

TIMBER GRADING OF *Pinus uncinata*, A LESSER KNOWN PINE SPECIES FROM THE PYRENEAN MOUNTAIN RANGE

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ABSTRACT

Timber grading is an essential step into the value process to determine wood usability for structural uses. It requires well-described characteristics obtained easily by taking non-destructive measurements to quantify reliable indicators of mechanical properties. In this paper we present an approach based on both timber scale and clear-wood scale measurements using the case of Mountain pine (*Pinus uncinata*).

An important experimental plan have been performed from collected trees of French and Spain Pyrenean regions allowing significantly the use of inter-correlations between measurements. The physical properties of clear wood present an important adaptation of tree growth condition with a lower modulus of elasticity as a consequence of microstructure at cell-wall level but a conventional modulus or rupture in bending for pines. However, the results on timber presents an important the difference between visual and machine grading for this species in view of mechanical properties considered. The results obtained also show possible improvement and limitations of current regulation in the grading mountain pine timber for structural use.

Keywords: Clear-wood properties, modulus of elasticity, modulus of rupture, mountain pine, variability.

INTRODUCTION

Pine species are very numerous in the forests of all continents and many of them are widely planted all over the world for structural uses (e.g. poles, carpentry, joinery, furniture) or for pulp and paper industry. Species like *Pinus caribea*, *P. oocarpa*, *P. elliottii* or *P. patula* are widespread in the tropics where those species account for 25% of all plantations. This proportion is even higher than 50% in boreal and temperate regions with species as *Pinus radiata*, *P. sylvestris*, *P. pinaster*, *P. nigra*, *P. contorta* (Brown 2000).

Mountain pine is a species belonging to the *Pinus mugho* complex that grows in the subalpine vegetation belt up to the upper forest limit (1000 - 2300m) in Western Europe (Heuertz *et al.* 2010). It is an important forest resource in terms of growing stock in the Pyrenean mountain range, in both southern France (FR-IFN-66-3 1994, Riou-Nivert 2015) and northern Spain. The trees are rather small in diameter (below 50 cm) which can be an asset in modern sawmills. However, this timber resource is both poorly valued by the forest industry and poorly described.

Literature concerning clear-wood pine properties and their links to growth parameters (ring width, juvenile wood, compression wood) is very abundant (Carson *et al.* 2014, Dumail *et al.* 1998, Harris and Meylan 1965, Ivković *et al.* 2008, Kang *et al.* 2005, Mazet and Nepveu 1991, Moore *et al.* 2015, Riesco-Muñoz *et al.* 2008, Roth *et al.* 2007, Watt *et al.* 2005), notably in the expansive volume (1660 pages) “*Utilization of the southern*

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pinus” (Koch 1972) dealing with all aspects of pines from botany to timber processing.

In order to be used in structural applications, pine timber must be mechanically graded and conform to regulations such as the European standard for structural timber NF EN-338 (2016) and NF EN-384 (2016). Many studies, often unpublished, were conducted to promote this standard, but only a few were focused on pine species (Hanhijärvi *et al.* 2005, Moya *et al.* 2015, Nocetti *et al.* 2010).

The objective of this paper is to study the physical and mechanical properties of *Pinus uncinata* clear-wood as well as grading timber products according to the European standards for predicting clear-wood properties from easily obtainable non-destructive parameters.

MATERIAL AND METHODS

Wood material

Sixty-two trees of Mountain pine (*Pinus uncinata* Ramond ex DC.) were harvested in nine representative forest plots (Table 1). For each tree a bottom log (2 m long), a middle log (1 m long) and a top log (2 m long) were crosscut (Figure 1). The logs were through-and-through sawn into 50 x 100 mm planks dried further in a conventional kiln to a mean moisture content of approx. 11%.

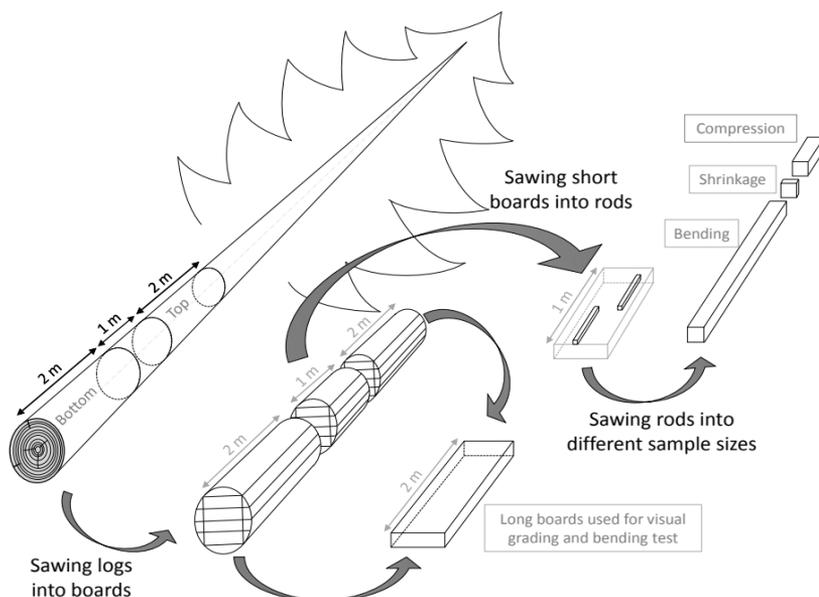


Figure 1: Sample preparation from tree to logs sawn to boards, rods and dedicated specimens for standard characterisations.

