Article

Assessment of Bending Properties of Sawn and Glulam Blackwood in Portugal

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Abstract: Portuguese forests have changed in recent years. These changes were mainly boosted by the wildfires that affected a significant percentage of the softwood area. Data from 2015, conveyed by the Portuguese Institute for Nature Conservation and Forests, indicates that hardwoods occupy 70% of the Portuguese forest area. This paper presents the Blackwood (*Acacia melanoxylon* R. Br.) species potential, focusing on construction applications, based on recent studies performed at the University of Coimbra and SerQ—Forest Innovation and Competences Center. The valuation of Blackwood for structural applications has been considered through the non-destructive and destructive assessment of their mechanical properties as sawn wood. Their potential was also assessed for a more technologically engineered wood product, the glulam. The dynamic modulus of elasticity (MOE) was estimated through the Longitudinal Vibration Method (LVM) and the Transformed Section Method (TSM); the static MOE and bending strength were assessed through a four-point bending test. Agreement was obtained between both approaches. Sawn Portuguese Blackwood showed a density of 647 kg/m^3, 13,900 MPa of MOE and a bending strength of 65 MPa (mean values). The glulam beams fabricated with this raw material had improved properties relative to sawn wood, most obviously concerning the bending strength, with an improvement of 29%. This proves the significant ability and potential of these species to be used in construction products with structural purposes like sawn wood and glulam.

Keywords: Portuguese hardwoods; blackwood; mechanical characterization; construction applications

1. Introduction

Portuguese forests and the wood products obtained from them represent a significant contribution to the Portuguese economy, being responsible for 3% of Gross Domestic Product in 2015 [1]. Data from the Sixth National Forestry Census [2] indicated that 36.2% of the Portuguese land area is occupied by forest, totaling 3,224,200 ha, which is close to the mean of all European Union countries (37.6%). The same report lists the 22 most common species grouped in softwoods (7) and hardwoods (15). The higher number of hardwood species is in line with the occupied area, 2,259,300 ha, representing 70%, with Blue gum being the dominant species (26%), followed by Cork Oak (22%), Holm Oak (11%), Oak (3%), Chestnut (1%), Acacia (0.3%) and a group of other hardwoods (Poplar, Beech, Ash, and others, 6%). Portuguese law prohibits the felling of species like Cork Oak and Holm Oak, unless duly and previously authorized, which means that, in most the cases, only branches from thinning are available, resulting in a material with dimensions unsuitable for construction applications. This implies a decrease in the available area of hardwood forests for these applications by approximately 37%.

In past decades, European hardwoods have been the focus of research due to their potential in terms of mechanical properties, as well as their potential for use in foreseeing the threats of climatic changes like Ash and Maple [3,4], Beech [5,6], and Birch [7]. In recent years, some studies have been developed considering the assessment of the potential of some hardwoods available in the Portuguese forest for glulam production, such as Poplar [8–11] and Blue gum [12].

According to Knapic et al. [13], Blackwood (*Acacia melanoxylon* R. Br.) has its origin in the temperate forests of south-east Australia and Tasmania and is considered a versatile and highly adaptive tree species being spread all over the world due to its ornamental value and the dark color of the wood, which makes it aesthetically appealing (Figure 1). Despite the quality of wood, in Europe, these species are considered invasive, since being a non-indigenous species they unbalance the structure or functioning of an ecological system, with the particularity that the seeds are stimulated by fire [13]. Knapic et al. [13] also state that, in Portugal, Blackwood occurs mainly in mixed stands with Maritime pine (*Pinus pinaster* Ait.) or Stone pine (*Pinus pinea* L.) in the West Coast or in pure stands or mixed with pines and other hardwoods in the inner part of Portugal.
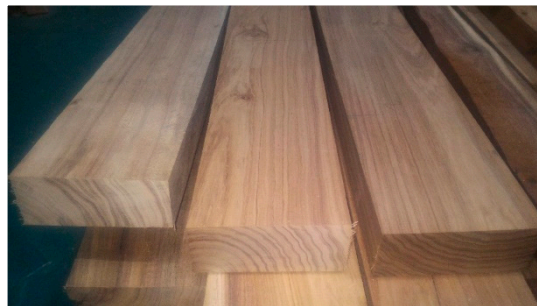

Figure 1. Blackwood visual aspect.

