Influence of Temperature and Moisture Content in Non-destructive values of Scots pine (*Pinus sylvestris* L.)

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Abstract

Good results evaluating material properties using non-destructive testing (NDT) techniques have been achieved for decades. Several studies to understand the influence of temperature and moisture content on NDT have concluded different effects. In this study, NDT parameters were measured on the principal structural Spanish sawn timber species, Scots pine (*Pinus sylvestris* L.).
NDT were conducted on 216 specimens of nominal dimensions 20 by 20 by 400 mm. Specimens were divided into several groups and studied at six different temperatures and four different moisture contents. Commercial equipment and techniques applied were Sylvatest Duo (ultrasonic wave technique), Steinkamp BPV (ultrasonic wave technique), and Grindo Sonic Mk5 "Industrial" (vibration analysis technique). Differences in NDT values within specimens at different temperatures and moisture contents were obtained.
Main results of this study and relationships that describe changes in NDT values by effect of temperature and moisture content are presented.

Keywords: Ultrasonic wave, vibration analysis, temperature, moisture content, climate conditions

Introduction

Evaluation of the influence of climate parameters on timber mechanical properties and on non-destructive testing (NDT) is not a new concept (James 1961; Gerhards 1982; Niemz 1993; Arriaga 2009).

Although it is relatively easy to conduct a NDT test, it is important to note that several factors affect NDT parameters. The applicability of ultrasound techniques in practice requires full knowledge of the effect of environmental conditions, which is why this present paper focuses on the influence of equilibrium moisture content (EMC) below fibre saturation point (FSP) and temperature (T) over *Pinus sylvestris* L.

Factors affecting ultrasonic measurements in wood have been profusely studied (Bucur 1984; Bucur 1994). There are several research works on the effect of EMC and T on ultrasound velocity and correction factors proposed for vibration and ultrasound velocity (Sandoz 1991; Moreno-Chan 2010; Unterwieser 2010).

The ultrasound velocity parallel to the fibres decreases dramatically with EMC up to the FSP (Sakai 1990; Kang 2002; Oliveira 2005; Bucur 2006; Gonçalves 2008), approximately eight times more than the EMC effect when EMC > FSP (Sandoz 1993). The same effect above and below the FSP was found for stress waves (Wang 2008).

Ultrasonic velocity generally increases linearly with decreasing T (+50 to -30ºC) and EMC below FSP (Bucur 2006).

The influence of T on acoustic properties is magnified when the EMC of wood increases (Sandoz 1993). The overall trend of the changes in velocity is similar for all dry wood (below FSP), below and above freezing point (Gao 2011).

Other studies focused on stress waves and concluded that the stress wave speed decreased reciprocally with increasing EMC and decreased linearly with increasing T. The T has the same effect on stress wave parameters on both studied species (softwood and hardwood), however the effect of EMC is different (Matthews 1994).

Different correction factors for EMC on NDT measurements were proposed for several authors. Considering 12% EMC as the reference value.

For ultrasound technique (Steinkamp BP-V) records, a correction factor with a decrease in velocity of approx. 0.8 % with an increase of 1 % of EMC, in the range of 5 to 30 % EMC, was proposed for spruce (Sandoz 1989).

For ultrasonic velocity, a correction factor with a decrease in velocity of 0.53% with an increase of 1% in EMC, in the range below 28% EMC, was proposed for spruce (Steiger 1996).

For ultrasonic velocity (Steinkamp BP7 45 kHz) of Parana pine, a correction factor equation was proposed. From it was obtained a decrease in velocity of 0.45% with an increase of 1% in EMC, below FSP (Gonçalves 2008).

For ultrasound technique (Sylvatest) and vibration technique (Viscan) records, correction factors with a decrease in ultrasound velocity of 0.60%, a decrease in dynamic modulus of elasticity (Edyn) of vibration of 0.87% and an increase of density of 0.42%, accompanying a 1% increase in EMC, in the range below 28% EMC, were proposed for spruce (Unterwieser 2010).

Less works were found dealing with adjustment factors of T on NDT measurements.

For ultrasound technique (Sylvatest) records, a correction factor was proposed with a decrease in velocity of approx. 0.08 % with an increase of 1 ºC (12% EMC), in the range of -20 to 60 ºC (Sandoz 1993). The same correction factor was proposed by Steiger in the range from 20 to 40 ºC (Steiger 1996).