Table 1: Provenance of trees and visual grading of boards.

Plot (index)	City (name)	Altitude (m)	Exposure (-)	Trees (number)	Boards (number)	VG ₁ (%)	VG ₂ (%)	VG ₃ (%)	VG ₄ (%)	R (%)
1	Camporells	1880	S-SW	8	161	5	39	23	23	10
2	Formiguères	1850	NE	8	124	3	23	34	26	14
3	Les Angles	1670	S-SW	6	121	6	26	27	25	15
4	Matemale	1700	NE	6	114	9	41	14	26	10
5	Ayguatèbia	1850	N-NW	8	151	5	36	23	21	14
6	Eyne	1900	N-NW	8	169	11	32	21	17	19
7	Osséja 1	1880	N-NE	6	106	5	18	28	19	31
8	Osséja 2	2000	NW	6	117	3	15	19	33	30
9	Porta	1740	N-NE	6	78	0	14	35	32	20
All				62	1141	6	29	24	24	17
Bottom				62	640	8	34	25	17	17
Top				62	501	3	24	25	30	18

Altitude (m), trees, boards, rods (number), VG 1 to 4 and R (% of total boards) with VG₁ to VG₄: visual grades of boards from best (almost no defects) to worst (large knots) and R: rejected (mostly severe warping).

All 2 m long samples were graded using the French standard NF B 52-001-1 2011 employing four classes for visual grading (VG₁ to VG₄) based on combined criteria like ring width, knot diameter, position, splits, warp, rot etc. Boards that do not fulfil these criteria for any reason are rejected (R). Table 1 describes the differences in visual grading both for each plot and between bottom and top logs. Only the graded boards (945 in total) were used for the measurement of density and mechanical properties.

Ninety-eight short boards were selected to cover the whole range of densities and provenances (around 10 boards per forest plot). These boards were cut to clear wood specimens for mechanical and physical tests. From each board, one to three rods, a mean of two per board, were cut to obtain 183 clear wood rods, free of compression wood (450 mm x 20 mm x 20 mm in the L, R, T directions). Each rod was then cut into 3 sub-samples (Figure 1) for physical and mechanical measurements. These rods were placed in a climatic chamber with regulated standard conditions (20°C +/- 2°C, 65% +/- 5% RH).

Measurements on boards

Mass (M), length (L), width (W) and thickness (T) were measured on all boards and density was calculated using the ratio: $D = M / (L * W * T)$, in kg/m³.

In order to measure both longitudinal MOE and MOR in the central third of the beam an edgewise bending test in accordance to the European standard NF EN-408 (2010) was performed on each board. Specific modulus (SM) for the board was calculated using the ratio: $SM = MOE / D$.

Shrinkage measurements on rods

Small wood cobbles measuring 10 mm x 20 mm x 20 mm (L, R, T) extracted from rods ends were measured to quantify ring width, mass, R and T dimensions on all these specimens at equilibrium moisture content in the standard climate. All samples were then fully saturated using a vacuum/pressure process. At that stage, mass (M_{sat}), R, T dimensions (R_{sat} , T_{sat}) were measured. The samples were successively placed in hygroscopic equilibrium under three different climates leading to usual wood equilibrium moisture contents, 18%, 14%, 8%. They were finally dried completely in an oven at 103°C. At each moisture content i , mass (M_i), R and T dimensions (R_i , T_i) were measured and the RT area calculated as $A_i = R_i * T_i$.

At the end, the following parameters were calculated:

- Basic density: $BD = M_0 / V_{sat}$
- Moisture content at each state: $H_i = (M_i - M_0) / M_0$
- Total shrinkage: tangential shrinkage $TS = (T_{sat} - T_0) / T_{sat}$, radial shrinkage $RS = (R_{sat} - R_0) / R_{sat}$, area shrinkage $AS = (A_{sat} - A_0) / A_{sat}$, volumetric shrinkage $VS = AS + 0,002$; 0,2% is taken as a unique value for longitudinal shrinkage (Glass and Zelinka 2010).
- Shrinkage anisotropy: $SA = TS/RS$
- Area reduction at each stage: $\Delta A_i = A_{sat} - A_i$

The fibre saturation point (FSP) is calculated as the intercept of the linear relationship $H_i / \Delta A_i$ and the moisture content axis (Choong 1969) (Figure 2).

