% of the sample being assigned to the higher strength class, with low percentages of rejection (varying between 1% and 14%). This demonstrates the high mechanical properties of the species and the performance improvement of machine grading with respect to current visual grading.

Keywords: dynamic modulus of elasticity; EN 14081-2; *Eucalyptus globulus* Labill.; indicating property; mechanical properties; non-destructive testing; strength class combinations; tensile strength

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1. Introduction

Portuguese and Spanish forests are mainly occupied by hardwoods, these having registered a significant increase of area in the last decades. According to the most recent National Inventories, in Spain, data from 2019 refers to 55.5% (10.184 million hectares) of forest land occupied by hardwoods (mixed stands not included) [1]. On the other hand, in Portugal, hardwoods represent 63.7% (2.055 million hectares), mixed stands not included [2]. In both countries, these percentages have been increasing over the last 50 years.

Southern blue gum (*Eucalyptus globulus* Labill.) is considered a fast-growing species and, according to Cesarolli et al. [3], in Europe covers 1.3 million hectares of forest, mainly in the Iberian Peninsula (more than 80%), France and Italy. Currently, it is one of the most representative hardwood species in the Iberian Peninsula with 619.9 kha in Spain (data from 2019) [1] and 845 kha in Portugal (data from 2015) [2]. *Eucalyptus* is mainly used in the pulp and paper industry, energy production and as firewood. However, cascading use of wood leads to a need to adapt the sector to the circular economy and bioeconomy strategies. A piece of wood may experience several reuse, recovery and/or recycling loops, where high-quality wood is used for high-value products (solid wood or engineered wood products), with lower-value products employing wood in transformed forms over its lifespan (particle based products, fiber based products, chemical products and finally incineration for energy) [4]. Since buildings are responsible for around 30% and 36% of the total waste per year and greenhouse gas emissions generated by the EU, respectively, the construction products regulation (Regulation No 305/2011) [5], which establishes the conditions for marketing of construction products and conditions for obtaining CE marking, is currently under review, with the aim of assessing the environmental and climate performance of these construction products [6]. Current sawn wood volume production worldwide is mainly focused on softwood species and it is expected that 50% of softwood production will be destined for construction purposes by 2030 as a substitute for steel, concrete and masonry [7]. According to data from FAOSTAT (2022), softwood sawn wood production in Europe accounts for around eight times that of hardwoods production [8]. Given the expected increase in hardwood demand, there is an opportunity for hardwoods to be used for structural purposes.

Some studies have reported that Southern blue gum, associated with high density, has higher mechanical properties which are of utmost interest for load-bearing timber structures. However, there are several issues related to sawing and drying processes that have been addressed during the last decades in order to avoid cross-section collapse and/or internal drying cracks [9,10]. Despite this, the advances were not enough to promote a significant increase of the use of Southern blue gum as sawn wood for structural applications. However, and despite the energy cost associated with drying for *Eucalyptus* species in general, there are some examples of complex structures built worldwide, such as the 3D structure of the Atchugarry Contemporary Art Museum in Uruguay, with curved rose gum (*Eucalyptus grandis* W. Hill) beams up to 26 m span [8], or the Southern blue gum grid-shell structure of the Impulso Verde building in Spain [11].

According to the available local standards, in Spain, blue gum is visually graded as MEF by the Spanish standard UNE 56546 [12]. The same standard refers to cross-sections below or equal to 60×200 mm^2, a characteristic value of bending strength of 46.4 N/mm^2, an average modulus of elasticity of 18.4 kN/mm^2 and average density of 792 kg/m^3, this being recognized in the EN 1912 [13] as D40. On the other hand, in Portugal, a technical data sheet, M6, from 1997 and developed by the National Laboratory of Civil Engineering (LNEC), refers only to some patterns associated with blue gum and average values of mechanical properties from clear wood specimens, i.e., density between 750 to 850 kg/m^3, bending strength of 127.5 N/mm^2 and modulus of elasticity of 17.5 kN/mm^2 [14].

Nowadays, the EN 338 [15] does not provide strength classes for hardwood species tested for tension in Europe. Even though visual grading is the most widely used method in Spain and Portugal for declaring the physical and mechanical properties of wood species, it becomes less efficient in terms of structural performance, material optimisation and grading time than machine grading [16–19]. Nevertheless, there is no European standard providing machine graded species by country and their corresponding strength classes, as is the case for visual grading (EN 1912—[13]). However, to obtain the CE marking, mandatory for marketing of construction products according to EU Regulation for construction products (EU No 305/2011) [5], machine grading of timber species is carried out using homologated equipment by the European Committee of Standardisation (CEN). Current homologated equipment is listed at the location of the convener of the task group for grading and strength properties (TG1) [20] of the working group *Solid Timber* of the Technical Committee *Timber Structures* (CEN TC124 WG2), but new ones can be used for machine grading after the approval of repeatability tests defined in EN 14081-2 [21].

