Journal homepage: www.fia.usv.ro/fiajournal
Journal of Faculty of Food Engineering,
Ştefan cel Mare University of Suceava, Romania
Volume XIV, Issue 1- 2015, pag. 108 - 116

CONTRIBUTIONS TO A METHOD AND A NEW TECHNIQUE FOR DETERMINATION OF SOME IMPORTANT MECHANICAL PROPERTIES OF MASSIVE WOOD TEXTURE

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Received 17th March 2015, accepted 31st March 2015

Abstract: *This article proposes and describes a new method and tehnique for testing and determining of some important mechanical characteristics of massive wood. The method is based on the use of a loading-unloading continuous cycle of steel indenter until its penetration to a predetermined depth in the wooden material. During the cycle the force-displacement values are recorded in real time, values that are shown in a graph by an adequate software that can determine the hardness (by measuring the force in correlation to the displacement it causes) and also the following mechanical characteristics: hardness under load, modulus of elasticity, total deformation energy, elastic deformation energy, plastic deformation energy, relaxation and creep of samples.The equipment used to implement the method are a mix of field and laboratory equipment which have a constant speed of continuos loading-unloading system of indenter, an electronic sensor system made of a dynamometer cell used for measuring the force applied to the indenter and an incremental electronic displacement sensor for measuring the depth of penetration for the sperical indenter of 5.5 mm in the wooden material, as well as a PC equiped with a specialized software to interpret the experimental data.*

Keywords: wood, universal hardness, texture, anisotropy

1. Introduction

Wood penetrations are made to determine it's hardness. Wood hardness is a mechanical property that expresses the resistance to penetration from a metalic element of a certain geometry called indenter. From a technological point of view wood hardness reflects it's resistance to machine cutting and resistance through friction. To determine wood hardness the usual methods that can be used are: the classic Brinell hardness test [1],[2],[3], the modified Brinell hardness test [3],[4] and the Janka test [5],[6]. The classic Brinell test uses optical measurements of the spherical imprint left on the test material after removing the indenter; it has the disadvantage that it doesn't show the elastic deformation component of the test material. The modified Brinell hardness test takes into consideration the depth of displacement of the indenter under a number of set forces. Because measurments are made under stress the elastic component for the test material is highlited. It's disadvantage is that it requires two sensors: one for the applied force and one for measuring the displacement. The Janka method is based on determining wood hardness by measuring the force needed to penetrate wood with a 11.28 mm steel indenter up to a depth of half the diameter (5.64 mm). This method of hardness testing determines both the elastic and the plastic deformation components. It has the advantage, compared to the modified Brinell method, of using one sensor, the one used to measure force.

The common disadvantage of the three presented methods is that all three determine only one mechanical parameter, respectively wood hardness. This article removes this disadvantage by, besides measuring the force and displacement parameters for a steel indenter in a constant speed loading-unloading cycle used to determine wood hardness, it also determines important material properties such as: modulus of elasticity, total deformation energy, elastic deformation energy, plastic deformation energy, and for multiple penetration the anisotropy coefficient of wood.

2. Materials and methods

To have a unitary hardness scale that follows the same test method so called "universal hardness" was promoted [7], [8],[9],[10] in which hardness is considered the ratio between the force applied to the indenter and the measured displacement for the test material. In 2003, in honor of the person who in 1898 foresaw the need for a hardness test under load for metals, this hardness was called Martens hardness. It takes into consideration both the elastic and plastic deformation.

The evolution of precision and sensitivity for electronic force and displacement sensors opened a wide field of so called "instruments for measuring hardness" [9],[11]. The result of such a test is a loading-unloading graph for the indenter as a result of continuous reading the pairs of force-displacement. This being a mechanical test that goes through both the elastic and plastic domain most mechanical material parameters can be deduced [11].

Because of the pronounced wood anisotropy, but also because the longest time, the Brinell and Janka [12] methods were considered sufficient, neither the universal hardness test nor the Martens hardness test so far haven't been used for the advanced mechanical characterization of this material.