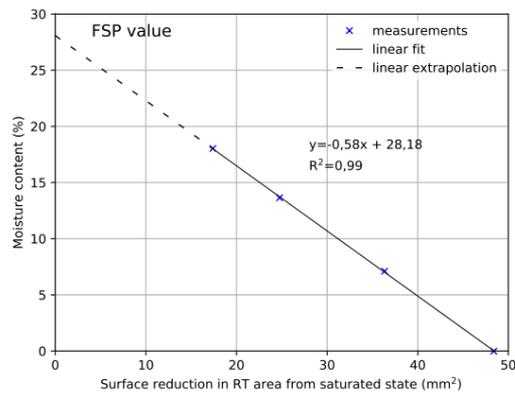


Figure 2: Fibre Saturation Point (FSP) calculation using surface variation. FSP is the intercept with the Y axis, i.e. the constant value in linear regression.

Compressive strength

The sample dimensions were 60 mm x 20 mm x 20 mm (L, R, T). The mass and dimensions of the small rod were measured first and the specimen compressed between plates in a universal testing machine (Adhameil Lhomargy DY 36 of 100 kN capacity) until rupture in accordance with the French standard NF B51-007 (1985). The maximum force was recorded and the crushing strength (CS) was measured from that force and the transverse dimensions of the sample. The density of the sample (D_{CO}) was also calculated for the sample under standard equilibrium moisture conditions.

Specific modulus

This measurement was carried out on long samples (360 mm x 20 mm x 20 mm, L, R, T directions) under standard equilibrium moisture conditions. The dimensions in the three directions and the mass of the specimen were measured. Each rod was placed in free vibration on elastic supports at the level of the first vibration mode in bending condition, induced by knocking one end of the rod. The values of the three highest resonance frequencies were recorded using a Fast Fourier Transform analysis. The specific modulus SM (m^2/s^2) was calculated using the Timoshenko solution (Brancheriau and Baillères 2002).

1. The density of the sample (D_{flex}) was calculated using the values of the mass and dimensions of the rod. The longitudinal modulus of elasticity (MOE) was calculated as the product of density and specific modulus: $MOE = D_{flex} * SM$.

2. When the crushing strength and MOE are known, their ratio, $SL = CS/MOE$ (SL: strain limit), is an interesting parameter which has the dimension of a strain. It is a lower limit for the real strain at rupture and can be considered as a proxy for the strain limit in compression for clear wood.

RESULTS

General results and visual grading

Table 1 gives the results for visual grading and shows that 10% to 30% of the boards, according to plot, were rejected (17% at a mean, with low differences between top and bottom logs). The percentage of top class logs (VG_1) is always low (6% at a mean, varying from 0% to 11% between plots) and the difference is remarkable between top (3,2%) and bottom (7,6%) logs. Among the classed boards, bottom logs generally give

higher grades (VG_1 and VG_2) than top logs.

Table 2 and Table 3 give the results for the mean properties of the 945 boards that were not rejected. At plot level (Table 2), VG_m is the mean value of visual notation (from 1 to 4), low values signifying better classification for the plot. There is consistent concordance between this mean visual classification and the mean strength (MOR) for the different plots, but this is not the case for mean density or mean stiffness of the boards (Table 3). The same concordance occurs between bottom and top logs: a 15% reduction in mean visual class (VG_m) leads to a 20% reduction for mean MOR but only 6% for MOE, 4% for D and 2% for SM. From grade 4 to grade 1 there is a 33% increase in mean MOE or SM and 64% increase in mean MOR.

Table 2: Mean properties of graded boards per forest plot.

Plot (index)	Type	Nb	VG_m	D (kg/m ³)	MOR (MPa)	MOE (MPa)	SM (x10 ⁶ m ² /s ²)
1	All	147	2,65	527	49,9	9217	17,5
2	All	106	2,93	531	49,3	9780	18,4
3	All	102	2,85	508	47,0	8371	16,5
4	All	103	2,62	503	49,2	9097	18,2
5	All	131	2,70	496	48,8	8293	16,7
6	All	135	2,49	523	53,5	9990	19,1
7	All	75	2,83	499	46,1	9536	19,1
8	All	82	3,21	504	40,5	8622	17,0
9	All	64	3,14	506	39,6	8389	16,6
All	Bottom	534	2,61	522	52,4	9333	17,9
All	Top	411	3,00	499	42,3	8741	17,5
All	All	945	2,78	512	48,0	9076	17,7

Nb: number of boards in the plot, VG_m : mean of visual grade (1 to 4) for the boards in the plot, D: density in kg/m³, MOR: flexure strength in MPa, MOE: modulus of elasticity in MPa, SM: specific modulus in 10⁶m²/s².

Table 3: Mean properties of boards per visual grade.