Based on EN 14080 [22], which provides the requirements, quality control and strength properties for glued laminated timber (glulam), the use of tensile properties from sawn wood is more adequate for designing its mechanical properties. Due to the need for the generation of tensile strength classes for European hardwoods, a new technical group was created in 2022 (CEN/TC124/WG2/TG2 *Tensile Strength Classes for Hardwoods*) with the aim of including these in a future version of the standard defining the strength classes (EN 338—[15]). Thus, in the last decade some studies were performed on the visual and machine grading of European hardwoods in tension, with special attention to European beech (*Fagus sylvatica* L.) [23–26], European ash (*Fraxinus* spp.) and maple (*Acer* spp.) [27]. Despite some studies focusing on the machine grading of hardwood species tested in tension, Southern blue gum from Spain and Portugal was the first and only hardwood species whose machine grading from tensile tests was approved by CEN. This paper presents the results from the testing of the report approved by CEN/TC124/WG2/TG1 [28], and whose results database has already been shared with CEN/TC124/WG2/TG2, contributing to the revision of EN 338 [15].

The use of Southern blue gum sawn wood for structural applications such as glulam has been considered in some research studies, in terms of bonding performance [29,30] and mechanical properties [31–33]. Its combination with other species has also been addressed, showing huge potential due to higher structural efficiency, especially when combined with poplar (*Populus alba* L., *Populus nigra* and *Populus x canadensis*) [31] or the combination of *Eucalyptus grandis* with poplar (*Populus x euroamericana* "Neva") [34].

The present paper aims to perform machine grading, using non-destructive equipment homologated by CEN, of the mechanical properties of Southern blue gum from the Iberian Peninsula in tension, contributing to the creation of tensile strength classes for hardwood species. Therefore, sawn wood from Portugal and Spain was collected from four different locations to ensure a reliable sampling for the characterization of the existing raw material.

2. Materials and Methods

2.1. Raw Material

A total of 569 boards of Southern blue gum were used for this study. The raw material was separated in five different samples (four distinct provenances), three from Spain and two from Portugal. For better comprehension, samples were named EG as an abbreviation of *Eucalyptus globulus* Labill. EG1 and EG2 were collected from the southern part of Galicia (coast and interior), while EG3 covers the north of Galicia. In terms of Portuguese grown Southern blue gum, EG4 corresponds to raw material from Viana do Castelo and EG5 from Porto (Figure 1). Due to the economic relations between both countries, Portuguese blue gum sold in Spain could be easily found, and vice-versa. The common length of logs is about 2.5 m (3.0 m maximum) and, consequently, the timber boards are sawn according to that. Nominal dimensions of each sample and respective sub-samples are presented in Table 1. All samples were stored in laboratory facilities, under environmental conditions, with temperature and relative humidity close to standard conditions.

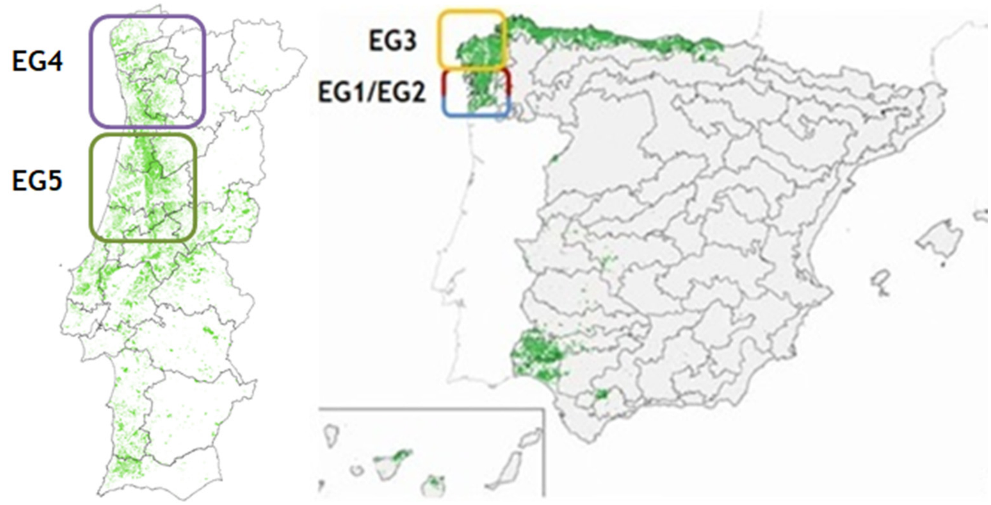

Figure 1. Location of regions from where the samples were taken in Portugal (**left**) and in Spain (**right**): EG1/EG2: Pontevedra; EG3: Coruña; EG4: Viana do Castelo; EG5: Porto.

