Mechanical Properties of Wood from the Relict *Abies pinsapo* Forests

Luis García Esteban
Paloma de Palacios
Francisco García Fernández
Julia Ovies

Abstract

The mechanical properties of *Abies pinsapo* Boiss., a relict species from the south of Spain, have been studied very little due to its scarcity and the high level of protection of this species. Forest fire prevention measures involving felling of mature trees have enabled the species to be characterized for the first time. A comparison of its three regions of provenance, (1) Sierra de Grazalema, (2) Sierra Bermeja, (3) Sierra de las Nieves, was included in this evaluation. Tests were conducted using small dimension defect-free test pieces in accordance with the corresponding Spanish mechanical property test standard. In order to relate the findings to the wood anatomy, measurements were taken of tracheid length and diameter, tracheid wall thickness, and growth rate.

The mean values per region of provenance (1, 2, 3) were Charpy impact strength, 16.9, 12.4, 14.3 (J); modulus of rupture (MOR), 74.9, 68.8, 71.1 (N/mm^2); tensile strength perpendicular to the grain (tangential), 1.9, 2.0, 1.8 (N/mm^2); tensile strength perpendicular to the grain (radial), 2.0, 2.0, 1.9 (N/mm^2); splitting strength, 2.4, 2.3, 2.3 (N/mm); and compressive strength parallel to the grain, 40.0, 39.9, 39.9 (N/mm^2). The findings showed that the values of most of the properties studied in the three regions of provenance did not present statistically significant differences.

Abies pinsapo Boiss. is a relict species from the Miocene period that has taken refuge in shady regions of the high mountain ranges in the westernmost part of the Betic Cordillera, in the south of Spain. Its specific location is Serranía de Ronda, the easternmost site of all the Circum-Mediterranean firs, where it grows in northern, eastern, and northeast exposures.

Its three regions of provenance, in the provinces of Málaga and Cádiz, are in close proximity. Ecological conditions are very similar, although the average annual rainfall and soil type differ substantially (Table 1). In Cádiz, the pinsapo forests are located in Sierra de Grazalema (1) over an area of 418 ha (Esteban et al. in press). Groves and isolated stands are also found in the western part of Monte Prieto, the sides of El Montón, and on the northern slopes of Zafalgar and Los Pinos (Ceballos and Martín-Bolaños, 1930). In Málaga, pinsapo firs are found in the small area of Sierra Bermeja (2), consisting of just 35 ha, in regression due to major fires in the area, which divided the forest into three groves. This province is also home to the largest area of pinsapo firs, consisting of 2,871 ha, in Sierra de las Nieves (3) (Esteban et al. in press). Smaller spots are also found in the ranges of Alcor, Caparaín, Real, Istán, Río Verde, and Gialda (Ceballos and Vicioso 1933) (Fig. 1).

Farther south, in the Moroccan Rif, two varieties of the Spanish pinsapo fir with similar morphological features are located. *A. pinsapo* var. *marocana* (Trabut) Ceballos & Bolaños is distributed at altitudes ranging from 1,400 to 2,100 m following the southeast–northeast mountain chain from the western end of the Beni Sey-yel region, over an area of 2,531 ha. *A. pinsapo* var. *tazaotana* (Cózar ex Huguet del Villar) Pourtet is located on Mount Tazaout in an area of 493 ha at altitudes ranging from 1,400 to 1,700 m (Esteban et al. in press) (Fig. 1).

Few studies have been made of pinsapo fir wood. The reasons for this are its scarcity, which means it has not been widely used, and the failure of reforestation attempts outside of its natural area. At a local level, it has been used in

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The authors are, respectively, Senior Univ. Lecturer, Univ. Lecturer (Doctor), Associate Lecturer, and Student (completing final degree project), Univ. Politécnica de Madrid, Escuela Técnica Superior de Ingenieros de Montes, Dept. Ingeniería Forestal, Cátedra de Tecnología de la Madera, Ciudad Universitaria, 28040 Madrid, Spain (luis.garcia@upm.es, paloma.depalacios@upm.es, francisco.garcia@upm.es, jovies@portalmadera.net). This paper was received for publication in May 2009. Article no. 10628.