Blackwood species was introduced in Portugal as an ornamental in the mid-19th century and its expansion occurred in the first half of the 20th century through national forestation programs, in which the afforestation projects of coastal dunes included exotics such as Acacia, Casuarina and Eucalyptus [14,15]. Blackwood is considered mainly for carpentry and cabinet applications, being typically highly valued. Several scientific studies have been developed on Blackwood, mainly focused on the silviculture of the species [16–18], anatomic properties [13,19] and physical properties [20]. Moreover, the potential for pulp and paper production was evaluated, showing great potential [21,22], especially for writing and printing paper production [23]. Machado et al. [20] evaluated the variation between trees (longitudinal and radial direction) in the physical properties (density) and mechanical properties of Blackwood in clear wood specimens collected from four different stands. The authors evidenced the potential of Blackwood as an alternative species to supply the industry with valuable hardwood timber. Mean values of density, modulus of elasticity (MOE) and bending strengths of 654 kg/m^3, 14,100 MPa and 139.0 MPa were obtained, respectively. The significant differences found between trees are pointed out as the knowledge needed for an accurate selection of the raw material to increase the wood quality. A study focusing on the density and growth of Blackwood in different sites in Portugal showed a mean ring width of 6 mm in 27–56-year-old trees [24]. These values are lower than other results found in other studies: 14 mm in 7-year-old [25], 6–7 mm in 7–21-year-old natural trees [26].

The knowledge of the mechanical properties of several hardwoods available in the Portuguese forest is becoming well defined. However, the characterization of Blackwood's potential is scarce and is focused on clear wood. Research was carried out at SerQ—Forest Innovation and Competences Center, aiming to assess the key bending properties (modulus of elasticity and bending strength) and evaluate the mechanical performance of a large sample of sawn wood with cross-sectional dimensions of 50 × 120 mm^2 (thickness × width). Non-destructive tools were used to predict those properties through simple linear correlation analyses. The Longitudinal Vibration Method (LVM), which consists

of the measurement of the material's natural frequency, was used, since it was previously validated for other species, like Maritime pine [27], Poplar [28] and Blue gum [29]. The present paper intends to improve the knowledge of the Portuguese Blackwood for structural applications, highlighting the species' potential to produce glulam as a way to add value to the raw material obtained from the proliferation of the species. It aims also to confirm the reliability of using non-destructive techniques, such as the LVM, as a predictor of the MOE, allowing resource optimization. Therefore, sawn wood from two different provenances was collected to access their mechanical properties and the LVM. Then, the glulam beams were fabricated to evaluate their potential by assessing their bending MOE and bending strength.

2. Materials and Methods

2.1. Portuguese Blackwood as Sawn wood: Raw-Material Characterization

Two samples of 40 boards each, from two different provenances, the Azores Islands (AI) and the North of Portugal (NP), were assessed in their dimensions (thickness, width, and length), moisture content and weight. The cross-section dimensions were measured in three different locations (both ends and mid-length). The moisture content was recorded by an electrical moisture meter at mid-length and 600 mm from each end, as required by EN 13183-2 [30] (Figure 2a). The referred data was considered as the input for the software of the device used (Timber Grader MTG) to assess the dynamic MOE through the LVM (Figure 2b). This device only requires access to one end of the element to be tested (the stress wave activator and the stress wave detector are located at the same device). The wave travels through the element and returns to the device. The wave frequency is sent to a computer, via a Bluetooth interface, which combines the input data and provides the dynamic MOE. Martins et al. [31] carried out a study on 18 glulam beams made of Poplar to assess the efficiency of this non-destructive method to predict both MOE and bending strength.


(**a**)	(**b**)
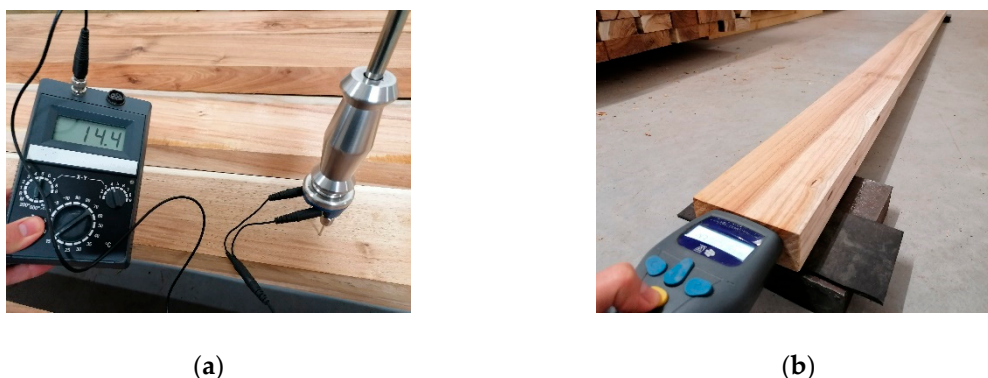
Figure 2. Measurement of: (**a**) the moisture content; and (**b**) of the dynamic modulus of elasticity (MOE) test.