Table 1. Summary of samples, provenance, nominal dimensions of cross-sections (average dimensions in brackets) and average length.

Sample	Sub-Sample	Provenance	Width (mm)	Thickness (mm)	Length (mm)	No. of Specimens	
EG1	EG1_1	Pontevedra (Spain)	90 (90)	30 (28)	2565	59	117
	EG1_2		110 (110)	30 (29)	2570	58	
EG2	EG2_1	Pontevedra (Spain)	85 (90)	20 (21)	2565	55	110
	EG2_2		110 (106)	27 (23)	2560	55	
EG3	EG3_1	Coruña (Spain)	120 (120)	30 (29)	2575	59	117
	EG3_2		140 (140)	30 (28)	2545	58	
EG4	EG4_1	Viana do Castelo (Portugal)	100 (101)	30 (29)	2565	57	107
	EG4_2		130 (131)	30 (29)	2540	50	
EG5	EG5	Porto (Portugal)	140 (140)	30 (26)	3090	118	

2.2. Non-Destructive Characterization

The non-destructive characterization followed the longitudinal vibration method, which considers the determination of the frequency of the first vibration mode and was applied to the whole sample (569 boards). It started by the measurement of its dimensions: (i) length; (ii) width; (iii) thickness; and also, its (iv) mass and (v) moisture content. The cross-section dimensions were measured in three different locations (both ends and mid-length). A similar procedure was followed for moisture content, which was recorded by an electrical moisture meter at a distance of 0.6 m from both ends and mid-length, as required by EN 13183-2 [35]. The data were used as input for the "Timber Grader MTG" software program (brookhuis.com, accessed date: 30 June 2023) for setting the handheld MTG-960 (Timber Grader MTG 960 by Brookhuis Applied Data Intelligence B.V., Enschede, The Netherlands). Samples EG1 to EG4 were non-destructively graded in dry conditions according to EN 14081-1 [36] (mean moisture content below 20% and no individual values above 24%) between June and August 2020 in the laboratory of Cesefor in Soria, Spain, while the EG5 sample was also graded in dry conditions between August and September 2021 in the laboratory of SerQ in Sertã, Portugal. (Figure 2). Table 2 presents the moisture content from each sample at the grading moment and the mechanical tests.

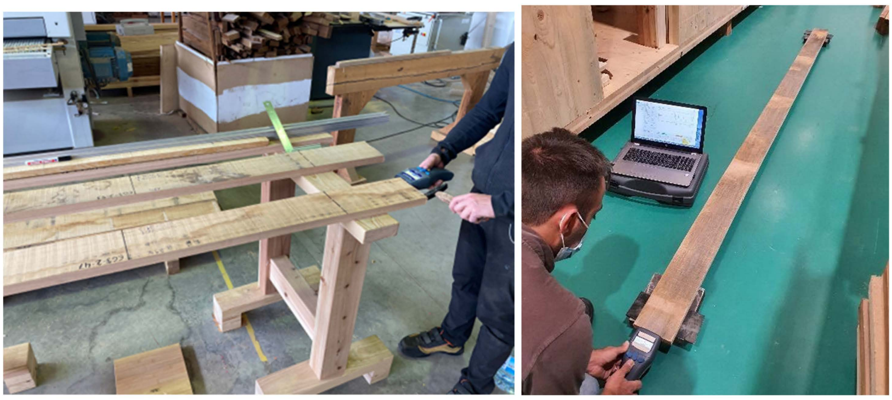

Figure 2. Measurements with MTG960 in the laboratory of Cesefor (**left**) and SerQ (**right**).

After each test, the indicating property (IP), which for this work was considered as the dynamic modulus of elasticity, E_{dyn}, was computed through the following Equation (1).

$$E_{dyn} = ((2 \times f_0 \times L \times CF_{Brookhuis})^2 \rho \times 10^{-6} \quad (1)$$

where f_0 is the natural frequency of vibration (Hz), L is the length of the specimen (mm), $CF_{Brookhuis}$ is the correction factor given for moisture content by the manufacturer as shown in Equation (2) [37], and ρ is the density (kg/m^3).

$$CF_{Brookhuis} = \begin{cases} 1 & u \leq 12\% \\ \left(1 - \frac{0.1(u-12)}{13}\right)^{-1} & 12\% < u \leq 25\% \\ (0.9)^{-1} & u > 25\% \end{cases} \quad (2)$$

where u is the average moisture content obtained by the electrical moisture meter.

