Compressive behavior and NDT correlations for chestnut wood (*Castanea sativa* Mill.)

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ABSTRACT: The goal of the present work consists in the characterization of the mechanical behavior of chestnut wood under compression perpendicular to the grain. After a review of the problems usually involved in characterizing timber under this type of loading, a mechanical test was set-up. The timber specimens used in the testing program were divided in two groups: (a) new chestnut wood (NCW), which has never been used structurally even so it comes from logs that could be used as such; and (b) old chestnut wood (OCW), which were already used in structural elements from ancient constructions (date and precise origin unknown). The mechanical behavior of the specimens is discussed taking into account the orientation of the annual growth rings along the direction of the load. Correlations between mechanical properties and NDT (ultrasonic pulse velocity and drilling resistance) are also provided, taking into account the density of the wood.

1 INTRODUCTION

Timber is one of the most used materials in the roofs and floors of monumental constructions in Portugal. In particular, Chestnut (*Castanea sativa* Mill.) is usually present in noble constructions, given not only its mechanical and durability properties, but also its aesthetic characteristics.

Carefully conservation or rehabilitation of existing constructions implies extensive knowledge about the constituent material from which the structure was made, both from the mechanical point of view and from the physical point of view. This knowledge constitutes the support to evaluate the short-term structural behavior and to foresee the continuous adaptation and capacity of response of the material under adverse factors (long-term structural behavior).

The last decades witnessed developments in the testing techniques and equipments that allow, diminishing the subjectivity and increasing the level of the structural analysis, diagnosis and inspection of historical constructions. NDT have an own special interest due to the fact that their application does not affect the present structural integrity and safety of the structure.

These methods can be classified in two distinct groups: Global Test Methods (GTM) and Local Test Methods (LTM) (Bertolini et al. 1998). The first ones include the application of the ultrasonic and vibration methods. The LTM, with the utilization of the Resistograph (Rinn, 1994) and the Pilodyn (Gorlacher, 1987) as the most common NDT devices, play usually a role support in the visual grading of the wooden elements and structures. The application concerns the evaluation of the incidence and severity of defects in the material state of conservation (Machado & Cruz, 1997), with the aim of comparing the residual section with the variations of density, usually associated with the loss of mass. These methods present several advantages such as their practical utilization, transport and efficiency.

Presently these methods are used alone or at the same time with others NDT methods or techniques. The effectiveness (in terms of results) could be increased if some laboratorial tests were used to study the variability of the mechanical characteristics of the wooden elements (Uzielli, 1992).

The main scope of the present work consists in the characterization of the mechanical behavior of chestnut wood (*Castanea sativa* Mill.) under compression perpendicular to the grain. The mechanical characterization aims at obtaining the elastic properties (namely the modulus of elasticity and the Poisson coefficient) and the compressive strength perpendicular to the grain, in laboratory with a predefined set-up for mechanical testing. Correlation of these properties with NDT techniques will be analyzed also.

The mechanical behavior of the tests specimens is discussed taking into account the orientation of the annual growth rings with respect to the direction of the applied load.

2 DESCRIPTION OF THE EXPERIMENTAL TESTS

2.1 *Specimens size and orientation*

The average size of the tests specimens was originally 5x5x30 cm. Ultrasonic tests were carried out in these specimens and, afterwards, all of them were cut in three samples of 5x5x10 cm: two of specimens were tested in laboratory up to failure and the other specimen was used for the NDT tests (Resistograph and Pilodyn 6J).

In total, 164 specimens of chestnut wood were tested. The specimens were divided in two groups: new chestnut wood (NCW), which has never been used structurally even so it comes from logs that could be used as such, and old chestnut wood (OCW), which were already used in structural elements from ancient constructions (date and precise origin unknown). All wood comes from the Northern region of Portugal.

The specimens were also divided in different groups taking into account the orientation of the annual growth rings with respect to the direction of the applied force. Therefore, four groups were considered: (a) diffuse, (b) diagonal, (c) tangential and (d) radial, as shown in Figure 1.