After the non-destructive test, the dynamic MOE of each board (E_{dyn-b}) was recorded and static tests were performed as a four-point bending test, according to EN 408 [32]. The static MOE test was performed with a displacement constant rate (0.36 mm/s) up to 40% of the estimated failure load, to obtain the static MOE of each board ($E_{global-b}$). The applied load was measured by a load cell (with 200 kN of maximum capacity) and deflections were measured by displacement transducers with 20 and 50 mm maximum capacities. The bending strength parallel to the grain (f_m) was determined by a destructive test, applying the load with a displacement constant rate of (0.17 mm/s) up to failure. Section 3.1 summarizes the boards' results.

2.2. Portuguese Blackwood Glulam Beams: Assembly and Mechanical Characterization

For the mechanical characterization of glulam beams made with Blackwood, eight glulam beams (BWi, with i = 1–8) were produced at the SerQ laboratory. A set of 40 boards with mean nominal dimensions of $50 \times 121 \times 2901$ mm^3 (thickness × width × length) was selected. All boards were weighted and non-destructively characterized. Their mean density and dynamic MOE (± standard deviation) were 665 ± 82 kg/m^3 and $13,864 \pm 2,177$ MPa, respectively.

Each board was planed to a final thickness of 24 mm, cut to a final width of approximately 100 mm, and 2400 mm nominal length. The lamellae were, again, non-destructively assessed and each group was then arranged into the final glulam beam configuration, based on the dynamic MOE of each lamella (E_{dyn_l}) (Figure 3, where $E_{dyn\text{-}l\text{-}av}$ is the mean E_{dyn_l} of each beam). The boards were sorted into groups of five for the production of three homogeneous (BW5, BW7, and BW8) and five combined glulam beams (BW1 to BW4, and BW6). The lamellae with lower values of E_{dyn_l} were adopted as the central layer and the higher values were arranged at the outer layers, ascending from the inner to the outer layers, resulting in a symmetrical display. The authors categorized as homogenous the beams whose lamellae had a range of variation of dynamic MOE lower than those considered as combined (Figure 3). The gluing process was performed in controlled conditions of temperature (20 ± 2 °C) and relative humidity ($65 \pm 5\%$). Two different adhesives, one-component polyurethane (1C-PUR-1 and 1C-PUR-2), were used. The technical data sheets regarding the amount of adhesive, clamping pressure and assembly time were followed. The adhesive was spread manually, with the amount applied controlled by weighing. The 1C-PUR-1 (180 g/m^2) was used for BW1 and BW2 glulam beams. It was applied after the primer application (PR 3105 – 20 g/m^2) and a minimum activation period of 10 min. The adhesive 1C-PUR-2 (200 g/m^2) was used for the remaining beams. For both adhesives, 1.0 MPa was considered as the pressure level, applied by a series of hydraulic jacks spaced by 500 mm and with a maximum load capacity of 5 tons each (Figure 4a).
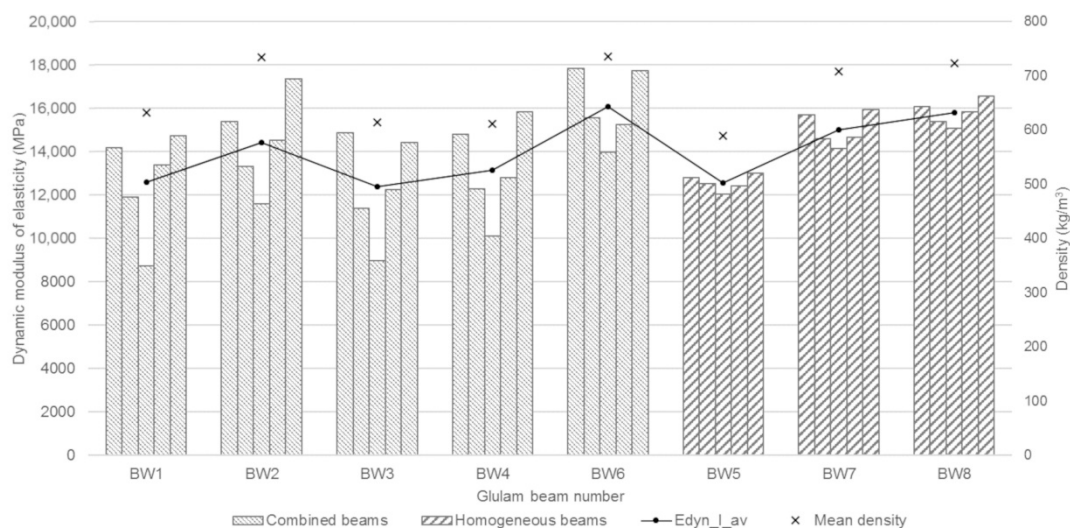
Figure 3. Summary of $E_{dyn\text{-}l}$ of individual lamellae and $E_{dyn\text{-}l\text{-}av}$ for the Blackwood glulam beams.