The settings to be implemented in the machine grading with the aim of assigning the strength classes to each IP value were derived from EN 14081-2 [21]. The methodology for the determination of the optimum grading, size matrix, elementary cost matrix and global cost matrix is described in Moltini et al. [16] and summarised in Figure 3.

Table 2. Average values from non-destructive and static tests (in brackets, the coefficient of variation as %).

Sub-Sample	EG1-1	EG1-2	EG2-1	EG2-2	EG3-1	EG3-2	EG4-1	EG4-2	EG5	All
Sample	EG1		EG2		EG3		EG4			
Specimens	59	58	55	55	59	58	57	50	118	569
	117		110		117		107			
$f_{t,0}$ (N/mm^2)	85.3	70.9	101.5	70.6	65.7	69.6	74.6	71.3	84.0 (33.8)	77.8 (16.2)
	78.2 (32.0)		86.1 (34.7)		67.7 (27.4)		73.1 (32.6)			
$E_{t,0}$ (kN/mm^2)	21.8	21.6	23.9	19.7	21.7	20.9	21.1	21.4	20.4 (15.5)	21.3 (20.5)
	21.7 (18.7)		21.8 (27.0)		21.3 (19.1)		21.2 (20.8)			
E_{dyn} (kN/mm^2)	21.8	22.8	25.2	20.6	21.7	21.2	21.0	21.5	19.0 (14.3)	21.4 (20.1)
	22.3 (17.0)		22.9 (25.5)		21.5 (16.1)		21.2 (19.0)			
ρ (kg/m^3)	877	851	868	870	861	847	817	835	789 (10.3)	840 (10.4)
	864 (10.5)		869 (10.3)		854 (9.5)		826 (11.0)			
$W_{grading}$ (%)	16.7 (9.1)		12.6 (14.9)		16.5 (10.4)		15.5 (8.5)		14.7 (6.2)	15.2 (13.7)
$W_{testing}$ (%)	9.3 (15.9)		9.6 (7.9)		10.0 (8.3)		10.3 (13.2)		12.8 (8.8)	10.4 (16.3)

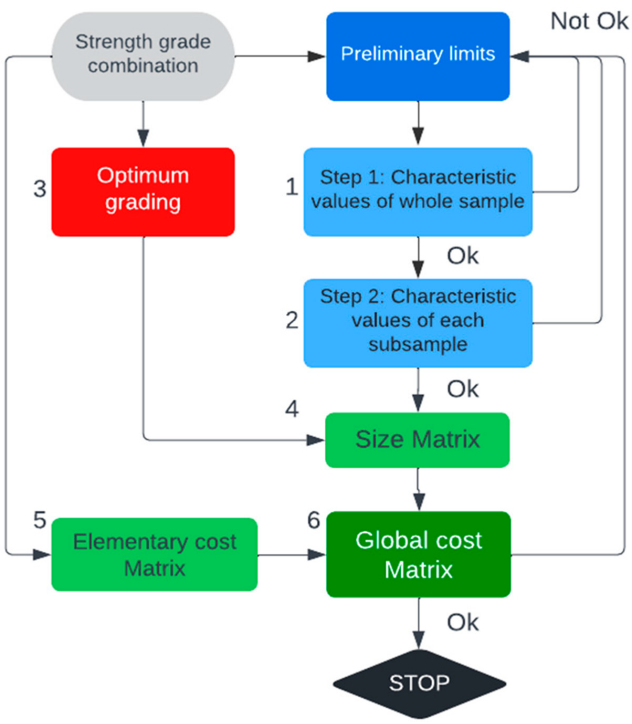

Figure 3. Scheme of the settings derivation [16].

2.3. Tensile Tests

The determination of mechanical properties of sawn wood follows EN 408 [38], and in the present study tensile tests were performed following the standard, both for modulus of elasticity, $E_{t,0}$, and tensile strength parallel to grain, $f_{t,0}$.

For both mechanical properties mentioned, the standard requires that the specimens should have a minimum length that allows for a clear length, between machine grips, of at least nine times the larger cross-sectional dimension. The specimens were gripped with a length of 400 mm on both ends (500 mm for EG5 sample). Modulus of elasticity determination comprised the measurement of the deformation over a length corresponding to five times the width. At the Cesefor facilities, two extensometers were considered and the mean value was adopted, while at SerQ two linear displacement transducers of 25 mm maximum capacity were coupled to a device (Figure 4). Whenever possible, the critical section was located within the tested range and modulus of elasticity was determined in the linear range of the stress–strain diagram between 10% and 40% of the maximum load, with a correlation coefficient between applied load and displacement of at least 0.99. The maximum load capacity of the hydraulic actuator was 500 kN. Modulus of elasticity in tension parallel to grain is determined through Equation (3).

$$E_{t,0} = \frac{l_1(F_2 - F_1)}{A(w_2 - w_1)} \quad (3)$$

where $F_2 - F_1$ is the load increment on the straight line portion of the deformation curve (N); $w_2 - w_1$ is the displacement increment corresponding to $F_2 - F_1$ (mm); A is the cross-sectional area (mm^2); and l_1 is the distance between measurement points (mm).