VG	Nb	D (kg/m ³)	MOR (MPa)	MOE (MPa)	SM (x10 ⁶ m ² /s ²)
1	65	515	62,8	10692	20,8
2	339	510	55,6	9876	19,3
3	280	516	44,4	8731	16,9
4	261	510	38,4	8004	15,7
1&2	404	511	56,8	10007	19,6
3&4	541	513	41,5	8381	16,3
All	945	512	48,0	9076	17,7

Nb: number of boards in the visual grade, 1 & 2: grouping of visual grades 1 and 2, 3&4: grouping of visual grades 3 and 4.

Histograms of D, MOR, MOE and SM (Figure 3) show that these values have a distribution close to a normal one.

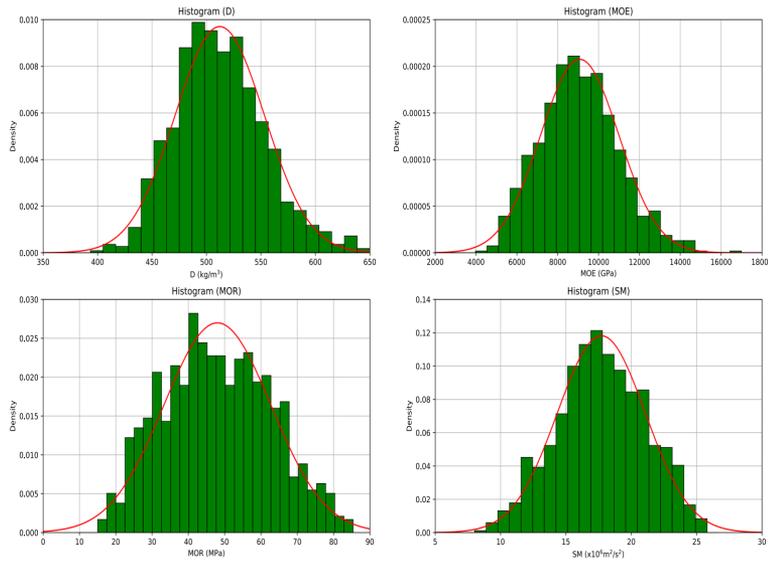


Figure 3: Histograms of graded boards properties. Continuous line: normal distribution associated to the population of boards.

Table 4 gives the correlation coefficient between properties of the all listed boards. There is a significant negative correlation between the visual grade and the mechanical properties of the boards. Density was not correlated to visual grade; however, there are also significant positive correlations between density, strength and stiffness. Variations in MOE help to predict 55% of MOR, which is rather usual in mechanical grading (Hanhijärvi *et al.* 2005, Srpčič *et al.* 2009).

Table 4: Correlation between board properties.

	VG	D (kg/m ³)	MOR (MPa)	MOE (GPa)	MOE/D (MPa/kg/m ³)
VG	1	0,833	0,000	0,000	0,000
D (kg/m ³)	-0,007	1	< 0,0001	< 0,0001	0,389
MOR (MPa)	-0,542	0,303	1	< 0,0001	< 0,0001
MOE (GPa)	-0,452	0,407	0,739	1	< 0,0001
MOE/D (MPa/kg/m ³)	-0,497	0,028	0,685	0,921	1

Bold characters: significant correlation (here always better than 0,001).

Using a linear regression model between MOR and MOE a predictive formula for the 5-percentile (5% MOR) is found at 5% MOR=5,6858*MOE-23,15 (MOR in MPa, MOE in GPa). This formula ensures that less than 5% of experimental MOR remains below the predicted value.

Mechanical grading

European rules for structural timber, NF EN-338 (2016), NF EN-384 (2016) are based on characteristic values (5-percentile) for MOR, MOE and density that must be determined by experimental tests on at least 900 timber pieces. Classes named C14-C50, based on the 5-percentile MOR (14 MPa-50 MPa) give references

for both characteristic (5-percentile) and mean values for MOE and density (Table 5). The values for specific modulus (SM = MOE/D) and a tentative estimation of prices for each grade are added in Table 5.

Table 5: Reference values for 5-percentile and mean value (D and MOE) for softwood grades in NF EN-338 (2016).

MG	5% MOR (MPa)	5% MOE (GPa)	5% D (kg/m ³)	MOEm (GPa)	Dm (kg/m ³)	SM (x10 ⁶ m ² /s ²)	Unit price €/m ³
C14	14	4,7	290	7	350	20,0	150
C16	16	5,4	310	8	370	21,6	175
C18	18	6	320	9	380	23,7	200
C20	20	6,4	330	9,5	390	24,4	225
C22	22	6,7	340	10	410	24,4	250
C24	24	7,4	350	11	420	26,2	275
C27	27	7,7	370	11,5	450	25,6	300
C30	30	8	380	12	460	26,1	325
C35	35	8,7	400	13	480	27,1	350
C40	40	9,4	420	14	500	28,0	375
C45	45	10,1	440	15	520	28,8	400
C50	50	10,7	460	16	550	29,1	425

SM: specific modulus calculated as MOEm/Dm, Price: Estimation of putative prices for the different grades in €/m³.