The objective of this experimental and theoretical research is to characterize and promote a new method that is based on measuring the hardness under a load that, alongside the hardness itself allows the determining of values for other important mechanical characteristics of wood.

The method proposed by the collective is also an experimental method [13],[14] [15],[16] that consists of using spherical shaped steel indenters and a system for the continuous progressive load of the indenter until a set displacement is reached, followed by a progressive unloading of the force until it reaches zero. The acquisition and data processing system consists of electronic sensor for measuring force, electronic sensor for measuring displacement as well as a specialized software for the automated memorizing of the force-displacement pairs. The same software allows the realization of the loading-unloading graph as well the calculus for the mechanical characteristics: hardness, modulus of elasticity, total deformation energy, elastic deformation energy, plastic deformation energy.

The recommended equipment for laboratory use is not in fact a hardness tester but an universal machine for material testing using small loads and a single column on which the device with the sperical indenter is mounted Fig.1.

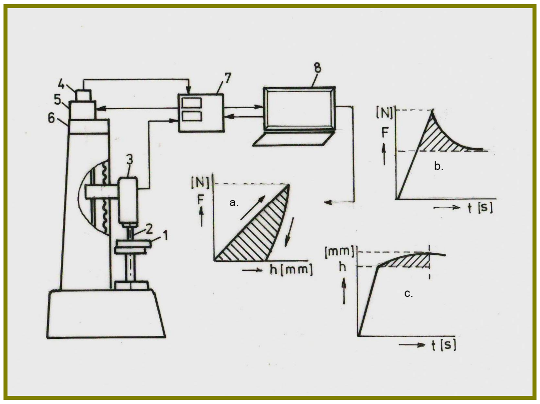
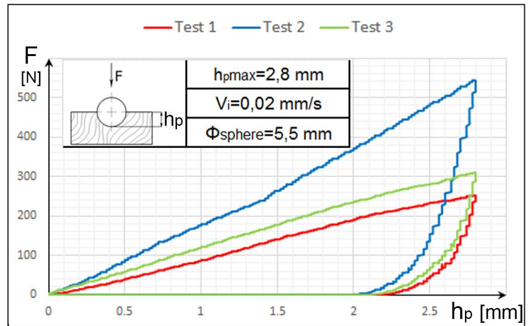


Fig.1. Universal machine for material testing under small loads 1. Sample 2. Indenter 3. Dynamometer 4.Displacement sensor 5. Electric motor 6.Speed reduction unit 7. Electronic unit and the measuring system for force and displacement. 8. Computer. a. loading-unloading graph. b. relaxation graph. c. creep graph

3. Results and discussion

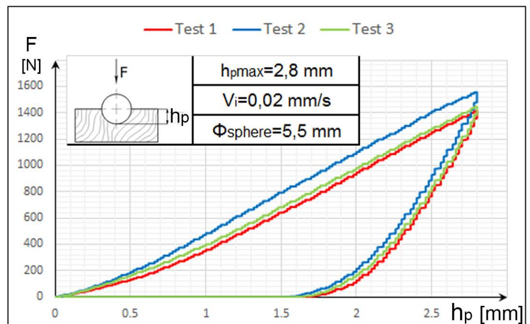
3.1 Experimental data

To establish the viability of the proposed test method a universal machine for material testing under small loads was used Fig.1. which corresponds to all the requirements for mechanical penetration testing. The method used was the incremental increase of the load for a spherical steel indenter with a diameter of 5.5 mm until reaching a displacement of 2.82 mm. The load speed for the indenter was 0.02 mm/s. The wood specimens had identical dimensions: 200 mm length, 40 mm width, 12 mm thickness. They were all dried and thermostated to a final humidity of 10.5%. Ten diffrent species of wood were used: fir , beech, ash , larch , spruce, walnut , maple , pine, acacia , oak . Following the experiments using a prescribed depth the loading-unloading graphs were obtained Fig.2.-11.:



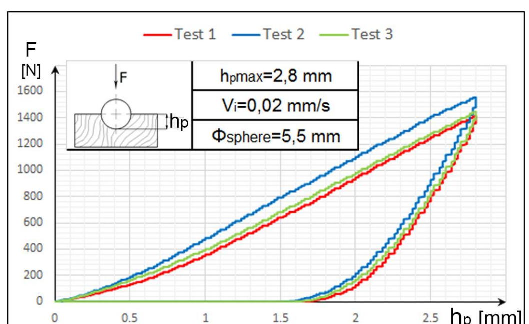
Dimension	Test 1	Test 2	Test 3	Average
Fmax [N]	253.00	544.00	310.00	369.00
Wp [N·mm]	346.70	694.70	434.80	492.07
Ep [N/mm²]	18.39	27.15	19.22	21.59
Ha [N/mm²]	10.65	22.90	13.05	18.87

Fig.2. Loading-unloading graph for fir



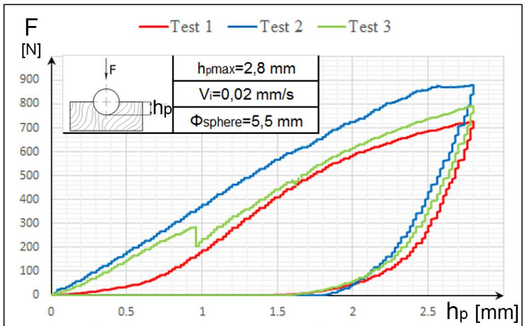
Dimension	Test 1	Test 2	Test 3	Average
Fmax [N]	1261.00	1327.00	1288.00	1292.00
Wp [N·mm]	1687.00	1717.00	1807.00	1737.00
Ep [N/mm²]	42.78	37.66	42.40	40.95
Ha [N/mm²]	53.08	55.85	54.21	54.38

Fig.3. Loading-unloading graph for beech



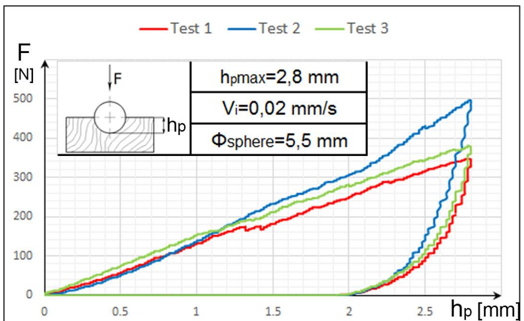
Dimension	Test 1	Test 2	Test 3	Average
Fmax [N]	1437.00	1536.00	1413.00	1462.00
Wp [N·mm]	1741.00	1958.00	1635.00	1778.00
Ep [N/mm²]	40.78	36.63	37.82	38.41
Ha [N/mm²]	60.48	64.65	59.47	61.53

Fig.4. Loading-unloading graph for ash



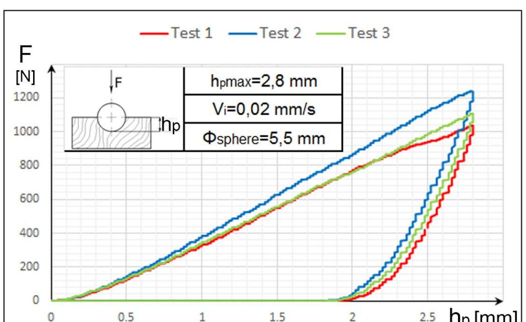
Dimension	Test 1	Test 2	Test 3	Average
Fmax [N]	347.00	496.00	381.00	408.00
Wp [N·mm]	487.00	600.40	551.10	546.17
Ep [N/mm²]	15.65	24.75	16.62	19.01
Ha [N/mm²]	14.60	20.88	16.04	17.17

Fig.5. Loading-unloading graph for larch



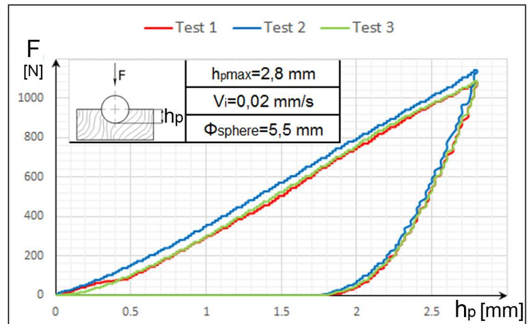
Dimension	Test 1	Test 2	Test 3	Average
Fmax [N]	347.00	496.00	381.00	408.00
Wp [N·mm]	487.00	600.40	551.10	546.17
Ep [N/mm²]	15.65	24.75	16.62	19.01
Ha [N/mm²]	14.60	20.88	16.04	17.17

