Vibration Method for the Prediction of Aging Effect on Properties of Particleboard and Fiberboard

Ignacio Bobadilla Maldonado
Guillermo Iñiguez González
Miguel Esteban Herrero
Francisco Arriaga Martitegui

Abstract

The physical and mechanical properties (density, modulus of elasticity, and modulus of rupture) of standard and humidity-resistant types of particleboard and fiberboard were determined by standardized test and wave propagation velocity, obtained from the natural frequency in a nondestructive longitudinal vibration test. Four batches of 66 specimens for each type of panel (particleboard and fiberboard) and for each kind of panel (standard and humidity resistant) were tested under initial conditions and after each one of the three aging cycles defined in European Standard EN 321:2001. Each aging cycle consisted of immersion in water, freezing, and high-temperature drying. The decreasing ratio of wave velocity was used to predict the decreasing ratio of properties. There was a strong relationship between both variables, and an exponential regression model is proposed to predict physical and mechanical properties, with a determination coefficient (R^2) from 0.93 to 0.98.

Because product quality is the most important factor when purchasing wood-based panels (Schulte et al. 1998), the massive increase in production of these products in the past 40 years has been a challenge, not only for process engineering, but also for the development of control systems. The use of nondestructive methods is now widespread in the industry, primarily as a continuous process control. This is not yet the case in the quality control of finished products, the standard techniques for which have not changed appreciably over the past 30 years. These standard methods of laboratory testing sometimes require significant investment to acquire and maintain complex and expensive laboratory equipment, as well as labor costs, given that testing takes a remarkable amount of time.

Furthermore, wood-based panel quality control European Standard EN 326-2 (European Committee for Standardization [CEN] 2011) allows the industry to use alternative methods (nonstandardized) for factory production control if they provide a statistically significant relationship between a specific characteristic and the measured characteristic. Appendix E of the standard sets minimum values for the correlation coefficient for acceptance of the alternative test procedure, depending on the number of tests.

Several nondestructive methods are currently widely used and studied to estimate the physical and mechanical properties of boards. In previous research works, good statistical relationships between different physical and mechanical properties of boards and nondestructive methods were obtained (Kaiserlik and Pellerin 1977, Ross and Pellerin 1988). The relationship between acoustic and elastic or mechanical properties of the boards has been examined in numerous studies (Pellerin and Morschauser 1974, Ross 1985, Vogt 1985, Sotomayor Castellanos 2003).

Many references can be found reporting on the use of ultrasound methods in different types of board to evaluate different properties. The elastic properties of particleboard have recently been studied (Najafi et al. 2005), as well as variation in density within boards (Kruse et al. 1996). Similar studies can be found for oriented strandboard (OSB;

The authors are, respectively, Associate Professor, Assistant Professor, Associate Professor, and Professor, Univ. Politécnica de Madrid, Ingeniería Forestal—EUIT Forestal, Madrid, Spain (i.bobadilla@upm.es [corresponding author], Guillermo.iniguez@upm.es, Miguel.esteban@upm.es, Francisco.arriaga@upm.es). This paper was received for publication in December 2011. Article no. 11-00137.
©Forest Products Society 2012.
Forest Prod. J. 62(1):69–74.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

Vun et al. 2003). Stress wave vibrations have also been used by several authors in OSB (Ross et al. 2003), other wood-based panels (Han et al. 2006), and wood-based composites (Hu et al. 2005). The influence of decay in solid wood on the dynamic properties obtained by acoustic methods similar to those used in this work has been analyzed (Yang et al. 2002). But little information can be found about the relationship between nondestructive methods and the deterioration of the panels due to physical aging.

Recently, vibration and acoustic methods have been successfully used in predicting the physical and mechanical properties of particleboard and fiberboard (Bobadilla et al. 2008) and even for board aging (Bobadilla et al. 2009).

This work proposes the use of vibration methods as an alternative system of evaluating and monitoring density, bending strength (modulus of rupture [MOR]), and modulus of elasticity (MOE) for aging of particleboard and medium-density fiberboard.

Materials and Methods

Materials

Two types of wood-based panels were studied in this work, 22-mm-thick particleboard and 22-mm-thick fiberboard, and two different kinds of each type were studied, standard and humidity resistant. For each type and kind of board, 66 specimens measuring 500 by 50 mm were obtained longitudinally. Afterward, 10 specimens more were tested for each kind of board to verify the model. Thus, four denominations were used: standard particleboard, humidity-resistant particleboard, standard fiberboard, and humidity-resistant fiberboard.