By using the table above, it is possible to propose a grading for all boards non-rejected by visual grading, or grade by grade, or by grouping the two best and the two worst grades (Table 6a and 6b). This was done using all characteristic values (left portion of the table) or using mean MOE instead of 5-percentile MOE.

Table 6a: Mechanical grading correlated to visual grading, using 5-percentile values only.

	Nb	%	MG MOE _{5%}	5% MOR (MPa)	5% MOE (GPa)	5% D (kg/m ³)	Unit price (€/m ³)	Value (€/m ³)
All	945	100%	C18	24,4	6,1	451	200	200
VC1	65	7%	C27	44,9	7,8	446	300	20,6
VC2	339	36%	C22	35,0	7,1	443	250	89,7
VC3	280	30%	C18	24,4	6,1	454	200	59,3
VC4	261	28%	C16	22,1	5,5	453	175	48,3
VC1&2	404	43%	C22	36,3	7,2	443	250	106,9
VC3&4	541	57%	C16	22,9	5,8	454	175	100,2

Legend as in Table 5. Value: product of unit price by percentage of the boards in the grade in €. Mean value is 200 €/m³ for all boards graded C18, 218 €/m³ if all visual grades are mechanically graded, 207 €/m³ for grouping visual grades.

Table 6b: Mechanical grading correlated to visual grading, using mean MOE instead of its 5-percentile values.

	Nb	%	MG MOE _m	mean MOE (GPa)	mean D (kg/m ³)	SM (GPa/kg/m ³)	Price MOE _m (€/m ³)	Value MOE _m (€/m ³)
All	945	100%	C18	9,1	512	17,7	200	200
VC1	65	7%	C22	10,7	515	20,8	250	17,2
VC2	339	36%	C20	9,9	510	19,3	225	80,7
VC3	280	30%	C16	8,7	516	16,9	175	51,9
VC4	261	28%	C16	8,0	510	15,7	175	48,3
VC1&2	404	43%	C22	10,0	511	19,6	250	106,9
VC3&4	541	57%	C16	8,4	512	16,4	175	100,2

See legend of Table 6a. Mean value is 200 €/m³ for all boards graded C18, 198 €/m³ if all visual grades are mechanically graded, 207 €/m³ for grouping visual grades.

It should be noted that grade is always determined using MOE (5-percentile or mean value) and 5-percentile MOR remains well above the reference for each grade.

Taking all visually graded timber as a population, C18 grade can be applied both using characteristic or mean values for MOE. Hence the value will be 200 €/m³ for all the population.

Class by class (or grouping 2 classes), grading using mean MOE is more severe than grading using characteristic MOE values. Characteristic or mean density is always far above established references. Using grouped visual graded classes gives around 43% C22 (VG₁ and VG₂) together with 57% C16 (VG₃ and VG₄), with a mean putative value of 207 €/m³ which means only 3,5% more than without difference among visually graded populations. The significance of this result remains to be determined.

Machine grading

Measuring both density and MOE of a board can be done either by flexure test (MOE_f) or by vibration techniques (MOE_v). MOE_f gives the MOE for the central third of the board while MOE_v gives the MOE for the entire board. The regression coefficient (r²) between the values obtained by both methods on the same population of boards is usually above 0,8 and vibration method is used most often.

In order to grade the boards in this population, we use the predictive model for 5-percentile MOR based on MOE_f measurements. Cxx grade is given for a softwood population having a predicted MOR above xx MPa. For each graded population, characteristic (5-percentile) and mean values are calculated for MOR, MOE and density (Table 7). In each graded population, characteristic values are well above standards but mean values for MOE are well below specified ones. With this machine grading, mean value for the population of boards (945 boards), using 100 €/m³ as the price for non graded boards (MOR <14 MPa), will be 262 €/m³, a value 30% higher than the C18 grade for all boards.

If mean MOE value for the population should necessarily be above specification, regardless of the machine grading, the solution is to grade all the visually graded population (without rejected pieces) in C18 class and machine grading becomes unnecessary. It should be noted that the mean specific modulus for mountain pine boards in the classes are very low when compared to the values in NF EN 338 (2016).

Table 7: Machine grading (NDT measurement of D and MOE) of the 945 boards, using 5-percentile reference.

MG	5% MORp (MPa)	Nb	%	5% MOR (MPa)	5% MOE (MPa)	5% D (kg/m ³)	MOE _m (MPa)	D _m (kg/m ³)	SM (GPa/kg/m ³)	Price (€/m ³)	Value (€/m ³)
NC	<14	89	9,4%	18,5	4915	442	5892	500	11,8	100	9,4
C14	14-18	76	8,0%	19,1	6578	440	6903	495	13,9	150	12,1
C18	18-24	180	19,0%	24,7	7312	438	7830	495	15,8	200	38,1
C24	24-30	193	20,4%	29,1	8319	448	8834	506	17,4	275	56,2
C30	30-35	163	17,2%	35,6	9387	462	9808	517	19,0	325	56,1
C35	>35	244	25,8%	40,8	10284	479	11536	536	21,5	350	90,4

Same legend as Table 6a. Mean value is 262 €/m³ for this kind of machine grading.