(a)   (b)

Figure 4. Blackwood glulam beam: (**a**) at a production stage under pressure; (**b**) subjected to a static MOE test.

A curing period of 7 days at the referred controlled conditions was considered. The glulam beams were planed laterally to a final width of 92 mm and cut to 2350 mm length. The beams were weighed and measured before non-destructive tests with the LVM to obtain the dynamic MOE (E_{dyn}). The prediction of static MOE was also considered by the use of the Transformed Section Method (TSM) (E_{TSM}). The TSM considers a cross-section with homogeneous properties, instead of the actual heterogeneous one, which allows for the application of conventional beam theory elastic formulas. Martins et al. [31] adopted both methods for glulam beams made by Portuguese Poplar, with both showing great potential as predictors of static MOE.

Finally, static MOE and bending strength tests were performed. The test layout, loading procedures applied and measuring devices considered were the same as those applied for the sawn wood tests (Figure 4b). After failure tests, the density and moisture content of each glulam beam was determined by one specimen with approximately 50 mm length and full cross-section. Section 3.2 summarizes the glulam beams' results.

3. Results and Discussion

3.1. Portuguese Blackwood Sawn Wood

The boards of the AI sample had a mean moisture content of 11% and mean dimensions of $49 \times 118 \times 2201$ mm^3 (thickness × width × length). As for the NP sample, the boards had a mean moisture content of 12% and mean dimensions of $50 \times 121 \times 2898$ mm^3 (thickness × width × length).

Tables 1–3 gather the values obtained for the entire set of sawn wood, the AI sample and the NP sample, respectively, namely: dynamic and static MOE, bending strength, moisture content (w) and density of a piece with no defects (ρ), the values of density and static MOE adjusted for a $w = 12\%$ ($\rho_{12\%}$ and $E_{global\text{-}b\text{-}12\%}$, respectively) computed based on the EN 384 [33] and the values of the bending strength adjusted ($f_{m\text{-}adj}$) based on the recommendations of EN 14,080 [34]. The characteristic values (Char.val.) were computed considering the 5% percentile.

Table 1. Physical and mechanical properties for the entire sawn wood sample.

	$E_{dyn\text{-}b}$ MPa	$E_{global\text{-}b}$ MPa	f_m MPa	w %	ρ kg/m^3	$\rho_{12\%}$ [1] kg/m^3	$E_{global\text{-}b\text{-}12\%}$ [1] MPa	$f_{m\text{-}adj}$ [2] MPa
Mean	14,104	14,038	68.6	11.5	646	647	13,908	65.2
Minimum	9420	8399	26.8	9.1	492	493	8618	25.7
Maximum	20,054	20,520	130.1	16.8	803	808	19,552	123.8
COV: %	15.5	16.1	30.2	14.4	14	14	16.3	30.4
Char.val.	-	-	-	-	-	518	10,402	36.9

[1] Computed according to EN 384 [33]. [2] Computed according to EN 14,080 [34].

Table 2. Physical and mechanical properties for the AI sawn wood sample.

	$E_{dyn\text{-}b}$ MPa	$E_{global\text{-}b}$ MPa	f_m MPa	w %	ρ kg/m^3	$\rho_{12\%}$ [1] kg/m^3	$E_{global\text{-}b\text{-}12\%}$ [1] MPa	$f_{m\text{-}adj}$ [2] MPa
Mean	13,452[b]	13,648	65.0	11.0	590	593[b]	13,351[b]	61.0[a]
Minimum	10,726	9954	27.7	9.1	492	493	9609	25.9
Maximum	20,054	20,520	130.1	15.4	772	779	19,552	121.9
COV: %	16.4	17.6	28.1	15.1	11	11	17.1	28.0
Char.val.	-	-	-	-	-	513	10,396	34.5

[1] Computed according to EN 384 [33]. [2] Computed according to EN 14,080 [34].