The determination of dimensions and preparation of the test pieces were performed according to European Standards EN 326-1 (CEN 1995) and EN 325 (CEN 1994c).

Methodology

General procedure.—The specimens were subjected to the humidity-resistance cycles procedure, as defined in European Standard EN 321 (CEN 2001). This was used to verify the moisture resistance of wood-based panels. In this procedure the test pieces were exposed to three cycles, each comprising immersion in water, freezing, and high-temperature drying. After the cycles and treatment, the test pieces were then reconditioned, and their residual strength was determined.

In this work acoustic properties, density, and static bending properties were determined after the initial conditioning as well as after each cycle to determine the rate of decrease. The final procedure is shown in Figure 1. The different phases of the test procedure are defined below.

- Conditioning: Climate chamber at 20°C ± 2°C and 65 ± 5 percent relative air humidity until constant mass. After conditioning, the moisture content of the samples was from 9.5 to 11.5 percent for particleboard and from 9 to 10 percent for fiberboard, which agrees with the results obtained by other researchers (see, e.g., McNatt 1974).
- Testing: The density, MOR, MOE, and natural longitudinal frequency of the specimens from the corresponding batch were obtained. These tests are explained below. During testing laboratory hygrothermal conditions were 20°C ± 5°C with 40 ± 10 percent relative humidity. All of the specimens in each ''Test Batch'' were destroyed during standard testing, so that statistical independence of the results is guaranteed.

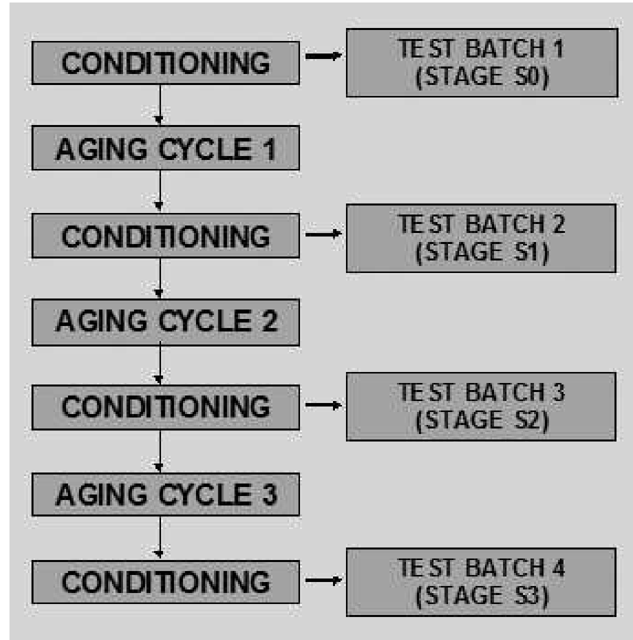

Figure 1.—Testing procedure.

- Aging cycle:

1. 70 ± 1 hours immersion in 20°C ± 1°C water.
2. 24 ± 1 hours in a freezer at –12°C to –25°C.
3. 70 ± 1 hours in an oven at 70°C ± 2°C.
4. 4 ± 0.5 hours at 20°C ± 5°C.

Physical and mechanical properties.—Density was determined according to Standard EN 323 (CEN 1994b). The static MOR and MOE were obtained according to Standard EN 310 (CEN 1994a) in a three-point bending test. The results of these tests are shown in Table 1.

Natural longitudinal frequency.—Vibration-based nondestructive tools generally use the well-known and accurate relationship between the natural frequency of oscillation of a simply supported beam and the dynamic elasticity modulus to estimate the mechanical properties of material.

In this work, determination of the longitudinal vibration frequency was performed applying a simple procedure. The specimens were placed on two supports with soft polyurethane pillows at the ends to ensure that they were free to vibrate. The end of the specimen was hit by a hammer, and the impact induced a stress wave of longitudinal vibration caught as sound by a microphone set close to the opposite end of the test piece. The natural vibration frequency, obtained by a Fast Fourier Transform analyzer, varied for the samples tested from 850 to 2,025 Hz, depending on the type of board and aging state.