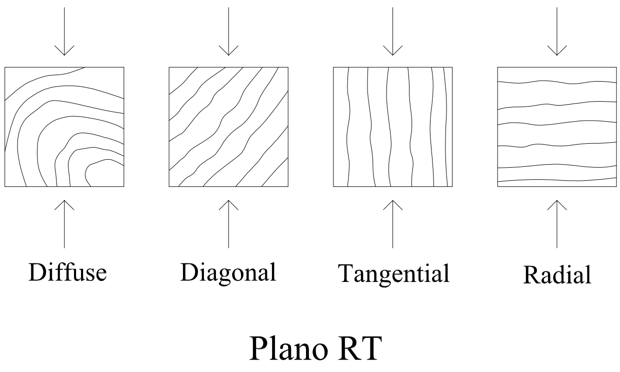


Figure 1. Orientation of the annual growth rings with respect to the direction of the applied load

All the specimens were previously conditioned in a climatic room capable of keeping a temperature of 20±2ºC and a humidity of 65±5%. The tests specimens were considered conditioned when the density variation is smaller than 0.5% in a period of two hours, as recommended by the NP-614 standard. The densities were measured through an electronic weighing machine with a precision of 0.01 *g*.

2.2 *Destructive tests*

The experimental research was carried out at the Structural Testing Laboratory of the National Laboratory for Civil Engineering, using a universal testing machine Baldwin, with a load cell of 300 kN. A power supply Schenk equipment was used, together with a HBM system (Spider 8) for the acquisition and amplification of the data, see Figure 2a.

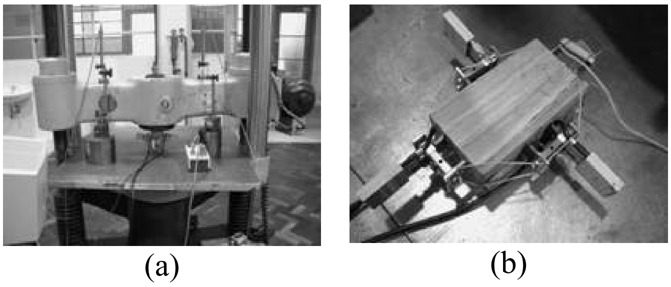


Figure 2. Laboratorial tests: (a) general view and (b) instrumented specimen.

The tests were carried using NBr7190/97 standard being the test velocity $6x10^{-3}$ mm/s, in the cyclical phase, and $6x10^{-2}$ mm/s in the last step (during the failure phase). This normative change was necessary, because the tests were performed under displacement control and not under force control, as prescribed by the standard.

Previously, a series of calibration tests of the apparatus was carried out, for the purpose of verifying the agreement between the vertical displacements in the faces of the tests specimens, measured using mechanical strain gauges, and the vertical displacements in the arms of the test machine, measured by means of LVDT's. Four mechanical strain gauges (one in each one of the faces) were used to measure the horizontal displacements and two additional LVDT's were placed in the arms of the test machine measuring the vertical displacements. As shown in Figure 3b, three mechanical strain gauges from HBM (DD1 type) and one mechanical strain gauge from Schenck were used. This last transducer was not always effective in measuring the displacements due to insufficient adhesion.

The normal compressive strength ($f_{c,90}$) is the conventional value determined by the residual specific deformation of 2‰, following the NBr7190/97 standard. The stiffness of wood, in the direction perpendicular to the grain, is determined by its modulus of elasticity. This is equal to the slope of the linear part on the stress-strain relationship (Fig. 3), defined by the points ($\sigma_{10\%}; \varepsilon_{10\%}$) and ($\sigma_{50\%}; \varepsilon_{50\%}$) corresponding respectively to 10% and 50% of the conventional stress, in compression perpendicular to the grain, and it is represented by:

$$E_{c,90} = \frac{\sigma_{50\%} - \sigma_{10\%}}{\varepsilon_{50\%} - \varepsilon_{10\%}} \qquad (1)$$

where $\sigma_{10\%}$ and $\sigma_{50\%}$ are the normal stresses corresponding to 10% and 50% of the conventional stress, and $\varepsilon_{10\%}$ and $\varepsilon_{50\%}$ are the specific strains corresponding to the values of $\sigma_{10\%}$ and $\sigma_{50\%}$.

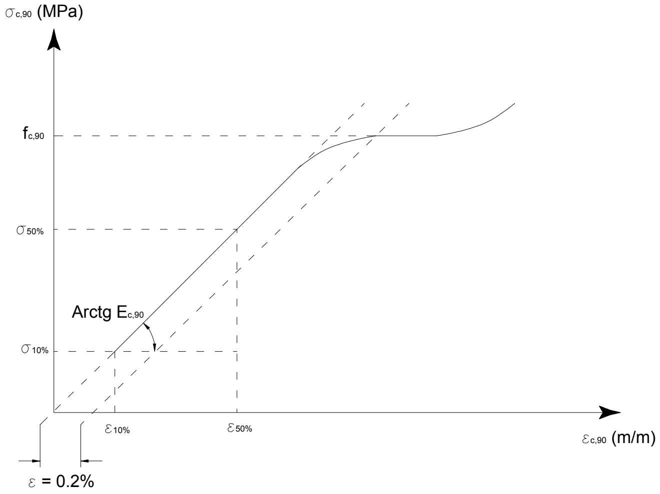


Figure 3. Stress-Strain relationship.