Table 3. Physical and mechanical properties for the NP sawn wood sample.

	$E_{dyn\text{-}b}$ MPa	$E_{global\text{-}b}$ MPa	f_m MPa	w %	ρ kg/m^3	$\rho_{12\%}$ [1] kg/m^3	$E_{global\text{-}b\text{-}12\%}$ [1] MPa	$f_{m\text{-}adj}$ [2] MPa
Mean	14,757[a]	14,429	72.3	12.1	702	701[a]	14,466[a]	69.3[a]
Minimum	9420	8399	26.8	9.2	535	538	8618	25.7
Maximum	18,137	17,660	129.1	16.8	803	808	17,514	123.8
COV: %	13.5	14.4	31.2	12.2	10	10	14.8	31.2
Char.val.	-	-	-	-	-	581	11,193	42.7

[1] Computed according to EN 384 [33]. [2] Computed according to EN 14,080 [34].

To perform an analysis of the experimental results, a detailed statistical analysis of variance (ANOVA), complemented with a *t*-test, was used. A confidence level of 0.05 was adopted. The analysis of Tables 2 and 3 clearly showed significant differences between the properties of the boards with different provenances (different letters, [a] and [b], indicate statistically significant differences between provenances). The analysis of the *p*-values corroborates this, with most of the listed properties presenting low values. Is the case of the density, dynamic and static MOE, for which *p*-values of 3.4×10^{-10}, 6.9×10^{-3} and 2.7×10^{-2} were observed, respectively. On the other hand, for the bending strength, there were no significant differences between provenances (*p*-value = 6.2×10^{-2}).

The AI sample had a mean density of 593 kg/m^3 (with a coefficient of variation (COV) of 11%), while the NP sample had a mean density of 701 kg/m^3 (with COV = 10%): 18% higher than the mean density of the AI sample. In terms of dynamic MOE, mean values of 13,500 MPa and 14,800 MPa were measured for AI and NP samples, respectively. There is a difference between the two samples in the same direction as that found for the density, but with less expression; the dynamic MOE of the NP sample was 10% higher than the same property of the AI sample. In terms of static MOE, mean values of 13,600 MPa (AI) and 14,400 MPa (NP) were obtained. Considering the overall sample, density (647 kg/m^3) and static MOE (13,908 MPa), were similar to previous values obtained for clear wood specimens by Machado et al. [20], which presented mean values of 654 kg/m^3 and 14,100 MPa for the same properties, respectively.

By comparing the results of this study on Blackwood with those from other hardwoods available in the Portuguese forest (Blue gum, Chestnut, and Poplar), Blackwood is not the strongest, but it has a very high density and mechanical properties. In comparison with Blue gum [29], Blackwood showed lower density (−29%), static MOE (−23%) and bending strength (−13%). As for Poplar, the dynamic MOE of Blackwood was about 35% higher [12,31], with a density ranging from 50% [12] to 59% [31] higher. On the other hand, if compared with the results obtained by Martins et al. [35] for Chestnut (a noble and durable species), Blackwood density and static MOE were 12% and 39% higher. If considering a Spanish Sweet Chestnut [36], the values were slightly different, with the Portuguese Blackwood showing about the same characteristic density (+2%), but lower characteristic static MOE (−15%) and higher characteristic bending strength (32%).

Beech (*Fagus sylvatica* L.) is one of the most-studied European hardwood species for structural applications. A comparison between the Portuguese Blackwood and Beech [37] in terms of mean values of density, static MOE, and bending strength showed small differences, for a sample with 85 ×

55 mm^2 (width × thickness). Blackwood density and bending strength were −6% and −7% lower than the Beech's corresponding properties and, as for the static MOE, the Blackwood's was 5% higher than the Beech's. For a sample with 120 × 55 mm^2 (width × thickness), the difference in the Blackwood density and bending strength increased a little (in absolute value) to −13% and −19%, respectively, while, for the static MOE, the difference relative to the previous sample was about the same (the Blackwood's was 6% higher than the Beech's).