RESULTS FOR CLEAR WOOD RODS

Variability of parameters and properties

Table 8 gives the statistical description of these parameters. The rings are narrow (a mean of 1,6 mm), but ring width variations were rather large (CV = 47%), which is usual (Koch 1972, Zhang 1995). On the other hand, the density or basic density variations were low (CV < 10%), but the values were in the usual range for pine wood (Koch 1972, Kretschmann 2010). Variability for the specific modulus was higher (CV = 14%) than for density, with a twofold range in this sampling. But specific modulus has low values, nearly 20% lower than

the values for southern pines in the US (Kretschmann 2010). This is probably a result of adaptive growth due to windy conditions in these mountains (Telewski 1989).

Volumetric, tangential and radial shrinkage were within the usual range of values for pines (Glass and Zelinka 2010) and variability was much higher for radial shrinkage (CV = 19%) than it was for volumetric or tangential shrinkage. FSP had very low variability (CV = 5%) but its range was nonetheless from 25% to 30%, a range founded by Choong (1969) on sample of ten different pines growing in the southern US.

Variability in compressive strength was the lowest among mechanical properties, while MOE variability was significantly higher (19%). All mechanical properties were in the usual range for pines (Kretschmann 2010).

Table 8: Statistical description of parameters and properties for the 183 specimens of clear-wood.

	Min.	Max.	Mean	C.V.
D12 (kg/dm ³)	0,40	0,66	0,5	10 %
RW (mm)	0,62	4,88	1,6	47 %
E/D (m ² /s ²)	14,8	30,1	23,7	14 %
BD (kg/dm ³)	0,34	0,54	0,42	9 %
VS (%)	8,23	15,79	12,34	12 %
RS (%)	2,02	5,95	4,15	19 %
TS (%)	6,07	11,18	8,34	11 %
T/R (-)	1,51	3,04	2,06	15 %
FSP (%)	23,5	32,0	28,2	5 %
CS (MPa)	29,0	58,4	42,7	13 %
MOE (GPa)	6,93	16,94	11,87	19 %
SL (‰)	2,43	6,71	3,66	14 %
MOR (MPa)	62,6	123,7	91,5	15 %

Min.: minimum value, Max.: maximum value, Mean: mean value, C.V.: coefficient of variation. D12: mean density (kg/dm³) in a standard climate (20°C, 65% RH), RW: ring width (mm), SM: specific modulus (m²/s²), BD: basic density (kg/dm³), VS: volumetric shrinkage (%), RS: radial shrinkage (%), TS: tangential shrinkage (%), T/R: shrinkage anisotropy, FSP: fibre saturation point (%), CS: compressive strength in longitudinal direction (MPa), MOE: modulus of elasticity in longitudinal direction (GPa), SL: strain limit from compression test (‰), MOR: bending strength in longitudinal direction (MPa).

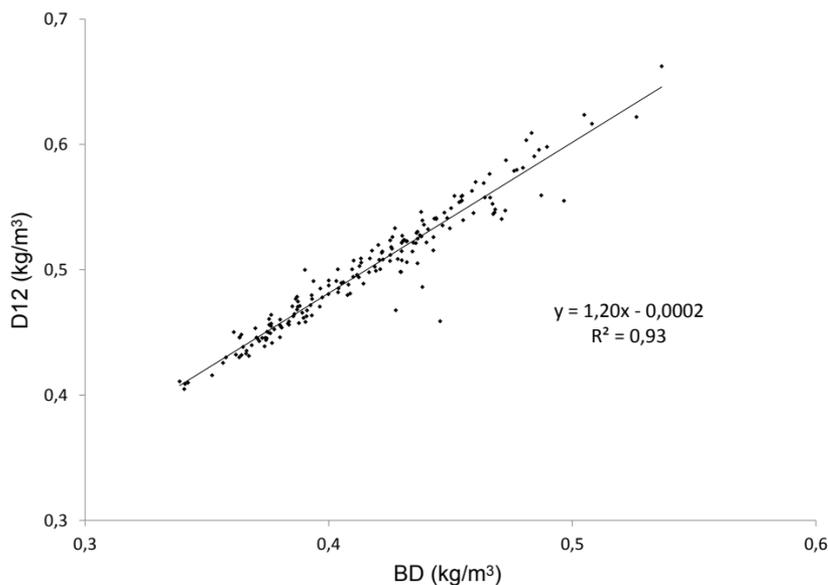
Correlation between parameters

Table 9 gives the results of the correlation analysis. Significant correlation at levels better than 5% probability are very numerous, as expected for a large number of data in this field. The basic density (BD) and density at moisture equilibrium for the standard climate (D12) were very strongly correlated ($R^2=93\%$) in a proportional way (Figure 4) and the formula $D12=1,2*BD$ can be used for these mountain pines.