Fig.6. Loading-unloading graph for spruce



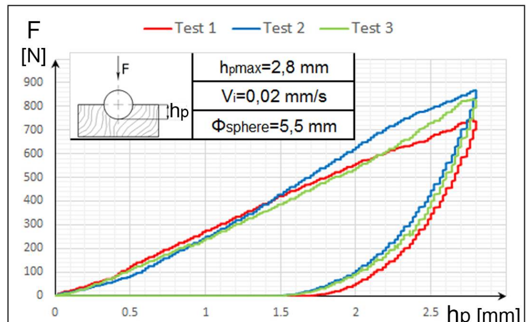
Dimension	Test 1	Test 2	Test 3	Average
Fmax [N]	1031.00	1241.00	1108.00	1126.67
Wp [N·mm]	1417.00	1606.00	1401.00	1474.67
Ep [N/mm²]	44.99	46.17	41.22	44.13
Ha [N/mm²]	43.39	52.23	46.64	47.42

Fig.7. Loading-unloading graph for walnut



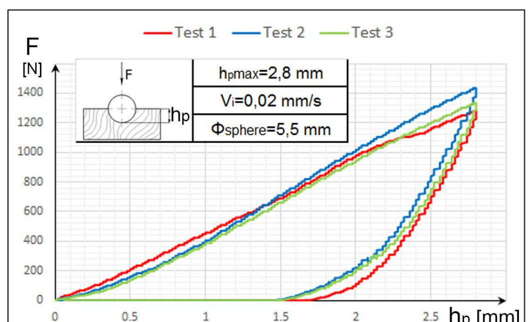
Dimension	Test 1	Test 2	Test 3	Average
Fmax [N]	1065.00	1142.00	1086.00	1097.67
Wp [N·mm]	1257.00	1422.00	1340.00	1339.67
Ep [N/mm²]	34.02	38.75	36.85	36.54
Ha [N/mm²]	44.83	48.07	45.71	46.20

Fig.8. Loading-unloading graph for maple



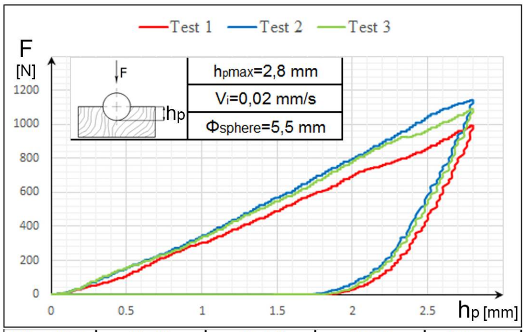
Dimension	Test 1	Test2	Test 3	Average
Fmax [N]	738.00	868.00	831.00	812.33
Wp [N·mm]	1023.00	1131.00	1036.00	1063.33
Ep [N/mm²]	22.88	19.55	19.82	20.75
Ha [N/mm²]	31.06	36.53	34.98	34.19

Fig.9. Loading-unloading graph for pine



Dimension	Test 1	Test 2	Test 3	Average
Fmax [N]	1281.00	1435.00	1334.00	1350.00
Wp [N·mm]	1775.00	1199.00	1359.00	1444.33
Ep [N/mm²]	37.43	31.40	30.04	32.96
Ha [N/mm²]	53.92	60.40	56.15	56.82

Fig.10. Loading-unloading graph for acacia



Dimension	Test 1	Test 2	Test 3	Average
F_{max} [N]	994.00	1144.00	1091.00	1076.33
W_p [N·mm]	1199.00	1430.00	1360.00	1329.67
E_p [N/mm²]	38.16	36.54	24.57	33.09
H_a [N/mm²]	41.84	48.15	45.92	45.30

Fig.11. Loading-unloading graph for oak

3.2 Data interpretation

Taking into consideration the phenomenology for penetration-withdrawal of indenter Fig.12. the obtained graph for this process Fig.14. as well as the fact that the described hardness test is actually a mechanical experiment with a progressively increasing/decreasing load [DIN EN ISO 14577] for which the wood material under the indenter passes from the elastic deformation domain to the plastic deformation domain, from this graph the same material properties usually deducted from a tensile testing are calculated. The definitions and calculus equations for these properties are described next.