A statistical analysis of the density and both MOE values revealed correlation coefficients of 0.66 for density ($\rho_{12\%}$) *vs.* static MOE ($E_{global-b-12\%}$) and 0.68 for density ($\rho_{12\%}$) *vs.* dynamic MOE (E_{dyn-b}), considering the entire sample. If considering the different provenances, by relating the same quantities, the correlation coefficients were similar: 0.64 (AI) and 0.69 (NP); and 0.65 (AI) and 0.68 (NP), respectively. The *t*-test showed insignificant differences when using the LVM as a predictor of the static MOE (p-value = 5.8×10^{-1}, considering the entire sample), which confirms this method as an effective and reliable tool. The correlation coefficients between the two variables (E_{dyn-b} *vs.* $E_{global-b-12\%}$) were 0.96, considering the entire sample, and 0.97 and 0.95 for AI and NP samples, respectively (Figure 5). Considering the bending strength prediction, correlation coefficients based on both dynamic and static MOE showed correlations with values of 0.50 (E_{dyn-b} *vs.* f_{m-adj}) and 0.52 ($E_{global-b-12\%}$ *vs.* f_{m-adj}) for the entire sample, 0.44 and 0.41 for the AI sample, and 0.50 and 0.52 for the NP sample, respectively.
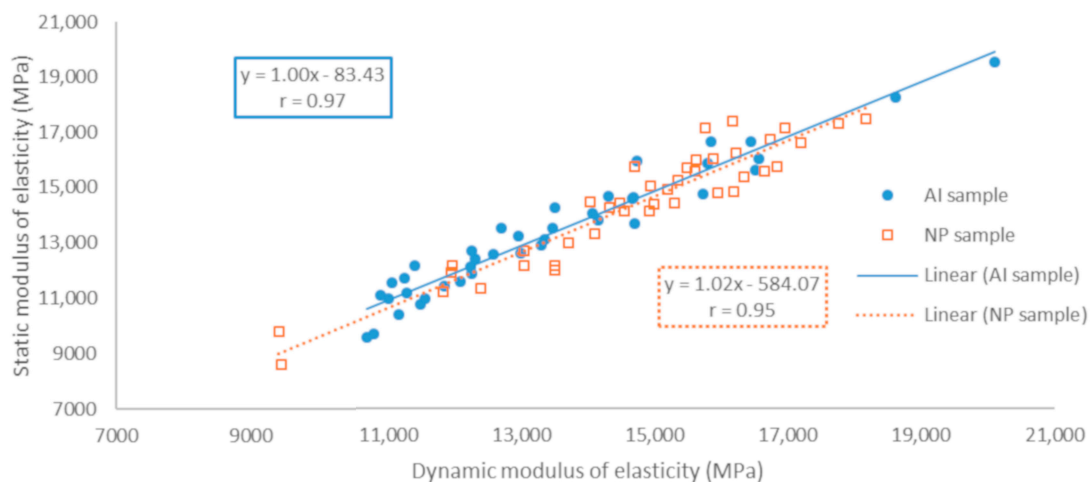

Figure 5. Correlation between dynamic (E_{dyn}) and static MOE ($E_{global-b-12\%}$).

3.2. Portuguese Blackwood Glulam Beams

Table 4 gathers the estimated values for the MOE, obtained with the TSM (E_{TSM}) and with the LVM (E_{dyn}), the bending strength (f_m) and the local and global MOE (E_{local} and E_{global}), computed based on the EN 408 [32], the moisture content and the density. The adjusted properties (for a w = 12%) such as the density ($\rho_{12\%}$) and, the values of both static MOE ($E_{local-12\%}$ and $E_{global-12\%}$), computed based on the EN 384 [33], or the values of the bending strength adjusted concerning the beam cross-section (f_{m-adj}), based on the recommendations of EN 14,080 [34], are also listed on Table 4. The characteristic values were computed considering the 5% percentile.

Table 4. Physical and mechanical properties for the Blackwood glulam beams.

	E_{TSM} MPa	E_{dyn} MPa	f_m MPa	E_{local} [1] MPa	E_{global} [1] MPa	w %	ρ kg/m^3	$\rho_{12\%}$ [2] kg/m^3	$E_{local-12\%}$ [2] MPa	$E_{global-12\%}$ [2] MPa	f_{m-adj} [3] MPa
Mean	15,048	14,129	88.8	17,569	14,377	13.1	671	679	17,764	14,533	83.9
Minimum	12,802	12,807	69.3	13,852	12,086	11.5	599	600	14,074	12,280	65.5
Maximum	17,261	15,896	102.3	21,231	16,197	13.8	744	746	21,571	16,456	96.7
COV: %	9.5	9.8	12.2	14.4	9.5	5.9	10	9	14.8	9.8	12.2
Char.val.	-	-	73.5	-	12,532	-	601	606	-	12,632	69.4

[1] Computed according to EN 408 [32]. [2] Computed according to EN 384 [33]. [3] Computed according to EN 14,080 [34].