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Table 1.—Regions of provenance of Abies pinsapo.[a]

Region of provenance	Altitude (m)	Phytoclimate and Phytoclimate subtype	Average temperature (°C)	Average rainfall (mm)	Soil
1. Sierra de Grazalema	1,000–1,650	Nemoral-Mediterranean, Cooler subnemoral	16.6	2,223	Leptosol and limestone, cambisol
2. Sierra Bermeja	1,300–1,400	Mediterranean, Less-dry exclusive sclerophyll	14.3	1,068	Luvisol
3. Sierra de las Nieves	1,000–1,800	Nemoral-Mediterranean, Cooler subnemoral	17.1	1,032	Leptosol and limestone, cambisol

[a] Data from Martín et al. 1998 and Esteban et al., in press.

construction (Peraza 1964). There are written records of pinsapo fir being used in shipbuilding, for railroad ties, in mining, and in tasks associated with ice pits. A good part of the major timber resources built up over time in some of the pinsapo forests even ended up as paper pulp (Ceballos and Ruiz de la Torre 1979). Although its firewood and charcoal are of poor quality, pinsapo fir was used for these purposes for some time by the local people, who overharvested the trees and considerably reduced their number (Barbey 1931).

The physico-mechanical properties of this species have only been studied by Peraza (1964) and Gutiérrez and Plaza (1967), but in both cases the number of test pieces was very limited and samples were only taken from the Málaga pinsapo forests.

Since this species was listed in danger of extinction in the *Catálogo Andaluz de Especies de la Flora Silvestre Amenazada* (Andalusian Catalogue of Threatened Species of Wild Flora), in Decree 104/94 of the Andalusian Regional Government, these forests are under full protection, and therefore it is difficult to study their wood. However, silvicultural treatment for fire prevention has allowed mature trees representative of the Spanish provenances to be felled.

The objective of this study was to characterize *A. pinsapo* wood using, for the first time, small dimensions defect-free test pieces prepared from trees in the three Spanish regions of provenance. The results of impact bending strength, static bending strength (modulus of rupture [MOR]), tensile strength perpendicular to the grain in the tangential and radial direction, splitting strength, and compressive strength parallel to the grain are discussed in relation to the specific gravity (SG) of the wood, growth rate, tracheid length and diameter, and tracheid wall thickness.

Materials and Methods

The material used for this study was collected in the three natural areas of *A. pinsapo* in the Iberian Peninsula (Table 1).