Material and methods

The materials used consisted of 216 small clear specimens of nominal dimensions 20x20x400 mm, cut from 24 dry timber pieces of dimensions 150x50x4400 mm at 20ºC and 65% of Scots pine (*Pinus sylvestris* L.) from Valsain, Segovia, Spain. The specimens were grouped into 9 batches of 24 specimens each and were tested in the ETH laboratories in Zurich, Switzerland.

The influence of EMC was studied over four batches of 24 specimens each, conditioned for 45 days before testing at a temperature of 20 ± 2ºC and at four different air relative humidities (55%, 65%, 75%, and 85% ± 5%). Table 1 summarizes these batches.

Table 1 - Specimens for study of EMC effect according to climate conditions.

Batch	Air Humidity (%)	T (ºC)	Number of specimens
H55T20	55 ± 5	20 ± 2	24
H65T20	65 ± 5		24
H75T20	75 ± 5		24
H85T20	85 ± 5		24
	TOTAL		**96**

The influence of T was studied using six batches of 24 specimens, each conditioned to normal conditions of 20 ± 2ºC and 65 ± 5% of air relative humidity. Then the specimens were wrapped individually in plastic bags. Each batch of 24 wrapped specimens was conditioned at different temperatures (50, 30, 20, -10, -20 and -40 ± 2ºC) using a Feutron KPK 200 GmbH chamber. The temperature of the specimens was monitored with internal sensors and recorded with a commercial data loger Almemo 2890-9 Ahlborn. Table 2 summarizes these batches.

Table 2 - Specimens for study of T effect according to climate conditions.

Batch	Air Humidity (%)	T (ºC)	Number of specimens
H65T50	65 ± 5	50 ± 2	24
H65T30		30 ± 2	24
H65T20		20 ± 2	24
H65T-10		-10 ± 2	24
H65T-20		-20 ± 2	24
H65T-40		-40 ± 2	24
	TOTAL		**144**

Several measurements using NDT were carried out at each climate condition.

Time of flight value was measured with two ultrasonic commercial devices. Sylvatest Duo (using conical sensors of 22 kHz frequency) and Steinkamp BP-V (using conical sensors of 50 kHz frequency). Measures were made end to end (longitudinal direction parallel to the grain) on each specimen, with a constant sensor coupling pressure.

According to the time results of ultrasound devices, the wave velocities (length/time) and Edyn were calculated using equation 1:

$$E_{dyn}=\rho\cdot V^2\cdot 10^{-6} \qquad (1)$$

Where: E_{dyn} is the dynamic modulus of elasticity, in N/mm^2; ρ is the density, in kg/m^3; and V is the velocity of the ultrasound wave, in m/s.

For the vibration analysis (with a commercial device Grindosonic Mk5 "Industrial") the specimen was simply supported at two nodal points at a distance of 0.224 l from the end; l being the total length of the specimen. The midspan of the specimen was hit with a small hammer and the impact induced an oscillation in the vertical (transverse) direction. The transverse frequency was registered by an accelerometer and Edyn was obtained according to equation 2 (Görlacher 1984).

$$E_{dyn,v}=\frac{4\,\pi^2\cdot l^4\cdot f_0^2\cdot\rho}{m_n^4\cdot i^2}\cdot\left(1+\frac{i^2}{l^2}\cdot K_1\right)\cdot 10^{-12} \qquad (2)$$

Where: $E_{dyn,v}$ is the dynamic modulus of elasticity, in N/mm^2; l is the length of the specimen, in mm; f_0 is the transverse frequency, in Hz; ρ is the density, in kg/m^3; m_n^4 is the constant = 0.5006x10^3; i is the radius of gyration, in mm; K_1: constant = 49.48.

After measurements were completed, the EMC of each specimen was determined using the oven dry method according to standard EN 13183-1. Four different average EMC (10.88, 12.00, 15.58 and 17.38 %) were obtained for each batch conditions (H55T20, H65T20, H75T20 and H85T20), respectively.

Results and discussion

The effect of EMC on non-destructive parameters is summarized in table 3.

Table 3 - NDT results for different EMC.