In the case of the longitudinal waves used in this work, the first harmonic or fundamental frequency corresponded to a one-half wavelength, which fit onto the piece. In this situation, according to the fundamentals of physics and waves, the wavelength and velocity of waves must be calculated using the following equations:

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

Table 1.—The physical and mechanical properties for each type of board.[a]

			Density (kg/m^3)		MOE (N/mm^2)		MOR (N/mm^2)		V (m/s)	
Board type	n	Aging cycle	Mean	CoV (%)	Mean	CoV (%)	Mean	CoV (%)	Mean	CoV (%)
STP	66	Initial	638	2	2,376	6	10.6	7	1,828	2
		1	519	1	980	5	3.0	2	1,216	2
		2	483	1	579	11	2.2	8	990	3
		3	459	1	381	7	1.2	15	837	3
HRP	66	Initial	695	2	2,449	4	11.9	6	1,936	2
		1	636	2	1,387	6	7.1	5	1,617	2
		2	619	2	1,197	8	6.2	5	1,514	2
		3	603	2	973	5	4.8	5	1,412	2
STF	66	Initial	710	2	3,002	4	36.1	6	2,001	2
		1	581	3	2,106	3	16.8	6	1,668	3
		2	553	3	1,720	12	13.1	16	1,565	3
		3	529	2	1,685	5	10.9	11	1,501	2
HRF	66	Initial	735	2	3,010	6	38.9	7	2,031	2
		1	646	2	2,437	2	24.7	5	1,815	1
		2	636	2	2,262	2	23.5	4	1,725	2
		3	619	2	2,214	4	22.2	5	1,722	1

[a] MOE = modulus of elasticity; MOR = modulus of rupture; CoV = coefficient of variation; V = velocity; STP = standard particleboards; HRP = humidity-resistant particleboards; STF = standard fiberboards; HRF = humidity-resistant fiberboards.

$$V = \lambda f \quad (1)$$

$$\lambda = 2L \quad (2)$$

$$V = 2Lf_1 \quad (3)$$

where V (m/s) is the velocity, λ (m) is the wavelength, f (Hz) is the frequency, L (m) is the length of the piece, and f_1 (Hz) is the fundamental frequency corresponding to the first mode of vibration or first harmonic (Hearmon 1966, Grundström 1998).

Table 1 also shows the results of velocity for each type of board.

Results and Discussion

Effect of cycles on physical and mechanical properties

Table 1 summarizes the evolution of properties for each type of board. Property values are higher in fiberboard than they are in particleboard, and within board type properties are higher in humidity-resistant type than they are in the standard type.

A decrease in the physical (density) and mechanical (MOR, MOE) properties and the wave velocity along the aging cycles are shown in Figure 2. In accordance with the results of other authors (Ross et al. 2003), the data show the relationship between the wave propagation velocity in the material and its properties, and the influence of aging on both. This relationship is also clear in the initial cycles as well as in late aging. We conclude that despite deterioration of the board, the relationship between wave velocity and the properties measured is maintained, as is suggested for solid wood in the work of Yang et al. (2002).

As shown in Figures 2 and 4, the properties decrease more for standard boards than for humidity-resistant boards. The mechanical properties of humidity-resistant boards have a decreasing ratio of approximately half of the ratio corresponding to standard boards. MOR and MOE values have a similar ratio of decrease in particleboards. A more pronounced reduction of MOR and MOE is observed in particleboard in comparison with fiberboard. Consistent with the results of other authors (Yang et al. 2002), the propagation velocity for particleboard is found to be a better estimator of aging than density loss. However, for fiberboard the velocity and density decrease in the same ratio, so that both parameters could be used as estimators with similar results.

Statistically significant differences for all the variables (density, mechanical properties, and nondestructive measurements) were checked according to aging cycle.

Estimation of properties from acoustic wave velocity

A strong relationship can be observed between the decreasing ratios of velocity and the properties (density, MOE, and MOR). There is an exponential correlation that can be expressed in general according to Equation 4 (Figures 3 and 4). The determination coefficient R^2 runs from 0.93 to 0.98 (Table 2)

$$P = e^{[A+BV+CZp+DZst]} \quad (4)$$

where P is the estimated property; A, B, C, and D are constants depending on the property (Table 2); V is the wave velocity (m/s); Zp is the qualitative variable for the type of board (particle or fiberboard, $Zp = 1$ for particleboards and $Zp = 0$ for fiberboards); and Zst is the qualitative variable for the class of board (standard and humidity resistant, $Zst = 1$ for standard boards and $Zst = 0$ for humidity-resistant boards).