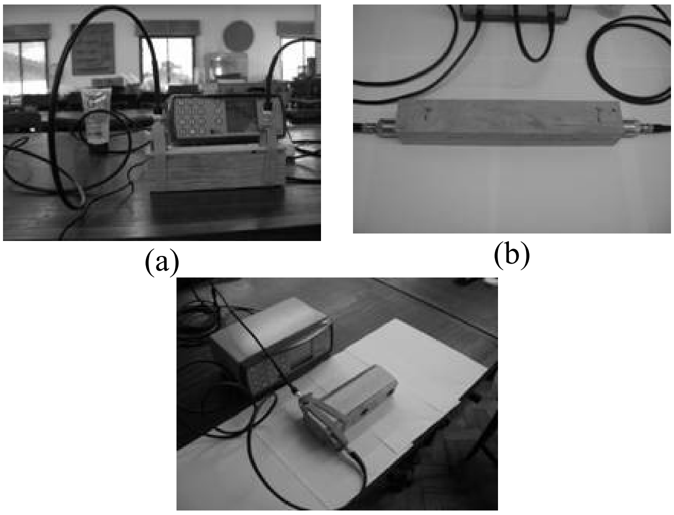
The relative moisture and the temperature during the tests were registered by an electronic device. During the tests, the average values of temperature and relative moisture were 24±2ºC and 52±12%, respectively.

2.3 *Non-destructive tests*

2.3.1 *Ultrasonic tests*

During the tests the ultrasonic equipment Pundit/Plus was used, with cylinder-shaped transducers of 150 kHz. The tests were divided in three distinct types of signal transmission: (1) Indirect Method; (2) Direct Method, parallel to the grain, and (3) Direct Method, perpendicular to the grain. The elastic properties of wood were estimated by the measurement of stress wave propagation time in these directions, assuming a continuous and homogeneous material. The transmission technique of elastic waves based on the Indirect Method was used in all the faces, for the case of diagonal and diffuse tests specimens (fig 1). For the case of radial and tangential tests specimens, the transducers were used in two opposite faces, depending on the orientation of annual growth rings, see Figure 4a. Average values were considered.

In the Direct Method, perpendicular to the grain, contiguous sections of the same specimen were used (the distance between each section was 6 cm), see Figure 4c, and once again average values were considered. In all tests, coupling between the transducers and specimens was assured by a conventional hair gel and a constant pressure was applied by means of a rubber spring, allowing adequate transmission of the elastic wave between the transducers and the specimen under testing.


(a) (b)

(c)

Figure 4. Test set-up: (a) Indirect Method, (b) Direct Method, parallel to the grain and (c) Direct Method, perpendicular to the grain.

2.3.2 *Resistograph tests*

The use of the Resistograph allowed to obtain the density profile of the used tests specimens, see Figure 5a. Drilling was made parallel to plan RT (plain TL and LR), which, in real cases, represents the accessible face of the timber elements.


(a) (b)

Figure 5. NDT devices: (a) Resistograph and (b) Pilodyn 6J.

For all the specimens, as a function of the obtained graphs with the Resistograph, a resistographic measure (RM) was determined. The selected resistographic measure represents the ratio between the integral of the area of the diagram and the height of the tests specimens (see Eq. 2). Using this quantity, the Resistograph results can be easily compared with the values of density and the strength values.

$$\mathrm{R}M = \frac{\int_0^h Area}{h} \tag{2}$$

2.3.3 *Pilodyn 6J tests*

The Pilodyn 6J is a device that allows, through the release of a spring that transforms the elastic potential energy into impact energy, to measure the penetration of a metallic needle with 2.5 mm of diameter. This impact is responsible for the penetration of the needle in the surface of the specimens, allowing to register the depth penetrated by the needle in plan TR or in plan RT of the specimens, see Figure 5b. The Pilodyn 6J was used with the aim of correlating the density of each specimen with the depth reached with the needle of the device (surface hardness or resistance to superficial penetration).