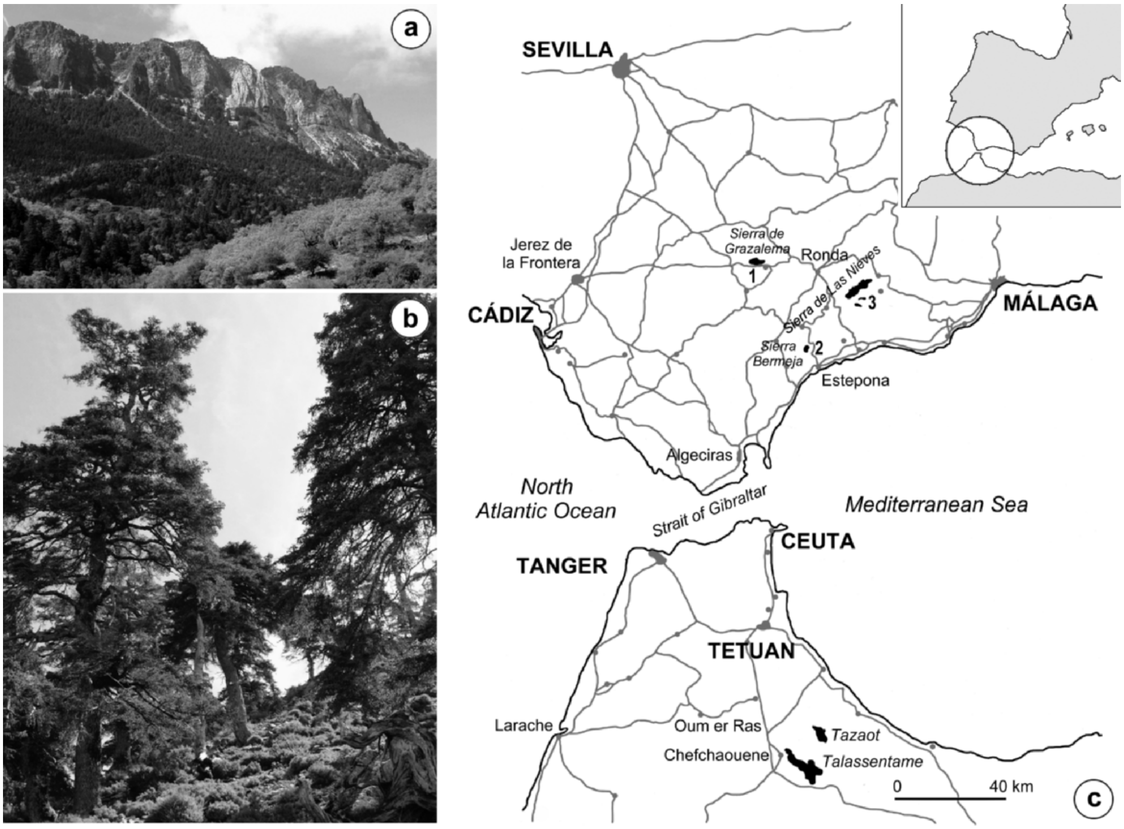


Figure 1.—(a) Sierra de Grazalema pinsapo forest (Cádiz). (b) Sierra de las Nieves pinsapo forest (Málaga). (c) Distribution map of the pinsapo forests in Spain and Morocco.

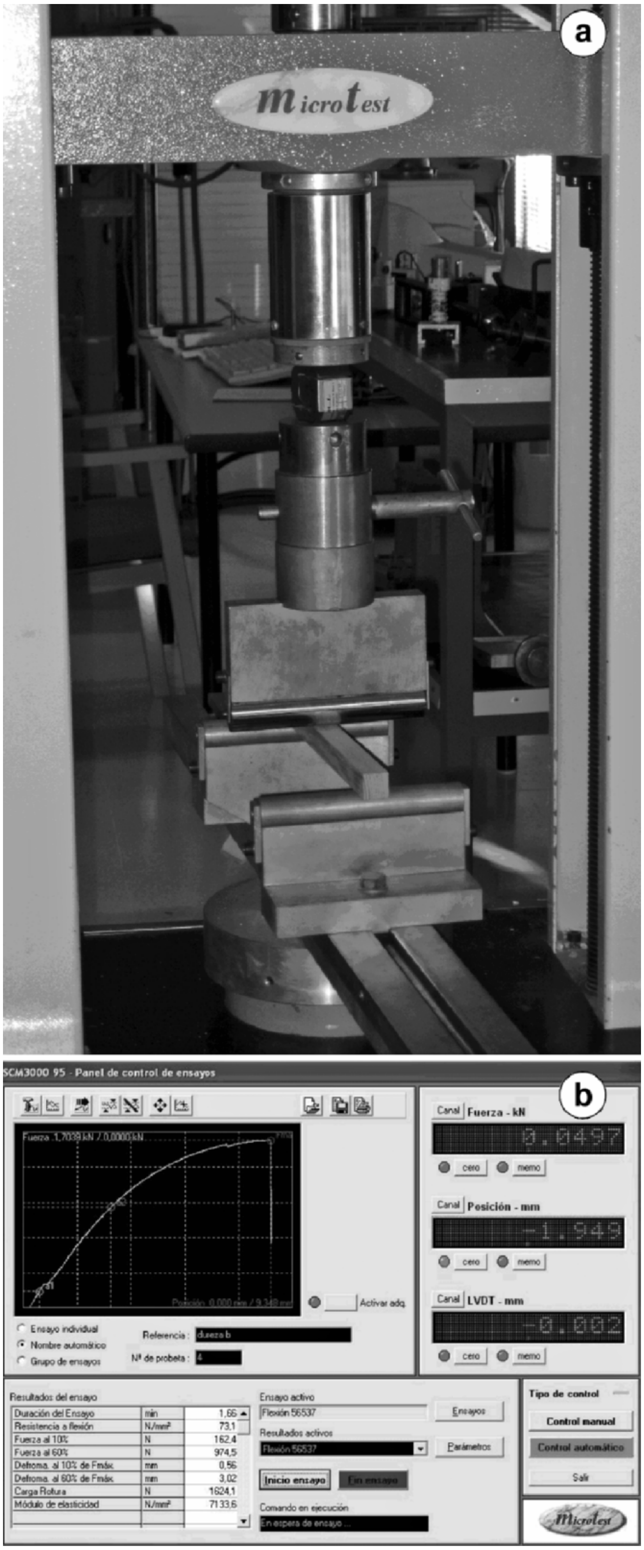
Five trees were felled in each area. All were mature specimens over 70 years old and representative of the forest. The publications used to classify the natural forests were Ceballos and Martín-Bolaños (1930) for the province of Cádiz; Ceballos and Vicioso (1933) for the province of Málaga; and the Forest Map of Spain (Ruiz de la Torre 2002).