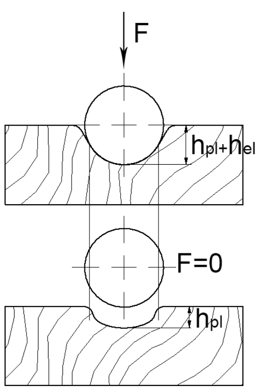


Fig.12. Phenomenology for penetration-withdrawal for the indenter

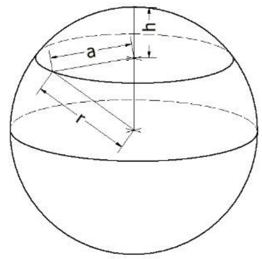


Fig.13. The spherical steel indenter with the dome detail

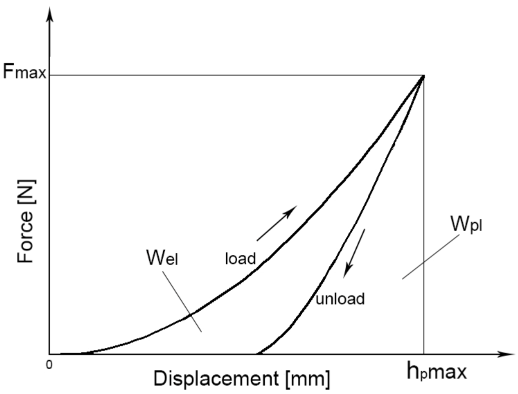


Fig.14. Example for a force-displacement diagram for wood

***H_h* Hardness**, [N/mm], is determined from the ratio between the maximum load force F_{max} and the surface of the dome made by the indenter in the wood specimens A_c for the maximum displacement of 2.82 mm. The spherical indenter has a radius r= 2.75 mm.

$$H_h = \frac{F_{max}}{A_c} = \frac{F_{max}}{2\pi \cdot r \cdot h} = \frac{F_{max}}{\pi\left(a^2 + h^2\right)} = \frac{50}{31{,}4h} = \frac{1{,}59}{h} \quad (1)$$

***H_a* Hardness**, [N/mm²], is determined by the ratio between the maximum load force for the spherical indenter with a radius of r=2.75 mm and A_p the surface for the projection of the contact area surface between the test material and the spherical indenter, a surface situated at a distance of *h* from the indenter extremity.

$$H_a = \frac{F}{A_p} = \frac{F}{2\pi \cdot r \cdot h - h^2} = \frac{50}{31{,}4 \cdot h - h^2} \quad (2)$$

H_m Hardness is determined from the *m* slope of the load curve. According to [DIN EN ISO 14577] the *m* slope can be determined from the graph or for the regression equations of the load curve. Applying that method for the load curves in Fig.3.-Fig.12. the data in Tab.1. resulted.

$$h = m \cdot \sqrt{F} \quad (3)$$

$$H_m = \frac{1}{m^2 A_s / h^2} \quad (4)$$

The fact that the linear regression equation is of the y =mx+c type, where *c* has a certain value different from zero (the linear regression equation doesn't go through the origin) is because the first reading of the dynamometer for the displacement *h* is made the first time the force F resulted from the contact between the indenter and the specimen appears (F>0). The advantage for determining the H_m hardness from the gradient of the load curve is that it is independent from the imprecision given by determining the point of zero penetration (h_0) as well as the geometrical deviations and the specimen roughness.