		NDT					
Batch	EMC (%)	Vel Sylvatest Duo		Vel Steinkamp BPV		Edyn Grindosonic Mk5	
		mean (m/s)	CV (%)	mean (m/s)	CV (%)	mean (Hz)	CV (%)
H55T20	**10.88**	5927	4.95	5572	4.20	13566	15.84
H65T20	**12.00**	5867	4.67	5505	4.04	13276	17.08
H75T20	**15.58**	5742	4.15	5455	3.71	12971	14.61
H85T20	**17.38**	5632	4.30	5325	3.83	12313	15.62

Statistical analyses were done in order to study the normality of variables prior to further analyses. All variables showed normal probability distributions. Figure 1, shows the frequency histogram for velocity of ultrasounds.

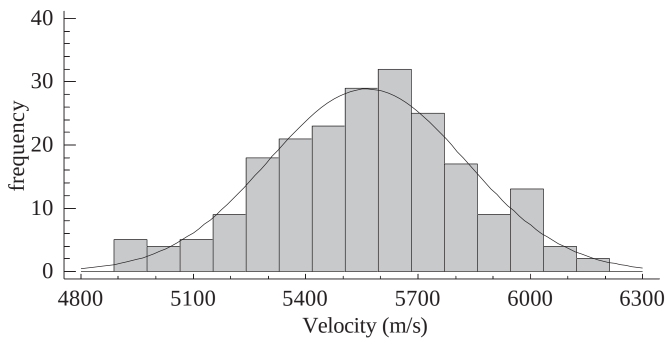

Figure 1 - Frequency histogram for velocity. Steinkamp BPV.

A clear tendency of change in properties with EMC was found, as was expected. This effect has been found in many similar studies (Gerhards 1982, Sandoz 1991, Steiger 1996, Gonçalves 2008). Despite the EMC of the studied batches being really close, some parameters exhibit statistically significant differences between two non-consecutive batches, determined from the one-way analysis of variance. Figure 2 shows an example of ultrasound velocity.

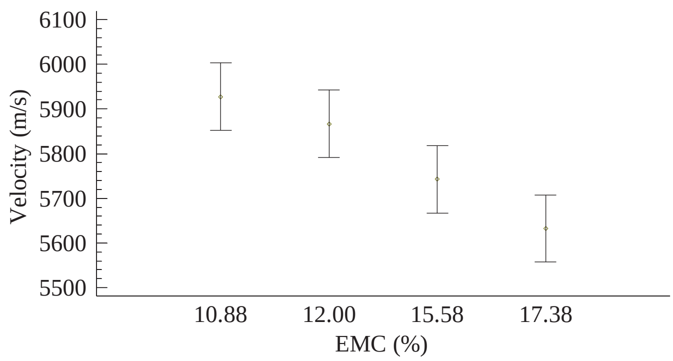

Figure 2 - Means plot of one-way analysis of variance: velocity Sylvatest vs. EMC.

Statistical diagnosis performed on each one-way analysis of variance confirms the validity of the assumptions of normality of distribution, homoscedasticity and independence.

The effect of T on non-destructive parameters is summarized in table 4.

Table 4 - NDT results for different T.

Batch	T (ºC)	Vel Sylvatest Duo		Vel Steinkamp BPV		Edyn Grindosonic Mk5	
		mean (m/s)	CV (%)	mean (m/s)	CV (%)	mean (Hz)	CV (%)
H65T50	**50**	5777	4.53	5455	4.11	12963	16.86
H65T30	**30**	5891	4.56	5545	3.90	13623	16.39
H65T20	**20**	5867	4.67	5505	4.04	13276	17.08
H65T-10	**-10**	6012	4.38	5671	3.95	14020	17.24
H65T-20	**-20**	6109	4.98	5704	4.38	14024	17.08
H65T-40	**-40**	6189	4.41	5841	3.86	14746	15.39

The one-way analysis of variance revealed statistically significant differences between some batches below 0ºC, but this difference does not appear between batches above 0ºC. Different tendencies above and below 0ºC has been found for some authors on ultrasound velocity (Gao 2011) above FSP, but it were not found works obtaining different tendencies in dry wood. Thus a different tendency above and below 0ºC was found. Figure 3 show an example for velocity of ultrasound waves using Steinkamp BPV.