The trunks were radially sawn at heights between 1.5 and 5 m to obtain boards 40 mm thick, which were then air-dried to 18 percent moisture content (MC). After discarding wood corresponding to the first 30 growth rings, square section strips measuring 35 by 35 mm were obtained from the boards and conditioned in a chamber at 20°C ± 2°C and 65 ± 5 percent relative humidity. The final defect-free test pieces, with a cross section of 20 by 20 mm, were then prepared. After each test, calculations were made of the MC of the wood in accordance with the standard UNE-EN 13,183 to 1 (Asociación Española de Normalización y Certificación [AENOR] 2002) and of the SG (12% MC) in accordance with UNE 56,531 (AENOR 1977a).

The tests for static bending, compressive strength parallel to the grain, tensile strength perpendicular to the grain and splitting strength were conducted in a universal testing machine of the Suzpecar brand, with three interchangeable load cells of 500, 5,000, and 50,000 N (Fig. 2). To determine the impact bending, the instrumented Charpy method was applied, using a Dart Tester drop-weight tester of the Ceast brand and a DAS4000 data acquisition program. The equipment used to determine the MC, SG, and dimensions of the test pieces consisted of a Sartorius Handy 110 balance with a scale division of 0.0001 g, a Heraeus VT 6025 oven with air recirculation capable of maintaining a temperature of 103°C ± 2°C, and a Mitutoyo Digimatic digital caliper with a range of 300 mm and a scale division of 0.01 mm. All the equipment was calibrated and the uncertainties complied with the general technical competence requirements for testing laboratories in accordance with the standard UNE-EN ISO/IEC 17,025 (AENOR 2005) and the testing standards.

To evaluate the biometry, thin section slides for light microscopy were prepared following the usual methods of softening, cutting, staining, and mounting. The tracheid measurements (cell wall thickness in earlywood and latewood, diameter, and length) were taken on 5 slides from each tree using mature wood between rings 50 and 70. In total, 35 measurements were taken on each slide (875 measurements per provenance). Tracheid length was measured in accordance with Ladell's indirect method (Ladell 1959). The growth rate (number of rings per centimeter) was measured on the north–south diameter. The measurements were taken with the WinCell image analysis program.

For the data processing, Lilliefors normality test and Bartlett's homogeneity of variance test (MathWorks Inc. 2002) were conducted, in both cases for a 95 percent significance level ($P < 0.05$). The Kruskal–Wallis analysis of variance (ANOVA) test (MathWorks Inc. 2002) was used to analyze the samples, given that at least one of the conditions was not met in each procedure. The statistically significant differences between provenances were determined by conducting least significant difference (LSD) tests using the data from the Kruskal–Wallis ANOVA test. The Matlab V.6.5 Release 13 program was used for the statistical calculations, for a 95 percent significance level.



SCM3000 95 - Panel de control de ensayos

Fuerza 1,7039 kN / 0,0000 kN

Posición 0,000 mm / 9,348 mm

Canal Fuerza - kN: 0.0497

Canal Posición - mm: -1.949

Canal LVDT - mm: -0.002

○ Ensayo individual
● Nombre automático
○ Grupo de ensayos

Referencia : dureza b

Nº de probeta : 4

Resultados del ensayo

Duración del Ensayo	min	1,66
Resistencia a flexión	N/mm²	73,1
Fuerza al 10%	N	162,4
Fuerza al 60%	N	974,5
Defroma. al 10% de Fmáx	mm	0,56
Defroma. al 60% de Fmáx	mm	3,02
Carga Rotura	N	1624,1
Módulo de elasticidad	N/mm²	7133,6

Ensayo activo: Flexión 56537

Resultados activos: Flexión 56537

Comando en ejecución: En espera de ensayo ...

Figure 2.—(a) Universal testing machine for determining static bending strength, compressive strength parallel to the grain, tensile strength perpendicular to the grain, and splitting strength. (b) Data acquisition screen.