The penetration modulus of elasticity E_p is determined mathmaticly from the foloowing equations from [DIN EN ISO 14577], [Gutt],[Weiler] :

$$E_p = \frac{1-(v_S)^2}{\frac{1}{E_r} - \frac{1-(v_i)^2}{E_i}} \quad (5)$$

$$E_r = \frac{\sqrt{\pi}}{2C\sqrt{A_p}} \quad (6)$$

where: v_S - Poisson's number for the tested wood with values between 0.0035 and 0.59, v_i - Poisson's number for the steel die with values between 0.27 and 0.30, E_r - the reduced penetration elasticity modulus, E_i – the elasticity modulus for the steel indenter, has a value of 210.000 N/mm^2, *C* – the value for the reciprocity contact rigidity, is calculated by deriving dh/dF for the indenter unload graph on the point for F_{max} , A_p – the surface of the contact area projection between the test material and the spherical indenter A_p, a surface situated at a distance of *h* from the indenter extremity.

Because of the fibers orientation wood is an orthotropic material with a pronounced transversal anisotropy. Using Eq.5. to determine the penetration modulus of elasticity E_p resulted variations between 2% and 75% which represent differences higher than an order of magnitude, an unacceptable situation from a measuring point of view. The calculation for the penetration modulus of elasticity from the load graphs in Fig.3.-Fig.12. can also be made with a sufficient low error through other methods. One of them consists of drawing a tangent to the graph's load curve in the following coordinates force (F)-surface (A_c). From there the penetration modulus of elasticity can be calculated from the tangent of the *α* angle created by this line and the abscissa:

$$E_p = tg\alpha = \frac{\Delta F}{\Delta A_c} = \frac{\Delta F}{\Delta(2\pi \cdot r \cdot h)} = \frac{\Delta F}{\Delta(31{,}4 - h^2)} \quad (7)$$

where: A_c – the surface of the dome created by the indenter in the tested material, r – the indenter's radius (2.75 mm), h – the displacement created by the indenter in the wooden tested material.

Another method which can be used to determine the penetration modulus of elasticity E_p, graphic method that does not involve the exercise described, consists of taking into consideration the liniar regression equation for the graph's load curve in coordinates force (F)-surface (A_c). where the slope m of the linear regression is in fact the penetration modulus of elasticity

The total deformation energy W_t It is the sum of the total elastic deformation energy W_{el} and the total plastic deformation energy W_{pl}.

The plastic and elastic components for the machine work are best visible in Fig.3.-Fig.12., but each can be determined through integration:

$$W_t = \int_0^{h_{max}} F \cdot dh \qquad (11)$$

$$W_{pl} = \int_0^{h_{pl}} F \cdot dh \qquad (12)$$

$$W_{el} = \int_{h_{pl}}^{h_{max}} F \cdot dh \qquad (13)$$

Or by difference from the total deformation energy W_t :

$$W_t - W_{el} = W_{pl} \qquad (14)$$

$$W_t - W_{pl} = W_{el} \qquad (15)$$

Table.1.

The linearreression equations for each wood speciment, highlighting the correlation coefficient R^2, the m gradient and calculating the H_m hardness

Test	Linear Regression Equation	R^2	m [N/mm]	F_{max} [N]	H_m x 10^7 [N/mm]	H_m x 10^7 [N/mm]
Fir test 1	y=95.703x-6.1062	0.9976	95.70	253	178.20	79.83
Fir test 2	y=193.41x-13.571	0.9969	193.41	544	15.47	
Fir test 3	y=112.38x+5.448	0.9979	112.38	310	45.80	
Beech test 1	y=480.97x-64.149	0.9982	480.97	1261	2.50	2.46
Beech test 2	y=502.81x-70.34	0.9977	502.81	1327	2.28	
Beech test 3	y=472.3x-1.4658	0.9991	472.30	1288	2.59	
Ash test 1	y=532.29x-126.36	0.9894	532.29	1437	2.04	1.89
Ash test 2	y=590.36x-90.864	0.9975	590.36	1536	1.66	
Ash test 3	y=541.46x-107.29	0.9941	541.46	1413	1.97	
Larch test 1	y=314.65x-88.389	0.9763	314.65	727	5.84	5.71
Larch test 2	y=342.76x+20.415	0.9903	342.76	903	4.92	
Larch test 3	y=301.31x-12.839	0.9917	301.31	792	6.37	