Comparing the mean values of density and mean adjusted static MOE obtained for the glulam beams with the corresponding quantities obtained for the boards, the values were similar, with $\rho_{12\%}$ and $E_{global\text{-}12\%}$ of the beams being 4% higher than the same quantities for the board samples. The *t*-test demonstrated insignificant differences between results from sawn wood and glulam beams with *p*-values of 4.6×10^{-1} and 2.9×10^{-1} for density and $E_{global\_12\%}$, respectively. However, the mean adjusted bending strength of the glulam beams was 29% higher than the same quantity for the board samples. This is corroborated by a *p*-value of 7.0×10^{-4}, showing significant differences between sawn wood and glulam beam results.

As was done with the Blackwood boards, the results found for these Blackwood glulam beams were also compared with those from studies using other hardwood species. Relative to Blue gum glulam beams [12], the ones made of Blackwood showed lower density (−31%), static MOE (−40%) and bending strength (−31%). The differences found in terms of dynamic MOE were similar to those found for the static MOE (−37% associated with E_{TSM} and −36% associated with E_{dyn}). Considering different Eucalyptus clones (*Eucalyptus grandis '330'* and *'329'*) [38], the differences were significant. Compared with the *E. grandis '330'* clone glulam beams, the Blackwood beams exhibited a lower density (−8%), static MOE (−17%) and bending strength (−10%). If the comparison considers the *E. grandis '329'* clone beams, the beams made of Blackwood showed higher density (21%), static MOE (25%) and bending strength (50%).

When compared with glulam beams made of Poplar (a sample composed by *Populus alba*, *P. nigra* and *P.* × *canadensis*), the dynamic MOE of Blackwood was about 39% higher [31], with a density of 56% [31] higher. These results are in line with the ones found comparing the boards of Poplar and Blackwood in the previous subsection. However, considering a different Poplar species (*P.* × *euramericana*, 'Neva' clone) [38] the differences were higher, with the Blackwood beams presenting higher density (73%), static MOE (51%), and bending strength (90%).

The statistical analysis of the data collected in the present study also revealed that there were no significant differences between the values of LVM and static MOE (*p*-value = 5.8×10^{-1}) and between TSM and static MOE (*p*-value = 4.8×10^{-1}). Additionally, no significant differences were observed between the values of LVM and TSM (*p*-value = 2.1×10^{-1}). As for the remaining properties, significant differences were found (*p*-value < 0.05). A simple linear correlation analysis, considering all beams, showed that there is an agreement between the density and both MOE with correlation coefficients of 0.94 and 0.90 for density ($\rho_{12\%}$) *vs.* static MOE ($E_{global\text{-}12\%}$) and density ($\rho_{12\%}$) *vs.* both dynamic LVM MOE (E_{dyn}) and dynamic TSM MOE (E_{TSM}), respectively. Once again, the dynamic prediction of the static MOE, using either the LVM or the TSM, showed to be an effective and reliable tool. The correlation coefficient between E_{dyn} and $E_{global\text{-}12\%}$ was 0.90 and between E_{TSM} and $E_{global\text{-}12\%}$ was 0.99 (Figure 6). Figure 6 also gathers the correlation coefficients between the same properties for the homogenous and combined sets of beams (they are only indicative of a possible trend of the non-destructive approach to predicting the static MOE). Concerning the bending strength prediction, the correlation coefficients, based on both dynamic LVM and TSM and the static MOE showed correlations with values of 0.74, 0.86 and 0.89, respectively.
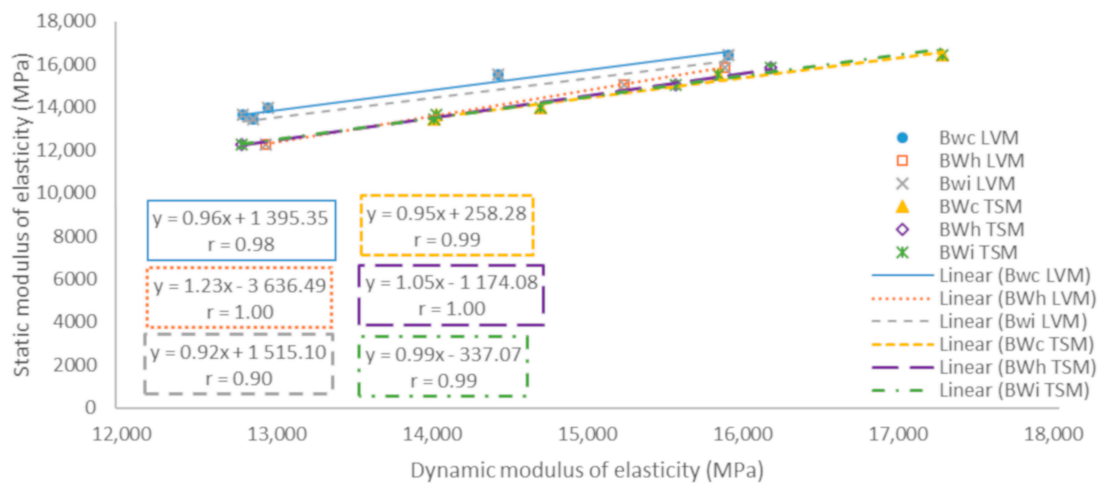
Figure 6. Correlation between dynamic (E_{dyn} and E_{TSM}) and static MOE ($E_{global-12\%}$). Bwc refers to the combined beams; Bwh refers to the homogenous beams; Bwi refers to the entire set of beams; Longitudinal Vibration Method (LVM); Transformed Section Method (TSM); Linear is the linear interpolation.