According to this equation, during production control it would be possible to solely measure the natural frequency of the longitudinal vibration of specimens (obtaining the wave velocity) before and after the aging cycles, thereby avoiding the need for standard physical and mechanical tests.

In agreement with the results presented by Ross and Pellerin (1988) in previous research using particleboard,

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

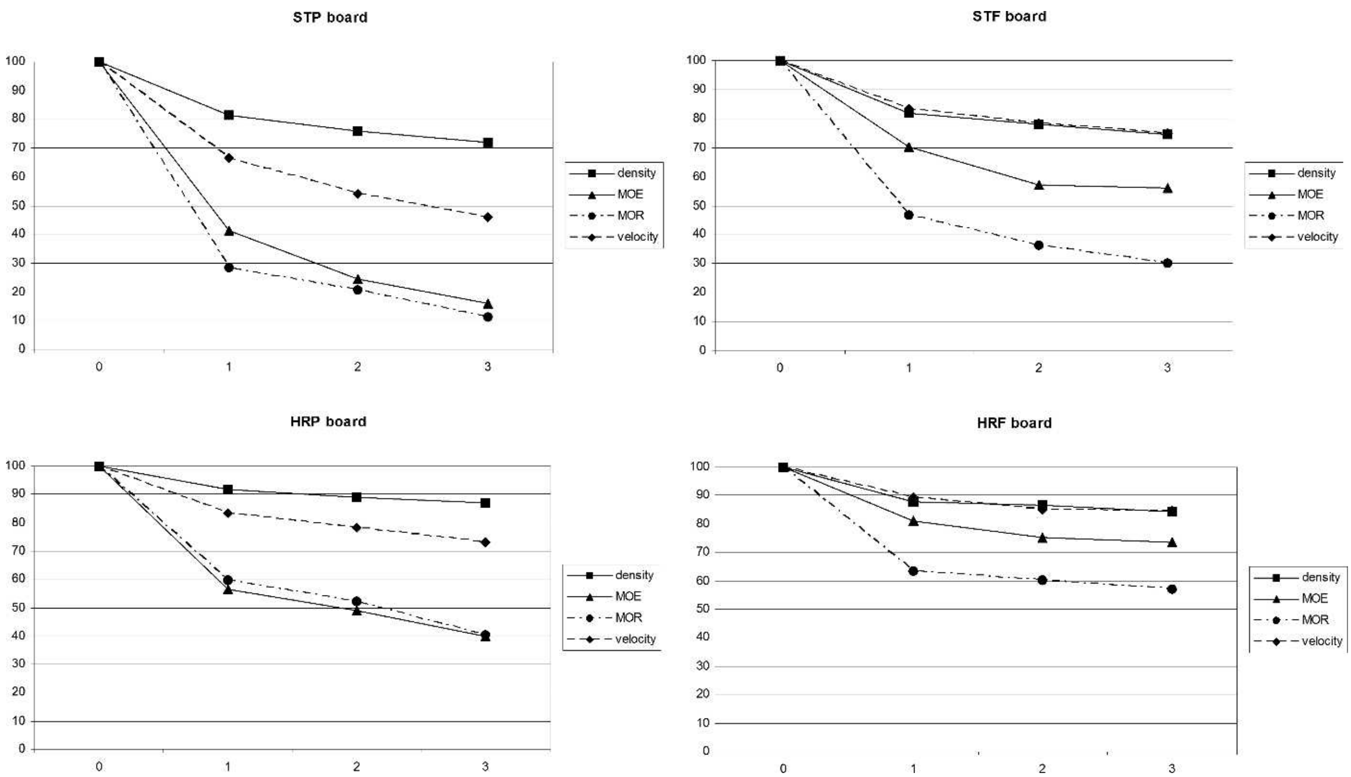

Figure 2.—The effects of aging on wave velocity together with physical and mechanical properties. Cycles on the x *axis and relative property value versus initial value in percentage terms on the* y *axis. STP = standard particleboards; STF = standard fiberboards; HRP = humidity-resistant particleboards; HRF = standard particleboards; STF = humidity-resistant fiberboards; MOE = standard particleboards; STF = modulus of elasticity; MOR = standard particleboards; STF = modulus of rupture.*

exponential regression models show the best statistical behavior. The determination coefficients, R^2, obtained by our models are also similar to those obtained by these authors to relate stress wave speed propagation to elastic and mechanical bending properties. These determination coefficients were always higher than 0.9, which shows the excellent performance of the models.