Spruce test 1	y=126.76x-1.9482	0.9979	126.76	347	36.02	28.63
Spruce test 2	y=177.67x-33.335	0.9918	177.67	496	18.33	
Spruce test 3	y=135.47x+8.0828	0.9986	135.47	381	31.54	
Walnut test 1	y=403.03x-60.591	0.9968	403.03	1031	3.56	3.15
Walnut test 2	y=475.38x-83.572	0.9978	475.38	1241	2.56	
Walnut test 3	y=415.59x-64.282	0.9981	415.59	1108	3.35	
Maple test 1	y=411.02x-85.756	0.9916	411.02	1065	3.42	3.32
Maple test 2	y=420.16x-50.989	0.9977	420.16	1142	3.27	
Maple test 3	y=420.05x-92.75	0.9946	420.05	1086	3.28	
Pine test 1	y=276.4x-8.754	0.9978	276.40	738	7.57	6.31
Pine test 2	y=341.1x-72.302	0.9930	341.10	868	4.97	
Pine test 3	y=301.08x-46.913	0.9935	301.08	831	6.38	
Acacia test 1	y = 479.69x-22.524	0.9978	479.69	1280	2.51	2.19
Acacia test 2	y = 552.15x-106.59	0.9945	552.15	1435	1.89	
Acacia test 3	y = 515.58x-102.62	0.9954	515.58	1334	2.17	
Oak test 1	y = 367.08x-53.144	0.9979	367.08	994	4.29	3.63
Oak test 2	y = 429.43x-59.593	0.9965	429.43	1144	3.13	
Oak test 3	y = 408.07x-52.474	0.9973	408.07	1091	3.47	

Table.2.

The different types of calculated hardnesses, the penetration modulus of elasticty and the transversal anizotropy coefficient

Species	H_h [N/mm]	H_a [N/mm^2]	H_m x 10^7 [N/mm]	E_p [N/mm^2]	W_t [N·m]
1. Fir (Abies Alba)	131.79	18.87	79.83	21.59	492.07
2. Beech (Fagus Sylvatica)	461.29	54.38	2.46	40.95	1737.00
3. Ash (Fraxinus Excelsior)	522.14	61.53	1.89	38.41	1778.00
4. Larch (Larix Decidua)	288.33	33.98	5.71	22.68	1170.40
5. Spruce (Picea Albis)	145.71	17.17	28.63	19.01	546.17
6. Walnut (Juglans Regia)	402.38	47.42	3.1	44.13	1474.67
7. Maple (Acer Pseudoplatanus)	392.02	46.20	3.32	36.54	1339.67
8. Pine (Pinus Sylvestris)	290.12	34.19	6.31	20.75	1063.33
9.Acacia (Robinia Pseudoacacia)	482.14	53.92	2.19	32.96	1444.33
10. Oak (Quercus Robur)	384.40	45.30	3.63	33.09	1329.67

4. Conclusion

The instrumental penetration test using a continuous loading-unloading cycle is a new performant method for the advanced characterization of wood concerning the main physical dimensions for materials like hardness under load, modulus of elasticity, total deformation energy, elastic deformation energy, plastic deformation energy, surface anisotropy modulus of elasticity, work of deformation and surface anisotropy.Taking into consideration the other known methods for hardness testing, the Brinell and Janka hardness tests, the testing under load, defined by the ration between the force applied to the indenter and displacement caused to the wooden material is superior because it can be used for any type of shape for the indenter and for any values for the maximum force and displacement. From the different ways of expressing hardness under load the most notable is the hardness determined from the slope of the load curve of the graph. It has the advantage that it's value is independent from the imprecisions resulted from determining the point of zero displacement as well as geometrical errors and the surface roughness of the tested wooden materials. Considering the high spread of the values for the material characteristics mentioned beforehand, to get a good reproducibility for the experimental data the mediation of three of the five values for certain dimensions, the two most extreme values being overlooked.

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