By comparing the results associated with the composite and homogeneous beams, the differences were very low, ranging between −6% (associated with E_{dyn}) and 4% (associated with f_m and f_{m-adj}). The composite beams had a mean dynamic MOE of about 13,800 MPa, while the homogeneous beams' dynamic MOE was about 14,700 MPa. As for the mean adjusted bending strength, values of 85.2 MPa and 81.7 MPa were obtained for the composite and the homogenous beams, respectively. As expected, these differences demonstrate that the composite beams can use inner lamellae with lower quality, compared with the higher quality of the outer lamellae, without compromising the mechanical properties of the whole beam.

The structural efficiency, which relates a mechanical property (such as static MOE or bending strength) with density, for the glulam beams made of the various hardwood species was assessed and is presented in Table 5. In terms of the structural efficiency for the static MOE, Poplar beams showed the highest value (25.7 associated with *P. alba*, *P. nigra* and *P. x canadensis* species) and Blackwood beams showed a value close to the lowest in Table 5 (21.8). However, concerning the structural efficiency for the bending strength, the Blackwood beams showed the highest value (0.13), together with those made of *E. grandis '330'*.

Table 5. Structural efficiency for $E_{global-12\%}$ and f_m of glulam beams made of different hardwood species.

Species	$E_{global-12\%}/\rho_{12\%}$	$f_{m-adj}/\rho_{12\%}$	Reference
Blackwood	21.8	0.13	-
Blue gum	23.1	0.12	[12]
E. grandis '330'	24.0	0.13	[38]
E. grandis '329'	21.0	0.10	[38]
P. alba, *P. nigra* and *P. × canadensis*	25.7	0.12	[31]
P. × euramericana, 'Neva'	25.0	0.11	[38]

4. Conclusions

Acacia is, nowadays, considered an invasive species in the Portuguese forest. To avoid the harms that this can bring to other native species and, at the same time, increase its value, using it as a construction material can be a good solution. This study focuses on the assessment of the potential of using this Portuguese hardwood for construction applications, either as sawn material or as engineered products, such as glulam, making use of the raw material obtained from the proliferation of the species. Despite the fact that the use of wood-based products has been largely governed by softwood species, most of which are imported from Europe, the findings in this study may help to change this situation.

The mechanical characterization of Portuguese Blackwood species showed the high density and mechanical properties of sawn wood (mean values of density, static MOE, and bending strength of 647.1 kg/m^3, 13,900 MPa and 65.2 MPa, respectively) and glulam beams (mean values of density, static MOE, and bending strength of 678.5 kg/m^3, 14,500 MPa and 83.9 MPa, respectively). This demonstrates the great quality of the studied hardwood, and its potential to produce high value-added products. The use of the LVM provides a reliable way to characterize the quality of the Blackwood products, proven by correlation coefficients between dynamic and static properties above 0.90. Thus, the prediction of the mechanical properties could be less time consuming and could avoid the breakage of material.

Hardwoods could be considered as an alternative to softwoods due to their fast growth rates and their inherent capacity to surpass the threat of climate change. The use of hardwood species for engineered wood products is also an alternative to softwoods, providing high-quality products with superior mechanical properties. Besides, in the case of the Portuguese Blackwood, it could also help to control the proliferation of these invasive species.

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