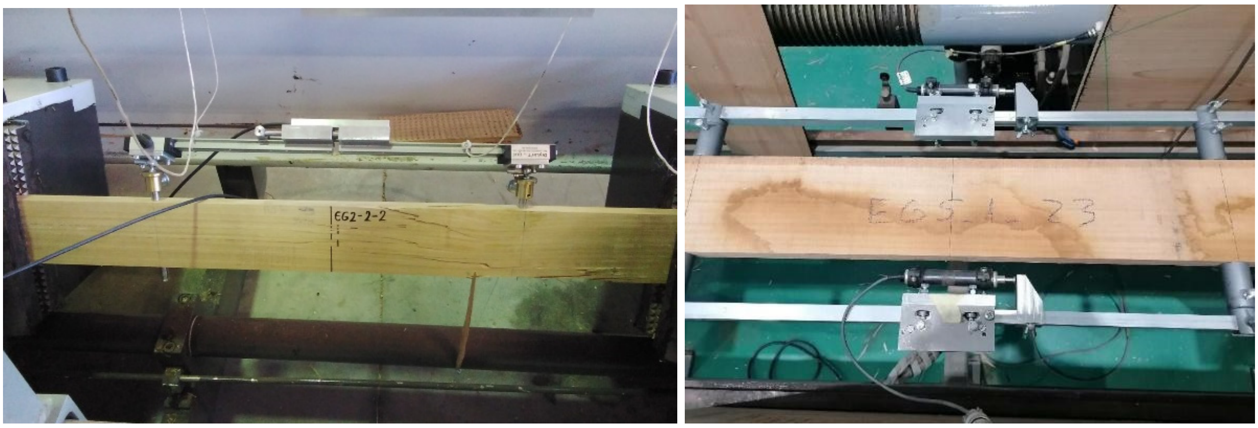

Figure 4. Tensile test layout at Cesefor (**left**) and SerQ (**right**).

The tension strength parallel to grain $f_{t,0}$ was determined with the same layout, only the applied load being recorded, which was considered in a constant rate of head movement so that the maximum load is reached in (300 ± 120) s. Equation (4) allows the determination of tensile strength.

$$f_{t,0} = \frac{F_{max}}{A} \quad (4)$$

where F_{max} is the maximum load applied during the test (N); and A is the area of the cross-section (mm^2).

After each test, a slice from the full cross-section was obtained from each specimen from a location as close as possible to the failure zone and without defects. This allowed determination of the density and the moisture content in accordance with EN 13183-1 [39].

3. Results and Discussion

3.1. Mechanical Properties

Average and coefficient of variation (CoV) values from all sub-samples are presented in Table 2 for physical (density, ρ, moisture content at grading, $W_{grading}$ and testing, $W_{testing}$) and non-destructive measurements (dynamic modulus of elasticity, E_{dyn}), as well as tensile modulus of elasticity, $E_{t,0}$ and tensile strength, $f_{t,0}$.

The analysis from Table 2 shows that the longitudinal vibration method provides closer average values to the static modulus of elasticity, being conservative in the EG5 sample. Considering the provenance of the samples, it is observed that EG4 and EG5, both from Portugal, had the lowest densities compared to EG1, EG2 and EG3, which are quite similar. Despite the differences between densities, the modulus of elasticity results are similar (between 21.2 kN/mm^2 and 21.8 kN/mm^2), being lower for EG5 (20.4 kN/mm^2). On the other hand, the tensile strength varied significantly, the lowest value being for EG3 (A Coruña) and the highest for EG2 (Pontevedra). Samples from Portugal were also quite different at EG5 (84.0 N/mm^2), 14.9% higher than EG4 (73.1 N/mm^2).

Considering the results from the sub-samples, there are no significant differences between densities, while a significant variation was observed between sub-samples EG2-1 and EG2-2 of 4.2 kN/mm^2 for modulus of elasticity and 30.9 N/mm^2 for tensile strength. A half of the variation (14.4 N/mm^2) was observed for tensile strength between sub-samples EG1-1 and EG1-2. This variation shows a clear relation between the area of the cross-section of all sub-samples and the mechanical properties. A regression analysis considering the cross-section area provided determination coefficients of 0.45 for tensile strength and 0.42 for modulus of elasticity, corresponding to the higher mechanical properties for smaller cross-sections, which could somehow be related to the lower probability of defects occurring.