Table 9: Correlation coefficients for clear-wood.

183 SP.	D12	RW	E/D	BD	VS	RS	TS	R/T	FSP	CS	MOE	SL	MOR
D12	1			93%	30%	37%	17%	21%		62%	41%		26%
RW	-0,25	1	6%										
E/D	0,190	-0,244	1		40%	37%	32%	14%		22%	75%	67%	13%
BD	0,967	-0,012	0,119	1	21%	28%	11%	17%		58%	32%		24%
VS	0,549	-0,105	0,635	0,461	1	82%	86%	31%	30%	42%	58%	19%	11%
RS	0,609	-0,116	0,601	0,528	0,903	1	46%	72%	30%	48%	60%	16%	20%
TS	0,415	-0,079	0,566	0,334	0,929	0,680	1		21%	26%	40%	17%	
T/S	-0,463	0,083	-0,380	-0,406	-0,559	-0,846	-0,223	1	21%	27%	29%		19%
FSP	0,094	0,168	0,140	-0,018	0,545	0,549	0,454	-0,458	1				
CS	0,789	-0,174	0,467	0,759	0,644	0,692	0,506	-0,522	0,070	1	57%		29%
MOE	0,642	-0,197	0,868	0,565	0,761	0,774	0,632	-0,537	0,169	0,757	1	48%	30%
SL	-0,110	0,106	-0,818	-0,021	-0,441	-0,399	-0,408	0,223	-0,166	-0,081	-0,693	1	
MOR	0,513	-0,211	0,358	0,490	0,327	0,445	0,174	-0,434	-0,136	0,537	0,543	-0,213	1

See legend as in Table 8; bold numbers: correlation significant at the 5% level or better; bold numbers: R² value over 50%.

**Figure 4:** Relationship between density and basic density

D12: mean density value measured under standard climate conditions on compression and bending tests.

Among the parameters, although it had the highest C.V., ring width (RW) was not correlated to density. This has also been found for pines in natural stands with a ring width smaller than 3 mm (Koch 1972). Ring width was only significantly negatively correlated to the specific modulus (R²=6%). This kind of negative correlation between ring width and specific modulus is usual in typical radial patterns of juvenile wood for softwoods (Lachenbruch *et al.* 2011) however in this case it is rather weak.

Density is only weakly correlated with the specific modulus and this is unusual for softwood. It may be the result of the following: *i*) a very small ring width in general and *ii*) a small radial expansion of juvenile wood for these slow growing trees.

Correlation between properties

Among the shrinkage properties there were the usual strong links (R²>80%) between volumetric and transverse shrinkage, but a rather weak link between radial and tangential shrinkage (R²=46%). Moreover, radial shrinkage variations explained most of the shrinkage anisotropy (R²=72%).

Despite its low level of variability, FSP was correlated with all the shrinkage properties and a rather high coefficient of determination ($R^2=21\%$ to 30%) was observed.

As expected there was very significant positive correlation between MOE and CS. The strain limit was very strongly negatively correlated with SM (and to a lesser extend to MOE as a consequence), which is the case for flexure wood (Telewski 1989).

Correlation between parameters and mechanical properties

Looking at the relationship between parameters (ring width, density, and specific modulus) and mechanical properties, there were highly significant correlations ($P<0,1\%$) for both density and specific modulus as related to the mechanical properties, except for the strain limit (which depends only on specific modulus). On the other hand, ring width only had a slightly significant negative correlation with mechanical properties, CS ($P<5\%$) and MOE ($P<1\%$), which is not usual for pines (Zhang 1995).

Density had the best coefficient of determination for strength properties: 76% (D) compared to 22% (SM) for CS. On the other hand, the specific modulus was the best for stiffness and flexibility: 75% (SM) compared to 41% (D) for MOE, 67% (SM) compared to 1% (D) for the strain limit. The fact that the specific modulus had a better determination coefficient than density for MOE in this experiment was merely a consequence of the greater variations in specific modulus (higher C.V.).

Correlation between parameters and shrinkage

There was no significant correlation between ring width and shrinkage except for a slightly positive significant correlation with FSP (5% level).

There were highly significant correlations ($P<0,1\%$) for density (positive) and specific modulus (negative) with all shrinkage properties except for FSP. The specific modulus had the best coefficient of determination for shrinkage properties (except for shrinkage anisotropy). Models of wood behaviour based on cell wall structure also explain the influence of these two parameters (Cave 1968, Neagu and Gamstedt 2007, Yamamoto *et al.* 2001).