The use of the dynamic MOE as an estimator of the mechanical properties of boards was rejected, since the results obtained in some previous works (Ross and Pellerin 1988) suggest similar and even lower statistical relationships than those obtained directly using wave velocity propagation.

Figure 3 shows actual versus predicted graphs for the three regression models. A close statistical relationship between the variables can be observed.

Verification of regression models

The three proposed estimation models were tested using 40 new specimens (10 of each type and kind) from the same source. Verification of the models shows the regression equations fit well with fluctuations in the measurements. However, there is overestimation of the actual values, very slightly for density but more markedly for mechanical properties (MOR and MOE). An example of this can be seen in Figure 5 for the MOR model verification.

For particleboard density, the model slightly overestimates the actual values of the variable by 3.6 percent on average, while for the fiberboard, the estimation is slightly lower than reality by 2.2 percent on average.

With regard to the MOE, regression models overestimate the actual values by 18.6 percent on average, 14.1 percent in particleboard and 20.7 percent in fiberboard.

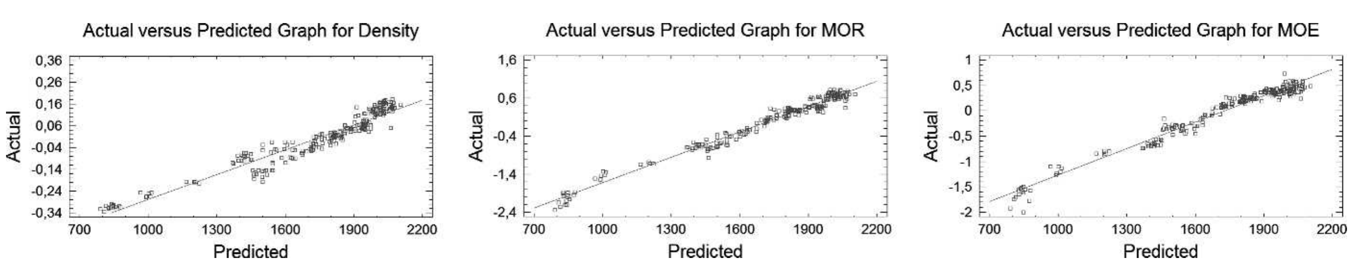

Figure 3.—Actual versus predicted graphs for the regression models of density, bending strength (MOR), and bending modulus of elasticity (MOE).