3.2. Adjustement Factors and Characteristic Values

According to EN 384 [40], mechanical properties should be adjusted to reference conditions, such as a moisture content of 12%, applicable to both density, $\rho_{12\%}$ (Equation (5)) and modulus of elasticity, $E_{0,t,12\%}$ (Equation (6)); the characteristic value for modulus of elasticity is also calculated. In terms of tension strength, the results should be adjusted to a reference size of a specimen of 150 mm width divided by the factor k_h, as the characteristic density of the whole sample was less than 700 kg/m^3 (Equation (7)). The characteristic values of tensile strength, $f_{t,0,k}$, are calculated considering a non-parametric approach and are presented in Table 3.

$$\rho_{12\%} = \rho_w \left(1 - 0.005(w - 12\%)\right) \tag{5}$$

$$E_{0,t,12\%} = E_{0,t,w} \left(1 + 0.01(w - 12\%)\right) \tag{6}$$

$$k_h = min\left((150/h)^{0.2};\ 1.3\right) \tag{7}$$

where ρ_w and $E_{0,t,w}$ are the density and the modulus of elasticity obtained with the moisture content at the moment of the static test ($W_{testing}$) and h is the width of the board.

Southern blue gum from Spain is visually graded as D40 for cross-sections below or equal to 60 $\times$ 200 mm^2 [13], which corresponds to a characteristic value of 24 N/mm^2 in tensile strength, parallel to grain, 550 kg/m^3 for density and 13.0 kN/mm^2 for modulus of elasticity (mean value in bending). Thus, it can be mentioned that the present sample shows a characteristic value of density which is 25% higher, as well as a tensile strength 43% higher. In terms of modulus of elasticity, the present sample has a 69% higher value (comparing values obtained from tensile tests with bending tests). Considering the present characteristic results for a tensile strength of 34.4 N/mm^2 and its relationship with 40 N/mm^2 (characteristic bending strength from D40), the relation is 0.84, well above 0.60, which is the relation defined in EN 338. This means that, for species of higher density and mechanical properties, specific relations should be developed, as has been done for a wide range of softwood species [41].

Table 3. Characteristic values from non-destructive and static tests (in brackets, the coefficient of variation in %).

	Samples					Total
	EG1	EG2	EG3	EG4	EG5	All
Specimens	117	110	117	107	118	569
$f_{t,0,k}$ (N/mm^2)	32.8 (32.0)	37.5 (34.7)	34.4 (27.4)	31.5 (32.6)	31.7 (33.8)	34.4 (16.2)
$E_{t,0,12\%}$ (kN/mm^2)	22.2 (18.7)	22.4 (27.0)	22.0 (19.1)	21.9 (20.8)	21.6 (15.5)	22.0 (20.5)
ρ_k (kg/m^3)	731 (10.5)	714 (10.3)	703 (9.5)	676 (11.0)	648 (10.3)	686 (10.4)

3.3. Definition of Tensile Strength Classes for Hardwoods: Southern Blue Gum (ET)

For the reports presented at TG1, different strength classes or profiles were created, namely "ET". Table 4 shows the declared characteristic values of tensile strength and density, and mean values of modulus of elasticity for the different strength profiles.

Table 4. Required characteristic values for the strength profile settings developed.

Property\Strength Profile	ET24	ET28	ET30	ET34	ET38	ET42
$f_{t,0,k}$ (N/mm^2)	24.0	28.0	30.0	34.0	38.0	42.0
$E_{t,0,mean}$ (kN/mm^2)	18.0	19.0	20.0	21.0	22.0	23.0
ρ_k (kg/m^3)	590	600	610	620	630	640

These profiles show large differences to those presented by Kovryga et al. [24], and the high density and stiffness profile makes it possible to use higher MOE values for the timber, achieving a greater efficiency in the structural design (Figure 5). These differences might be associated with beech being a medium density hardwood, while Southern blue gum shows high density values.