Charpy impact strength

The hammer had a mass of 11,000 g and a drop height of 1,000 mm. The test piece dimensions were 20 by 20 by 300 mm (tangential by radial by longitudinal direction). A striking tup with a radius of 1.5 mm was chosen, which proved to have a major influence on the energy transmitted (Tanaka et al. 1995). The distance between supports was set at 240 mm. In each test piece a 45° notch was made to a depth of 2 mm, with a radius of 0.25 mm at the base of the notch in accordance with the specifications of the standard Charpy test (ASTM International 2005). For the speed, Kalthoff's (1996) recommendations were taken into consideration. The response was fitted by reducing the force of impact until the appropriate graph was achieved. The Charpy testing method was chosen because the support system at the two ends of the test piece removes the effect caused by clamping in the Izod method (McCowan et al. 2000).

Deflection during the test was determined using Equation 1:

$$s(t) = \int_0^t v_0 \, dt - \left(\frac{1}{m}\right) \int_0^t F(t) \, dt \tag{1}$$

where

s = test piece deformation at the point of impact (m),
v_0 = initial pendulum velocity (m/s),
m = pendulum mass (kg),
F = force indicated by the strain gauge (N), and
t = time interval from the initial moment at which the load is applied to the test piece.

The energy consumed until a specific deformation occurred was calculated using Equation 2:

$$W_{(s)} = \int_0^s F(s) \, dt \tag{2}$$

Static bending strength

Static bending strength was determined in accordance with the standard UNE 56,537 (AENOR 1979). The test piece dimensions were 20 by 20 by 300 mm. The MOR was calculated using Equation 3:

$$\mathrm{MOR}_m = \frac{3PL}{2bh^2} (\mathrm{N/mm}^2) \tag{3}$$

where

MOR_m = static bending at m% MC (N/mm^2),
P = breaking load (N),
L = distance between supports (240 mm),
b = test piece dimension in the radial direction (20 mm), and
h = test piece dimension in the tangential direction (20 mm).

Tensile strength perpendicular to the grain

The tensile strength perpendicular to the grain was determined in accordance with the standard UNE 56,538 (AENOR 1978a) using Equation 4, carried out on two series of test pieces, one in the radial direction and the other in the tangential direction. The test piece dimensions were 20 by 20 by 70 mm.

$$\sigma_{Tm} = \frac{P}{F} \tag{4}$$

where

σ_{Tm} = tensile strength perpendicular to the grain at m% MC (N/mm^2),
P = breaking load (N), and
F = cross sectional area of the test piece (mm^2).

Splitting strength

Splitting strength was determined in accordance with the standard UNE 56,539 (AENOR 1978b) using Equation 5. The test piece dimensions were 20 by 20 by 70 mm.

$$\sigma_{Sm} = \frac{P}{w} \tag{5}$$

where

σ_{Sm} = splitting strength at m% MC (N/mm),
P = breaking load (N), and
w = test piece width (mm).

Compressive strength parallel to the grain

For compressive strength parallel to the grain the standard used was UNE 56,535 (AENOR 1977b). The test piece dimensions were 20 by 20 by 60 mm. The strength value was calculated using Equation 6:

$$\sigma_{Cm} = \frac{P}{F} (\mathrm{N}^2) \tag{6}$$

where

σ_{Cm} = compressive strength at m% MC (N/mm^2),
P = breaking load (N), and
F = cross sectional area of the test piece (mm^2).

Although the test pieces were conditioned to meet standards before testing, the final values were fitted to 12 percent MC using Equation 7:

$$\sigma_{12} = \sigma_m[1 + K(m - 12)] \tag{7}$$

where

σ_{12} = strength at 12 percent MC,
m = actual MC %, and
K = constant (0.04 for static bending strength; 0.015 for tensile and splitting strength; 0.06 for compressive strength).

Results

Tables 2 and 3 show the results for SG, mechanical properties and biometry by region of provenance. Significant differences between provenances for a 95 percent significance level are also presented.

Discussion

The physical, mechanical, and chemical properties of wood can vary as a result of environmental conditions, soil type (Bektas et al. 2003, Gundogan et al. 2005), silvicultural factors, tree age (Miranda et al. 2001), tree anatomy (Bhat and Priya 2004), and even the position of the test piece within the tree (dePalacios et al. 2008).