2.3.4 *Density determination*

Density was measured according to NP-616 standard. Given the conditioning conditions of the specimens, the average density is determined for a moisture content of 12%, given by:

$$r_{12\%} = \frac{m_{12\%}}{V_{12\%}} \tag{3}$$

3 DESTRUCTIVE TESTS

The results of the destructive tests, following the grouping detailed above, are presented taking into account the orientation of the annual growth rings along the direction of the force. The tables presented next (Table 1 to Table 8), provide the values obtained for all groups.

Table 1. Radial specimens: NCW.

Radial (NCW)					
	E (MPa)	**Poisson**			**$\sigma_{0,2\%}$ (kPa)**
		ν_{LR}	**ν_{TR}**	**ν_{LT}**	
Average	800,6	0,04	0,32	0,13	7806,9
Max.	985,6	0,06	0,39	0,18	10896,8
Min.	621,0	0,03	0,21	0,10	5344,8
No.	19				
CV	13	18	12	16	19

Table 2. Radial specimens: OCW.

Radial (OCW)					
	E (MPa)	**Poisson**			**$\sigma_{0,2\%}$ (kPa)**
		ν_{LR}	**ν_{TR}**	**ν_{LT}**	
Average	846,3	0,05	0,32	0,16	8011,6
Max.	1058,9	0,08	0,45	0,20	12045,5
Min.	562,7	0,04	0,23	0,11	5365,0
No.	12				
CV	17	22	21	15	26

Table 3. Diagonal specimens: NCW.

Diagonal (NCW)					
	E (MPa)	**Poisson**			**$\sigma_{0,2\%}$ (kPa)**
		ν_{LR}	**ν_{TR}**	**ν_{LT}**	
Average	551,5	0,04	0,26	0,16	6233,0
Max.	673,1	0,05	0,32	0,19	7400,0
Min.	453,8	0,02	0,13	0,12	5224,4
No.	20				
CV	10	22	16	13	10

Table 4. Diagonal specimens: OCW.

Diagonal (OCW)					
	E (MPa)	**Poisson**			**$\sigma_{0,2\%}$ (kPa)**
		ν_{LR}	**ν_{TR}**	**ν_{LT}**	
Average	620,8	0,04	0,26	0,16	6623,1
Max.	929,2	0,06	0,32	0,23	9124,8
Min.	421,6	0,02	0,21	0,11	4376,3
No.	26				
CV	21	21	12	19	21

Table 5. Tangential specimens: NCW.

Tangential (NCW)					
	E (MPa)	**Poisson**			**$\sigma_{0,2\%}$ (kPa)**
		ν_{LR}	**ν_{TR}**	**ν_{LT}**	
Average	527,6	0,05	0,28	0,18	6667,4
Max.	660,2	0,07	0,39	0,23	8792,5
Min.	331,0	0,04	0,23	0,16	5170,9
No.	18				
CV	15	17	13	12	14

Table 6. Tangential specimens: OCW.

Tangential (OCW)					
	E (MPa)	**Poisson**			**$\sigma_{0,2\%}$ (kPa)**
		ν_{LR}	**ν_{TR}**	**ν_{LT}**	
Average	572,4	0,06	0,32	0,18	7484,2
Max.	687,6	0,08	0,38	0,23	9199,2
Min.	467,6	0,05	0,29	0,14	6310,0
No.	12				
CV	12	13	8	13	10

Table 7. Diffuse specimens: NCW.

Diffuse (NCW)					
	E (MPa)	**Poisson**			**$\sigma_{0,2\%}$ (kPa)**
		ν_{LR}	**ν_{TR}**	**ν_{LT}**	
Average	592,7	0,06	0,36	0,17	6523,3
Max.	751,8	0,08	0,44	0,22	9307,2
Min.	516,0	0,03	0,30	0,07	4684,8
No.	22				
CV	12	19	9	18	16

Table 8. Diffuse specimens: OCW.

Diffuse (OCW)					
	E (MPa)	**Poisson**			**$\sigma_{0,2\%}$ (kPa)**
		ν_{LR}	**ν_{TR}**	**ν_{LT}**	
Average	618,3	0,06	0,35	0,18	6559,6
Max.	705,9	0,08	0,43	0,24	7968,0
Min.	479,2	0,04	0,29	0,10	4730,4
No.	29				
CV	8	18	9	16	14

4 CORRELATIONS BETWEEN NON-DESTRUCTIVE AND DESTRUCTIVE TESTS

4.1 *Ultrasonic tests*

It is well known that stress waves velocity can be directly related to the elastic properties of timber.