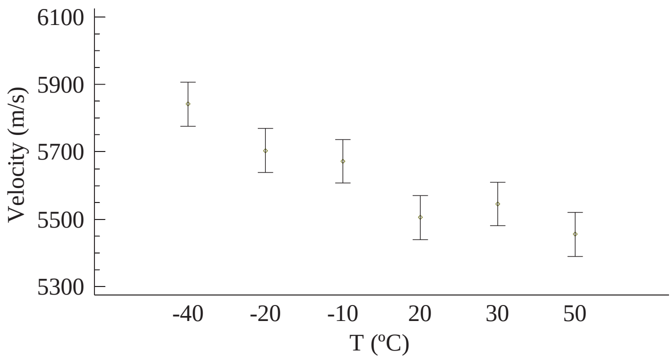

Figure 3 - Means plot of one-way analysis of variance: velocity Steinkamp vs. T.

Adjustment factor for EMC

Linear regressions were done using the average value of different variables of each batch and EMC in order to study EMC tendencies (Figure 4), as a result, several equations were obtained (equations 3 to 5):

Vel Sylvatest = 6392 - 43 EMC R^2=0.99 (3)
Vel BPV =5920 - 33 EMC R^2=0.90 (4)
Edyn freq = 20313 - 191 EMC R^2=0.95 (5)

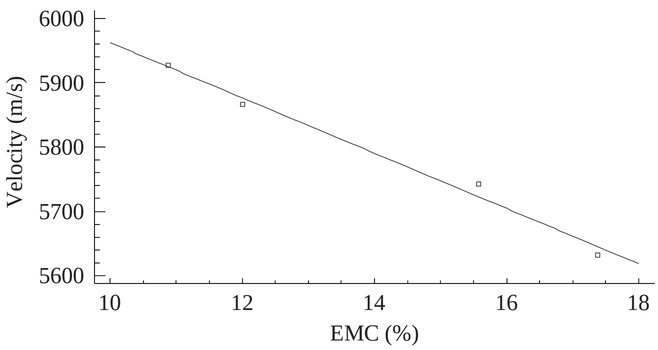

Figure 4 - Linear regression: velocity Sylvatest vs EMC.

The influence of EMC (between 10.88 and 17.38 %) on ultrasonic waves and vibration were determined. From equations 3 to 5, and considering 12% EMC as the reference value, adjustment factors (6 to 8) were obtained for each variable.

For ultrasound Sylvatest Duo: $V_{12} = V_H / [1-k_{H1} (H-12)]$ $k_{H1}= 0.0073$ (6)

For ultrasound Steinkamp BPV: $V_{12} = V_H / [1-k_{H2} (H-12)]$ $k_{H2}= 0.0059$ (7)

For vibration Grindosonic MK5: $Edyn_{12} = Edyn_H / [1-k_{H3} (H-12)]$ $k_{H3}= 0.0106$ (8)

Where: V_{12} is the ultrasound velocity in the longitudinal direction, at 12% EMC, in m/s; V_H is the ultrasound velocity in the longitudinal direction, at H EMC, in m/s; H is the EMC, in %; k_{Hi} is the EMC adjustment factor; Edyn is the dynamic modulus of elasticity obtained by vibration, in N/mm^2

For ultrasound velocities a decrease by 0.73% was achieved, using the Sylvatest Duo device, and 0.59%, using the Steinkamp BP-V device with an increase of 1% in EMC. If it is compared with other studies this adjustment factor is slightly greater than ones proposed by other authors for Sylvatest in Spruce (Steiger 1996, Unterwieser 2010) and lower than 0.8% proposed by Sandoz for Steinkamp BPV(Sandoz 1989). In addition, with an increase of 1% in EMC, the Edyn, estimated using the vibration technique , decreased by 1%, this adjustment factor is slightly greater than 0.87% proposed by Unterwieser (Unterwieser 2010) but in this case a different device was used.

Adjustment factor for T

Linear regressions were done between the average values of different variables of each batch and T, in order to study tendencies occurring with T changes (Figure 5), consequently several equations (below zero) were obtained (equations 9 to 11):

Vel Sylvatest = 5966 - 6 T R^2=0.98 (9)
Vel BPV =5591 - 6 T R^2=0.97 (10)
Edyn freq = 13689 - 25 T R^2=0.92 (11)

Different tendency above and below zero for different variables are shown in figure 5. This difference was found in every variable.