Table 2.—SG and mechanical properties by region of provenance (1) Sierra de Grazalema, (2) Sierra Bermeja, and (3) Sierra de las Nieves.[a]

	Provenance					
	1		2		3	
Property	No. of test pieces	$\bar{x} \pm \sigma$ (range)	No. of test pieces	$\bar{x} \pm \sigma$ (range)	No. of test pieces	$\bar{x} \pm \sigma$ (range)
SG (g/cm^3)	932	0.40 ± 0.45 A (0.39–0.66)	756	0.45 ± 0.51 A (0.39–0.66)	885	0.50 ± 0.51 A (0.39–0.65)
Charpy impact strength (J)	178	16.9 ± 7.2 A (3.9–46.0)	123	12.4 ± 3.7 B (4.9–18.6)	147	14.3 ± 8.2 AB (2.9–42.1)
Static bending strength MOR (N/mm^2)	199	74.9 ± 19.3 A (23.7–103.1)	120	68.8 ± 14.2 A (477–100)	150	71.1 ± 22.0 A (19.4–111.17)
Tensile strength perpendicular to the grain (tangential) (N/mm^2)	171	1.9 ± 0.4 A (1.1–2.7)	124	2.0 ± 0.4 A (1.2–2.5)	152	1.8 ± 0.3 A (1.3–2.8)
Tensile strength perpendicular to the grain (radial) (N/mm^2)	155	2.0 ± 0.3 A (1.4–2.9)	115	2.0 ± 0.2 AB (1.6–2.6)	169	1.9 ± 0.2 B (1.5–2.6)
Splitting strength (N/mm)	109	2.4 ± 0.2 A (2.0–3.0)	136	2.3 ± 0.2 A (2.0–2.7)	108	2.3 ± 0.2 B (1.6 to 3.0)
Compressive strength parallel to the grain (N/mm^2)	120	40.0 ± 8.0 A (22.0–61.3)	138	39.9 ± 7.9 A (20.8–54.6)	159	39.3 ± 7.0 A (22.0 to 56.4)

[a] Different letters indicate statistically different values ($P < 0.05$).

The first log of each tree was removed in order to avoid disperse data (Climent et al. 2003, Baonza et al. 2001, Xu and Walker 2004). Some authors attribute abnormal behavior observed in the data to the fact that the cell wall microfibrils have a greater angle in the lower part of the trunk than in the higher part (Donaldson 1992). In fact, physico-mechanical characteristics are usually obtained starting at breast height, although some standards are more restrictive and require heights between 2 and 4 m from the base (Güler et al. 2003).

In the case of defect-free wood, as in this study, the variables considered to affect mechanical behavior were microfibril angle, tracheid length, SG, latewood percentage, and cell wall thickness and lumen diameter of the tracheids.

Through biometric measurements, significant differences were observed only in tracheid length and growth rate in the Sierra Bermeja provenance in comparison with the other two.

Charpy impact strength

Analysis of variance of the Charpy test values revealed a significant difference between provenance 1 and provenance 2. Provenance 3 did not show significant differences in comparison with the other two. The higher value obtained in provenance 1 contradicts the expected value (Bektas et al. 2003), since the growth rate was significantly lower than the other provenances. Although growth rate was different, the SG values of the three provenances were not, and SG is a determining factor in impact response (Kollmann 1951). Specimens chosen for testing did not include material with juvenile wood (Evans et al. 2000) or excessive slope of grain (Bodig and Jayne 1993).

Tracheid length was significantly lower in provenance 1 compared with the other two provenances and was expected to result in lower impact strength in provenance 1 (Bektas et al. 2003), but this was not the case. Although tracheid length is the second most important factor affecting the mechanical properties of wood (Zobel and Buijtenen 1989), the similar SG values may cancel out its influence. In addition, some authors have determined that, in certain species, tracheid length does not greatly affect the mechanical properties (Koizumi et al. 2003).

Static bending strength

Analysis of variance for the MOR values showed that there were no significant differences between provenances. This agreed with the SG trends, but not with the significant differences between provenance 1 and provenances 2 and 3 for the growth rate. Results did concur with studies by other authors (Fernández-Golfín and Díez 1994), which showed that growth rate had little influence on bending strength variation. Others, however, did establish significant differences based on ring variations (Barrett and Kellogg 1991, Biblis et al. 1997), but their studies included very low correlation coefficients. This is due to the fact that the influence of growth rate is not as important as the cambial age (Hiler 1995); i.e., whether the wood is mature or juvenile is more relevant than growth rate.