The propagation velocity of the longitudinal stress waves in an elastic media depends essentially on the stiffness and the density of the media itself.

On the other hand, it is normally possible to measure the propagation time of a set of elastic waves in the axial direction of the wooden elements or in the perpendicular directions to this (it is stressed again that the propagation time is an average time obtained from the measurement of the faster elastic waves).

For prismatic, homogeneous and isotropic elements and for those with section width smaller than the stress wavelength, the relation:

$$E_{din} = v^{2}\ ´\ r \qquad (4)$$

holds, where E_{din} represents the dynamic modulus of elasticity (N/mm²); v is the propagation velocity of the longitudinal stress waves (m/s) and r is the density of the specimens (kg/m³).

For practical purposes, the relation between the dynamic modulus of elasticity and the static value $E_{med,\,static}$ is particularly relevant (E_{din} ³ E_{med}). Generally (Wood Handbook, 1974), a linear relation is adequate:

$$E_{med} = a\ ´\ E_{din} - b \qquad (5)$$

Table 9 to Table 11 provides the values measured for all specimens. The obtained values with the ultrasound test emphasize the good relation between the dynamic and static moduli of elasticity.

Table 9. Dynamic modulus of elasticity (Direct Method, perpendicular to the grain).

Dynamic modulus of elasticity (MPa)								
Direct Method, perpendicular to the grain								
	Tangential		Diagonal		Diffuse		Radial	
	New	Old	New	Old	New	Old	New	Old
Average	1456	1662	2256	2109	1664	1867	2997	3083
No.	19	12	11	16	10	13	18	13
CV	16	9	19	18	13	25	19	14

Table 10. Dynamic modulus of elasticity (Indirect Method).

Dynamic modulus of elasticity (MPa)								
Indirect Method								
	Tangential		Diagonal		Diffuse		Radial	
	New	Old	New	Old	New	Old	New	Old
Average	12932	12008	12189	13237	13306	12391	13084	12897
No.	19	12	11	16	10	13	19	12
CV	16	26	14	21	12	16	16	22

Table 11. Dynamic modulus of elasticity (Direct Method, parallel to the grain).

Dynamic modulus of elasticity (MPa)								
Direct Method, parallel to the grain								
	Tangential		Diagonal		Diffuse		Radial	
	New	Old	New	Old	New	Old	New	Old
Average	14445	14540	13368	15091	16057	14601	14445	14525
No.	19	12	11	16	10	13	18	13
CV	19	22	15	13	13	21	19	22

Figure 6 illustrates different correlations obtained between the dynamic modulus of elasticity, taking into account the orientation of the annual growth rings along the direction of the force, considering the Direct Method, perpendicular to the grain, for the NCW group.

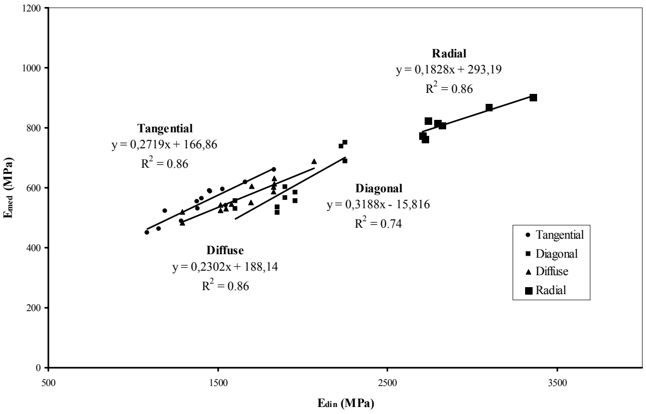


Figure 6. Relation between *Edin* and *Emed*, for the group NCW, using the Direct Method, perpendicular to the grain.

4.2 *Resistograph tests*

Figure 7 and Figure 8 show the correlations between the resistographic measure and the density of each specimen for the NCW group and for the OCW group respectively.

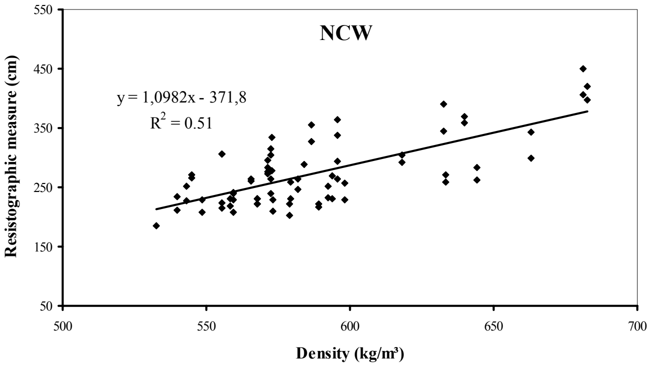


Figure 7. Relation between the resistographic measure and density (NCW).