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

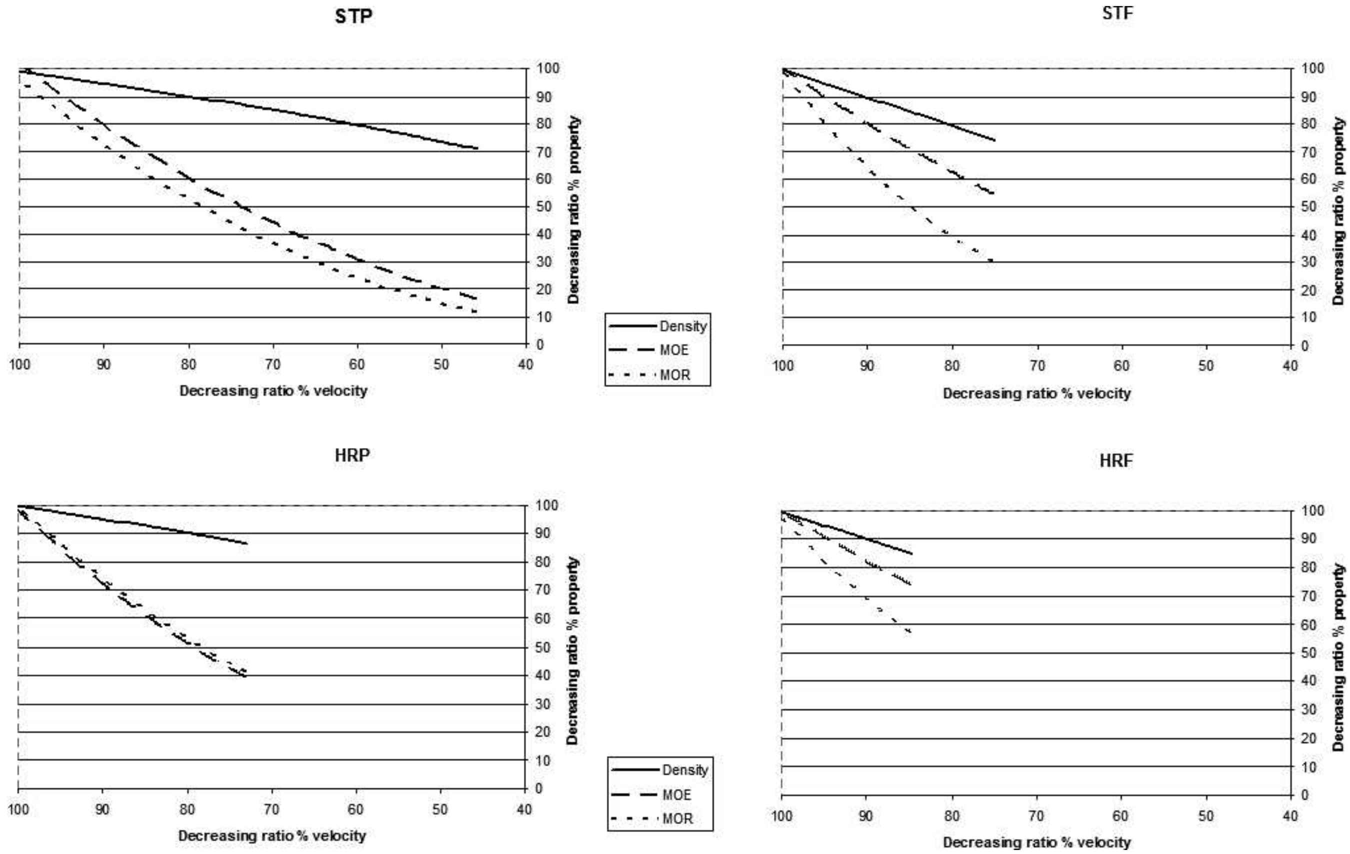

Figure 4.—The decreasing ratio of velocity and its relationship with decreasing property ratios for each type of board. STP = standard particleboards; STF = standard fiberboards; HRP = humidity-resistant particleboards; HRF = humidity-resistant fiberboards; MOE = modulus of elasticity; MOR = modulus of rupture.

Table 2.—Constants and determination coefficients of Equation 4.

Property[a]	*A*	*B*	*C*	*D*	R^2
Density	5.80718	0.000380525	0.0208431	−0.0461607	0.93
MOE	4.61018	0.00173391	−0.0689111	0.124536	0.96
MOR	−0.766463	0.00221331	−0.834818	−0.00840762	0.98

[a] MOE = modulus of elasticity; MOR = modulus of rupture.