Table 3.—Biometry per region of provenance (1) Sierra de Grazalema, (2) Sierra Bermeja, (3) Sierra de las Nieves.

	Biometry, $\bar{x} \pm \sigma$ (range), by provenance		
	1	2	3
Axial tracheid diameter (μm)	46.9 ± 9.4 A (23.4–76.0)	44.4 ± 9.8 A (22.7–71.3)	44.9 ± 10.8 A (25.3–73.4)
Axial tracheid length (μm)	2,591 ± 793 A (1,335–4,625)	3,154 ± 861 B (1,500–7,250)	2,946 ± 934 B (1,420–6,167)
Growth rate (rings/cm)	3.6 ± 0.76 A (2.8–4.5)	11.4 ± 1.64 B (10.6–11.5)	7.5 ± 1.07 B (10.0–14.6)
Cell wall thickness (μm)			
Earlywood	4.82 ± 1.45 A (2.52–8.84)	5.20 ± 1.23 A (3.31–8.41)	5.65 ± 1.20 A (3.11–8.22)
Latewood	2.23 ± 0.36 A (1.57–3.28)	1.92 ± 0.36 A (1.25–2.97)	1.62 ± 0.22 A (1.13–2.20)

[a] Different letters indicate statistically different values ($P < 0.05$).

Tensile strength perpendicular to the grain

For tensile strength perpendicular to the grain, analysis of variance showed that there were no significant differences in the tangential direction between the three provenances. However, in the radial direction there were significant differences between regions 1 and 3.

SG is not known to be one of the most influential factors for this property, and some authors found no correlation between these two parameters (Peszlen 1998). In relation to tracheid length and growth rate, the lower values in provenance 1 did not explain the higher tensile strength values in the radial direction when compared with provenance 3. Although there were significant differences between these two regions, this was not so in the case of provenance 2, which had higher values for both anatomical features.

Splitting strength

As expected, the splitting response followed the same pattern as tensile strength perpendicular to the grain in the radial direction. There was no correlation with SG, growth rate, or tracheid length.

Compressive strength parallel to the grain

SG, growth rate, and grain direction are some of the factors with most importance in compressive strength parallel to the grain (Kollmann and Côté 1968). The grain direction was controlled by appropriate preparation of the test pieces. Although significant differences existed for the growth rate, the fact that SG did not show significant differences between provenances explained why there were no differences in the values of compressive strength parallel to the grain.

The influence of environmental factors, such as altitude, soil, and climate, on the mechanical properties of some timbers has been demonstrated (Bektas et al. 2003, Korkut and Gullerb 2008). However, in the case of *A. pinsapo,* which shows notable differences in soil types (particularly in the Sierra Bermeja forest) and climate (Sierra de Grazalema), the mechanical properties of the wood showed almost no difference. This may be due to the strong influence of the genetic factor on SG (Polge 1971) and the homogeneity observed in the biometry of the three provenances.

Some researchers maintain that the Spanish and Moroccan populations of *A. pinsapo* could even have formed a single species before the final separation of the Iberian Peninsula from the North of Africa at the end of the Tertiary era (Jeanmonod and Bocquet 1981). This shared past prior to speciation may have been the common vector of the southern phylum of the easternmost firs and could explain why all the pinsapo forests maintain similar anatomical (Esteban et al. 2007), physical, and mechanical features. Future studies on the African pinsapo forests could confirm this hypothesis.

Conclusions

It can be concluded from the results that the SG and mechanical characteristics of the *A. pinsapo* wood studied from the three Spanish regions of provenance showed similar values, with few significant differences between the regions of provenance.

Although the growth rate showed significant differences between provenance 1 and the other two provenances, the fact that the SG was not statistically significant between provenances explains the similar mechanical behavior of the three *A. pinsapo* timbers studied.

Such homogeneous behavior supports the hypothesis that the *A. pinsapo* forests once formed a single forest that included the Moroccan pinsapo forests before the final separation of the Iberian Peninsula from the North of Africa.

The results obtained have applications when replacing structural pinsapo fir timber in emblematic buildings in towns near the area of distribution of the species.

Acknowledgments

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