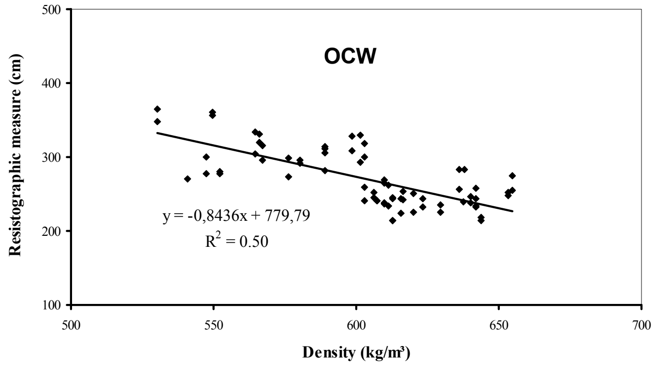


Figure 8. Relation between the resistographic measure and density (OCW).

4.3 *Pilodyn 6J tests*

Figure 9 and Figure 10 show the correlations obtained (depth reached for the needle and the density of each specimen) through the use of the Pilodyn 6J device, for the NCW group and for the OCW group, respectively.

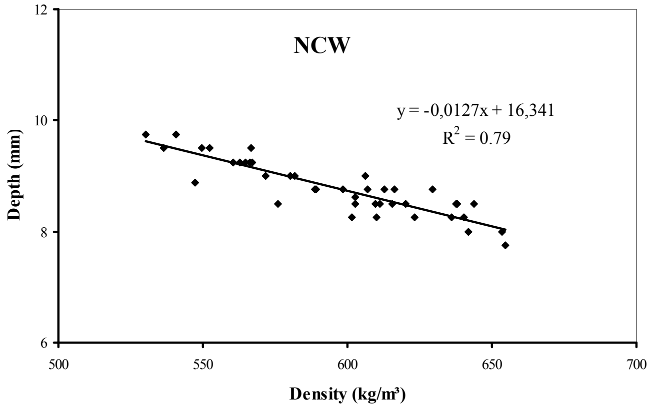


Figure 9. Relation between depth and density (NCW), with the Pilodyn 6J.

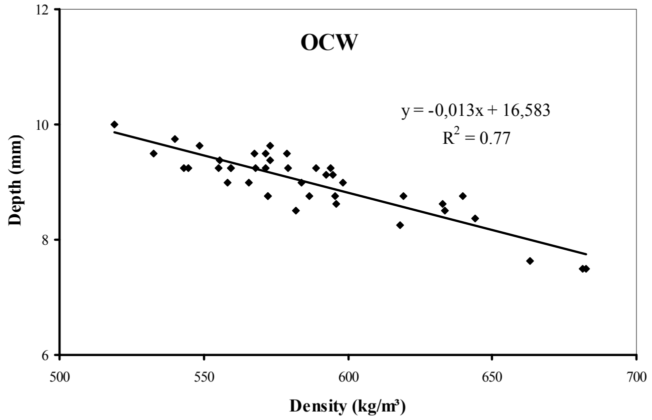


Figure 10. Relation between depth and density (OCW), with the Pilodyn 6J.

5 CONCLUSIONS

The analysis of the destructive tests carried out in timber specimens indicates that results must take into account the orientation of the annual growth rings, not only in terms of numerical values but also in terms of observed failure modes (Bodig, 1965, Tabarsa & Chui, 2001). In this paper, both new and old sound chestnut wood are considered in the testing program.

As a first conclusion, the mechanical characteristics of the old wood are, usually, slightly higher than the new wood (7-8%). A reason for this it not clear but it is possible that the old specimens have been obtained from larger trees.

The radial specimens present the highest values of modulus of elasticity and characteristic strength (a due to differences in the anatomy and cell wall microstructure) and all others have similar behavior and elastic properties. The coefficients of Poisson found corroborated values found in the literature.

Single-parameter linear regressions showed acceptable agreement between non-destructive parameters (Pylodin 6J and Resistograph), and elastic values or density. In future communications, the issue of correlations between non-destructive parameters and strength values will be addressed.

Taking into account the subjectivity of the results associated with the Resistograph, the concept of resistographic measure needs revising, to reduce reading errors and increase graphical interpretation.

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