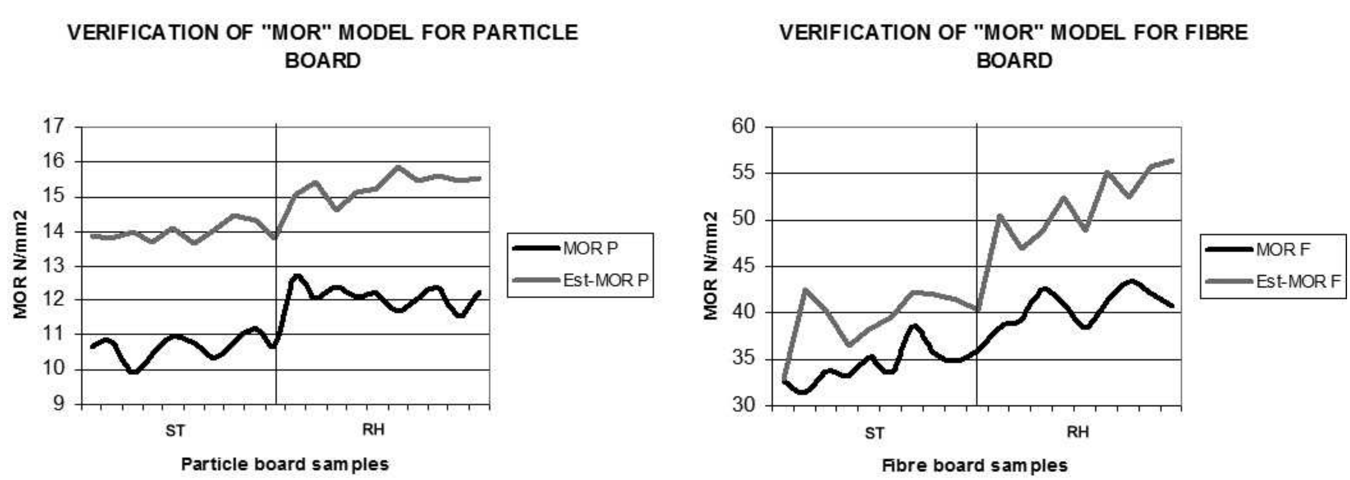

Figure 5.—Real and estimated modulus of rupture (MOR) values for the proposed models. P = particleboard; F = fiberboard; ST = standard samples; RH = humidity-resistant samples; Est = estimated.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26

Finally, for MOR, the models analyzed overestimate the actual values of the variable by 18.7 percent on average, 22.2 percent in particleboard and 17.5 percent in fiberboard.

A correction to the regression models to give more accurate results may be proposed, if this is necessary. On the other hand, we compared the results achieved by standardized tests of these new 40 specimens, with those estimated using the proposed models, in order to establish the correlation coefficient, *R,* as required by Standard EN 326-2 (CEN 2011). The proposed three models were shown to have higher correlations than are recommended by Annex E of the standard. The correlations obtained (*R*) were 0.84 for density estimation, 0.91 for MOE, and 0.98 for MOR.

Conclusions

There are statistically significant differences in the destructive and nondestructive measurements among all three aging cycles. In addition, the effect of the first cycle is higher than of the two following cycles, and deterioration is greater at first.

The physical and mechanical properties of the boards decrease with aging cycles, as does wave velocity in the material. Density is the parameter that is least affected by aging. There is a relationship between the physical, mechanical, and acoustic properties of boards that can be used as an estimation tool. There is an exponential correlation between properties and wave velocity, with a determination coefficient, R^2, from 0.93 to 0.98, depending on the type of board and property. The acoustic method described could be considered for quality control of the physical (density) and mechanical (MOR, MOE) properties of particle and fiberboard (standard and humidity resistant). The verification of this model with new samples of the same boards has an average correlation coefficient, *R,* of 0.91, which is well above the value set in Annex E of Standard EN 326-2 (CEN 2011).

Furthermore, acoustic methods offer a significant saving in time and in labor costs. Acoustic methods are therefore proposed as a valid alternative method, from the technical, regulatory, and economic point of view.

Acknowledgments

We thank the Timber Industry Technical Research Association (AITIM), AITIM-FUCOVASA (Fundación Conde del Valle de Salazar) 2005, 2006, and 2009–2010 research projects. We also thank Rosa García and Jesús Terrádez from the Quality Control Department from UTISA. We finally thank Ministerio de Educación y Ciencia Research Projects BIA 2006-14272 and BIA 2010-18858.

Literature Cited

Bobadilla, I., F. Arriaga, M. Esteban, G. Iñiguez, and I. Blázquez. 2008. Density estimation by vibration, screw withdrawal resistance and probing in particle and medium density fibre boards. *In:* Proceedings of the 10th World Conference on Timber Engineering, June 2–5, 2008, Miyazaki, Japan. p. 241.

Bobadilla, I., M. Martín de Hijas, M. Esteban, G. Íñiguez, and F. Arriaga. 2009. Non destructive methods to estimate physical and biological aging of particle and fibre boards. *In:* Proceedings of the 16th International Symposium on Non-Destructive Testing and Evaluation of Wood, H. Zhang and X. Wang (Eds.), October 12–14, 2009, Beijing, China; Forest Products Society, Madison, Wisconsin. pp. 222–228.

European Committee for Standardization (CEN). 1994a. Wood-based panels. Determination of modulus of elasticity in bending and of bending strength. EN 310. CEN, Brussels.