The primary wall (P) and S1 layer of the secondary wall while very thin have microfibril orientation nearly perpendicular to the tracheid direction and will limit transverse shrinkage (Abe and Funada 2005, Donaldson and Xu 2005). On the other hand, the S2 layer is thick and the microfibrils limit longitudinal shrinkage more than transverse shrinkage. The thicker is the S2, the lower will be the efficiency of the P+S1 layer in limiting transverse shrinkage, thus explaining the positive influence of density on transverse shrinkage.

An increase in MFA in the S2 layer (lower values for the specific modulus) induces a restriction of transverse shrinkage in that layer and thus a lessening of global transverse shrinkage, regardless of the thickness (and density) of S2. The respective influence of the density and specific modulus on shrinkage variation will depend on both the C.V. of each layer (pure mathematical effect) and on the structural organisation of the cell wall.

Prediction of properties by parameters

Ring width, density and specific modulus are parameters that are easy to measure by non-destructive techniques such as X-ray tomography and vibration or ultrasound techniques (Freyburger *et al.* 2009, Van Den Bulcke *et al.* 2009). These parameters are also linked to the wood formation inside of the tree during cambial activity and cell wall thickening.

The different properties were predicted by stepwise linear regression. The combined influence of density and specific modulus can be additive or multiplicative (as for MOE) as a result, the product between these two parameters was introduced as an option in the analysis.

Table 10 gives the global results of these regression calculations providing for each property, the parameter involved with its entry rank and the cumulative determination coefficients (R^2) obtained after each addition of a parameter (F to enter 0,05; F to remove 0,1).

Table 10: Prediction of properties for clear-wood See legend as in Table 8, bold characters: best prediction.

Property	Parameter	R ²
CS	D12	62%
	E/D	72%
	RW	73%
SL	E/D	67%
	RW	67%
MOR	D12	26%
	E/D	33%
	RW	34%
VS	D*E/D	58%
RS	D*E/D	60%
	E/D	62%
TS	D*E/D	40%
T/R	D*E/D	29%
	E/D	31%
FSP	RW	2%
	D*E/D	6%

Compressive strength was well predicted using density and specific modulus alone ($R^2=73\%$), with ring width contributing very little to variability. Strain limit was also well predicted by the specific modulus alone ($R^2=67\%$).

The product of density and specific modulus (MOE) was the best predictor of all shrinkage properties, often alone (VS and TS) and sometimes with a small contribution (less than 2%) from the specific modulus per se. Radial and volumetric shrinkage were rather well predicted ($R^2=62\%$ and 58%) but tangential shrinkage and shrinkage anisotropy were poorly predicted by the parameters ($R^2=40\%$ and 31%). In pine wood, variations in tracheid geometry follows a radial trend so that the successive hard and soft layers of late and early wood act as serial components for radial shrinkage, while they acting as parallel components for tangential shrinkage. In a study to predict anisotropic shrinkage of softwood (Pang 2002) found that radial shrinkage grows linearly with the proportion of late wood in the ring width, like mean density, while tangential shrinkage is mostly dependent on the late wood density value.

FSP could not be predicted ($R^2=6\%$). FSP describes the maximum amount of bound water of the cell wall. The results suggested that variations in FSP were not linked to structural parameters like cell wall thickness or

MFA. The occurrence of extractives in pine is rather frequent (Choong 1969) and varies substantially between a single tree and within individual trees. It could be a major factor accounting for both FSP and shrinkage variations in addition to hemicellulose content variations between species.

CONCLUSIONS

Mountain pine in the Pyrenean mountain range is slow growing wood species with small ring width (below 4 mm) and a mean density of 500 kg/m³ showing few variations within a large population of timber representative of the forest resource.

For clear wood specimens, density and specific modulus enable accurate prediction of mechanical properties, but less accurate prediction of shrinkage.

Specific modulus measured on boards or on clear wood specimens is much lower than usual for pine species, probably as an adaption of tree growth to windy conditions. As a result, MOE and shrinkage are low while MOR values are more typical. Such a description can be induced by higher MFA in tracheid cell walls.

After visual grading, grouping of the two best French visual grades allows the use of the C22 mechanical grade and the C16 grade for the grouping of the two worst grades.

Grading mountain pine timber by non-destructive MOE measurement, regarding the 5-percentile for MOR, MOE and density together, allows the separation of populations of rather high grade (C24 to C35) making this machine grading highly profitable.

Surprisingly, for MOE alone, it is not the 5-percentile but the mean MOE for the tested population that is required in the final regulation. In this case, machine grading is not applicable since the mountain pine timber would only be down-graded.

Given the empirical evidence there should be a reassessment about this regulation to account for traditional softwood forests made of Spruce and Scots Pine having a typical range of correlated values for density and specific modulus (or MFA) as these characteristics may not be the displayed in different forest populations. The use of 5-percentile in MOE appears to be as safe as the use of mean MOE and provide a viable alternative to the procedures specified by current regulations.

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