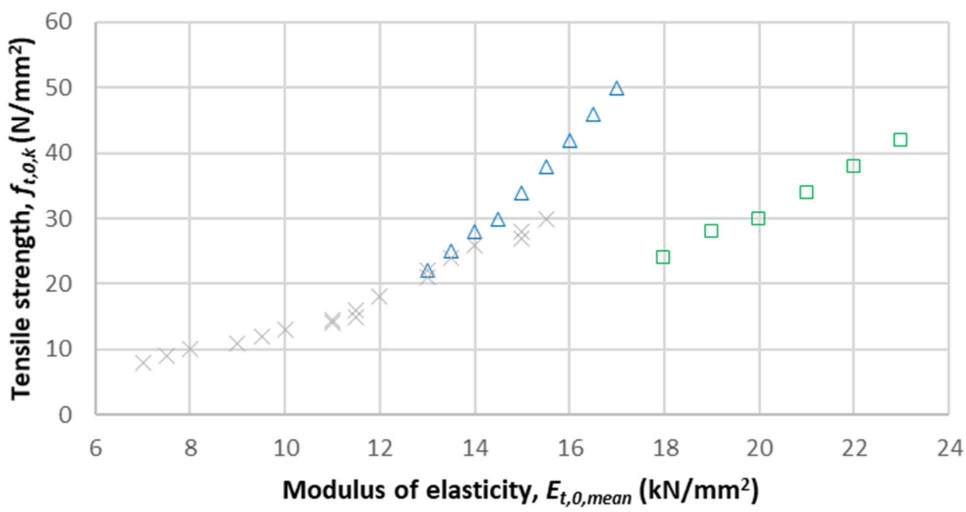

Figure 5. Relation between modulus of elasticity and tensile strength for the proposed ET classes in comparison to DT classes [24] and T classes (EN338—[15]).

Based on the density and the mechanical properties listed in Table 3, a simple process of allocation to a strength class results in an allocation to T30, considering the tensile strength classes defined for softwoods in EN 338 [15]. Considering the strength classes proposed by Kovryga et al. [24], a DT34 could be declared, but using the strength profile settings developed (Table 4), the whole sample can be assigned to ET34, declaring also a much higher stiffness value compared with both Kovryga et al. [24] and EN 338 [15].

The characterization/grading of European hardwoods has been performed largely due to its abundant presence in Central European countries. Despite being a fast-growing species, Southern blue gum has a high density (840 kg/m^3), being 14.4% higher than oak (*Quercus petraea* and *Quercus robur*) [42]. The same study presents the results from oak visually graded, with LS10 and LS13 grades with tensile strength of 24.4 N/mm^2 and 30.6 N/mm^2, respectively, which means that EG was 41% and 12.4% higher compared to LS10 and LS13. Sweet chestnut (*Castanea sativa* Mill.) is also a representative species within Central Europe; however, its medium density corresponds to low mechanical properties as observed by Aicher et al. [42]. EG presents a higher modulus of elasticity of about 70% compared to LS10 (12.3 kN/mm^2) and a 104% higher tensile strength (16.9 N/mm^2).

In comparison with other relevant species in the Iberian Peninsula, beech from Spain (second quality) showed high potential for structural applications [43]. Even though with a higher density compared to European chestnut, EG had 12% higher density, 58% higher modulus of elasticity and 37% higher tensile strength when compared with second quality beech from Spain.

In view of the difference in mechanical properties of hardwoods depending on density, and as shown in Figure 5, it seems logical that the definition of tensile strength classes for hardwoods should consider density groups: (i) tensile strength classes for high-density temperate hardwoods, as shown in Table 4 for Southern blue gum; (ii) tensile strength classes for medium-density temperate hardwoods, as presented by Kovriga et al. [24]; and (iii) tensile strength classes for low-density temperate hardwoods (such as poplar, sweet chestnut and shining gum), which could fit with the current classes for softwood species.

3.4. Strength Class Combinations for the Whole Sample

Machine grading allows for a more reliable and optimized characterization of the raw material. Thus, a more detailed analysis of the studied sample resulted in a total of six strength class combinations (SCC). Table 5 shows the strength class combinations and the performance for every strength class, as well as the percentage of rejection per combination.

Table 5. Strength class (SC) combinations and yield/performance (%) for the whole sample.

Combinations	First SC	Second SC	Third SC	Rejected
1	ET42 (40%)	ET34 (30%)	ET28 (16%)	R (14%)
2	ET42 (40%)	ET34 (30%)	ET24 (24%)	R (6%)
3	ET42 (40%)	ET30 (54%)	-	R (6%)
4	ET42 (40%)	ET24 (59%)	-	R (1%)
5	ET38 (44%)	ET24 (55%)	-	R (1%)
6	ET34 (99%)	-	-	R (1%)

In comparison with the strength classes obtained from machine grading in softwood species (Maritime pine, Radiata pine and Scots pine) from Spain [16], Southern blue gum showed better performance in terms of higher strength class. A lower percentage of rejection was also observed for all the strength class combinations (varying between 1% and 14%), but Southern blue gum showed a lower number of strength classes. The current proposal for strength class combinations based on machine grading applied to Southern blue gum increases the performance of the material compared to the EN 338 procedure. SCC1 to SCC4 allows grading of 40% of the sample as ET42 (tensile strength 24% higher than ET34), while SCC1 and SCC2 allows grading of 70% of the whole sample as ET34 or above.