European Committee for Standardization (CEN). 1994b. Wood-based panels. Determination of density. EN 323. CEN, Brussels.

European Committee for Standardization (CEN). 1994c. Wood-based panels. Determination of dimensions of test pieces. EN 325. CEN, Brussels.

European Committee for Standardization (CEN). 1995. Wood-based panels. Sampling, cutting and inspection. Sampling and cutting of test pieces and expression of test results. EN 326-1. CEN, Brussels.

European Committee for Standardization (CEN). 2001. Wood-based panels. Determination of moisture resistance under cyclic test conditions. EN 321. CEN, Brussels.

European Committee for Standardization (CEN). 2011. Wood-based panels. Sampling, cutting and inspection. Part 2: Initial type testing and factory production control. EN 326-2. CEN, Brussels.

Grundström, F. 1998. Non-destructive testing of particleboard with ultra sound and eigen frequency methods. Master's Thesis of Science in Mechanical Engineering, Wood Technology. Lulea Tekniska Universitet, Lulea, Sweden. 58 pp.

Han, G. P., Q. L. Wu, and X. P. Wang. 2006. Stress wave velocity of wood based panels: Effect of moisture, product type, and material direction. *Forest Prod. J.* 56(1):28–33.

Hearmon, R. R. S. 1966. Vibration testing of wood. *Forest Prod. J.* 16(8):29–40.

Hu, Y., T. Nakao, T. Nakai, J. Gu, and F. Wang. 2005. Dynamic properties of three types of wood based composites. *J. Wood Sci*. 51: 7–12.

Kaiserlik, J. H. and R. F. Pellerin. 1977. Stress wave attenuation as an indicator of lumber strength. *Forest Prod. J*. 27(6):39–43.

Kruse, K., F. W. Broker, and A. Fruhwald. 1996. Interrelation between internal bond, density distribution and ultrasonic velocity of particle board. *Holz Roh- Werkst*. 54(5):295–300.

McNatt, J. D. 1974. Properties of particleboards at various humidity conditions. USDA Forest Service Research Paper 225. Forest Products Laboratory, Madison, Wisconsin.

Najafi, S. K., V. Bucur, and G. Ebrahimi. 2005. Elastic constants of particle board with ultrasonic technique. *Mater. Lett*. 59(16): 2039–2042.

Pellerin, R. F. and C. R. Morschauser. 1974. Nondestructive testing of particleboard. *In:* Proceedings of the 7th International Particleboard Symposium, March 1973, Washington State University, Pullman.

Ross, R. J. 1985. Stress wave propagation in wood products. *In:* Proceedings of the 5th Non-Destructive Testing of Wood Symposium, September 9–11, 1985, Washington State University, Pullman, pp. 291–318.

Ross, R. J. and R. F. Pellerin. 1988. NDE of wood based composites with longitudinal stress waves. *Forest Prod. J*. 38(5):39–45.

Ross, R. J., V. W. Yang, B. L. Illman, and W. J. Nelson. 2003. Relationship between stress wave transmission time and bending strength of deteriorated OSB. *Forest Prod. J*. 53(3):33–35.

Schulte, M., J. Welling, J. Evertsen, J. Hague, J. Ljorring, and D. Serrant. 1998. Directory of non destructive testing methods for the wood based panel industry. Official Publications of the European Communities, Luxembourg.

Sotomayor Castellanos, J. R. 2003. Caracterización mecánica de madera reconstituida: módulo de elasticidad de tableros de partículas de madera evaluado con métodos no destructivos. *Maderas Cienc. Tecnol*. 5(1):20–43.

Vogt, J. J. 1985. Evaluation of tensile and flexural properties an internal bond of medium density fibreboard using stress wave speed attenuation. Master's thesis. Washington State University, Pullman.

Vun, R. Y., Q. L. Wu, and C. J. Monlezum. 2003. Ultrasonic characterization of horizontal density variations in oriented strandboard. *Wood Fiber Sci*. 35(4):482–498.

Yang, J., J. Ilic, and T. Wardlaw. 2002. Relationships between static and dynamic modulus of elasticity for a mixture of clear and decayed eucalypt wood. *Aust. Forestry* 66(3):193–196.

http://prime-pdf-watermark.prime-prod.pubfactory.com/ | 2024-12-26