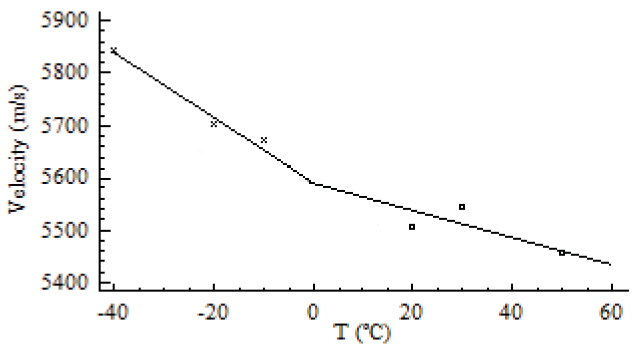

Figure 5 - Linear regressions: velocity Steinkamp BPV vs T.

Influence of T (between -40 and 0 ºC) on ultrasonic waves and vibration was evaluated at 12% EMC. From equations 9 to 11, and considering 0ºC as the reference value, adjustment factors (12 to 14) were obtained for each variable.

For ultrasound Syl: $V_0 = V_T / [1-k_{T1} (T-0)]$ $k_{T1}= 0.0010$ (12)

For ultrasound BPV: $V_0 = V_T / [1-k_{T2} (T-0)]$ $k_{T2}= 0.0011$ (13)

For vibration: $Edyn_0 = Edyn_T / [1-k_{T3} (T-0)]$ $k_{T3}= 0.0018$ (14)

Where: V_0 is the ultrasound velocity in the longitudinal direction, at 0ºC, in m/s; V_T is the longitudinal ultrasound velocity at temperature T, in m/s; T is the temperature, in ºC; k_{Ti} is the temperature adjustment; Edyn is the dynamic modulus of elasticity estimated by vibration, in N/mm^2

With an increase of 1ºC, a decrease of around 0.1% and 0.18% was recorded for ultrasound velocities and Edyn respectively. Ultrasound velocities adjustment factor 0.1% is slightly greater than 0.08% proposed by Sandoz (Sandoz 1993)

The effects of T are less significant than the EMC effects in common conditions of inspection of structures (from 0 to 30 ºC and from 8 to 30 % of EMC).

Conclusions

The present study shows that non-destructive measurements (wave velocity and frequency) of Scots pine are affected by equilibrium moisture content and temperature conditions. These results are consistent with findings from previous studies on spruce and fir.

Influence of equilibrium moisture content on ultrasound velocities and dynamic modulus of elasticity in the range 10 to 18% could be considered lineal.

Adjustment factors for the influence of equilibrium moisture content on Scots pine were obtained for non-destructive testing. In the case of ultrasound techniques, a slight difference between devices was found, Steinkamp (using sensors of 50 kHz frequency) presents smaller correction factors than Sylvatest (using sensors of 22 kHz frequency) and the reason could be founded in the different frequencies.

Influence of temperature on non-destructive testing shows a different tendency above and below 0 ºC. A clear lineal tendency was found below 0ºC and no significant tendency was found above 0 ºC for dry timber.

Adjustment factors for influence of temperature were proposed for non-destructive testing in the range -40 to 0ºC and considering 0ºC as the reference value. No differences between ultrasound devices were found.

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Madison, Wisconsin, USA
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Abstract

The 18th International Nondestructive Testing and Evaluation of Wood Symposium was hosted by the USDA Forest Service's Forest Products Laboratory (FPL) in Madison, Wisconsin, on September 24–27, 2013. This Symposium was a forum for those involved in nondestructive testing and evaluation (NDT/NDE) of wood and brought together many NDT/NDE users, suppliers, international researchers, representatives from various government agencies, and other groups to share research results, products, and technology for evaluating a wide range of wood products, including standing trees, logs, lumber, and wood structures. Networking among participants encouraged international collaborative efforts and fostered the implementation of NDT/NDE technologies around the world. The technical content of the 18th Symposium is captured in this proceedings.

Keywords: International Nondestructive Testing and Evaluation of Wood Symposium, nondestructive testing, nondestructive evaluation, wood, wood products

September 2013

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