An increase of performance based on machine grading is also observed for all combinations defined in Table 5 if compared with visual grading of Southern blue gum (D40 accoridng to UNE 56546) as, in the worst case (combination 4), a minimum of 40% of the whole sample is graded with a class of higher tensile strength, as the characteristic tensile strength from D40 is 24 N/mm^2.

3.5. Statistical Analysis

A statistical analysis is made between different measurements to determine if the dynamic modulus of elasticity is indeed a good indicator property for grading hardwoods in tension. Similar analysis was performed for density and other mechanical properties, for which the coefficients of determination are presented in Table 6.

Table 6. Coefficients of determination from linear regression analysis.

	Sample					
	EG1	EG2	EG3	EG4	EG5	ALL
E_{dyn} vs. $f_{t,0,k}$	0.15	0.49	0.10	0.27	0.19	0.17
E_{dyn} vs. $E_{t,0,mean}$	0.67	0.86	0.74	0.64	0.85	0.71
E_{dyn} vs. ρ_k	0.19	0.06	0.10	0.23	0.04	0.16
$f_{t,0,k}$ vs. $E_{t,0,mean}$	0.18	0.49	0.06	0.20	0.21	0.21
$f_{t,0,k}$ vs. ρ_k	0.23	0.05	0.07	0.23	0.00	0.05
$E_{t,0,mean}$ vs. ρ_k	0.21	0.06	0.09	0.18	0.03	0.10

The correlation results show a poor correlation between the IP (dynamic MOE) and density (maximum R^2 of 0.23), and it was suggested by Frühwald and Schickhofer [44] that density could be an optional indicative parameter, rather than a mandatory one. Slightly higher but still poor correlation was also obtained between the IP (dynamic MOE) and strength (maximum value of R^2 of 0.49), while showing a very good correlation with static MOE (R^2 above 0.64). This makes dynamic MOE a good predictor for stiffness, while making it difficult to grade strength. The values determined are in line with the literature, which presents typically lower values of determination coefficients in hardwoods than for softwoods, both for bending and tension tests [45]. Contrary to what is common for softwoods, where dynamic modulus of elasticity usually provides high correlation with mechanical properties, some studies, especially on European beech, have also focused on the use potential of visual features, such as grain deviation and knots (e.g., KAR), to improve the correlations for grading [46]. Bacher [17] proposed a method for hardwood grading based on fiber deviation combined with dynamic MOE measuring to predict strength values. In respect to Southern blue gum, the present of knots is not significant, and when they occur their dimensions are small compared to softwoods. The combination of slope of grain with E_{dyn} measurements is mentioned by Rais et al. [45] as a means to improve the prediction of mechanical properties, both for bending and tension tests. However, developments are still required, as sensors are being tested in recent years as an easier and more reliable way to measure slope of grain, as performing this manually is not adequate.

4. Conclusions

The present work aimed to provide a relevant input for the definition of strength grading classes based on tensile tests for high density hardwoods. Up to date relevant work was performed on medium density European hardwoods, the use of Southern blue gum being negligible based on the strength classes proposed.

The mechanical characterization of Portuguese and Spanish Southern blue gum showed very high mechanical properties with a characteristic value of 686 kg/m^3 22.0 kN/mm^2 and 34.4 N/mm^2, for density, modulus of elasticity and tensile strength.

The low correlation between the IP and the tensile strength values (R^2 = 0.17 for all samples) makes it difficult to achieve a high efficiency in timber grading, while the good correlation between IP and MOE (R^2 = 0.71 for all samples) makes it possible to declare high values for static modulus of elasticity. This is of utmost importance, as grading by the prediction of MOE allows for the prediction of engineered wood products such as glulam which, in terms of bending strength, will be conditioned by finger-joint resistance.

Tensile strength classes for the hardwood species Southern blue gum were determined (ET24 to ET42), with values of characteristic tensile strength varying from 24.0 N/mm^2 to 42.0 N/mm^2 and modulus of elasticity varying between 18.0 kN/mm^2 and 23.0 kN/mm^2. Characteristic density values were defined from 590 kg/m^3 and 640 kg/m^3.

Six strength class combinations were obtained from the whole sample, with percentages of rejection lower than 14% in SCC1, 6% in SCC2 and 1% for the remaining SCC.

Based on recent studies, further research needs to be addressed to obtain the other mechanical properties defining the ET strength classes, and taking into account visual features, such as grain deviation and/or knot size.

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