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INVESTIGATION ON THE PROPERTIES OF PEDUNCULATE OAK WOOD AFFECTED BY OAK DECLINE

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Abstract:
The combination of damaging agents, as biotic and abiotic factors, has as effect the deterioration in the appearance of the foliage of affected trees and then, progressive death of branches. Large numbers of pedunculate oak (Quercus robur) and sessile oak (Quercus petraea) trees are declining in the Central Romania. Depending on the deterioration of the foliage and of the branches, five grades of infestation levels of oak trees were determined. The objective of this study was to investigate the quality of wood obtained from those infested trees by analysing the cellulose and lignin content, physical properties such as moisture content, density, shrinkage from fibre saturation moisture content, permeability of wood to water, and mechanical properties, such as MOE, MOR for static stresses, tensile strength perpendicular to the grains, shearing strength and Janka hardness perpendicular to the grains. The more representative samples of trees affected by oak decline for the five grades of infestation levels of trees were randomly selected and harvested. They were cut into logs and then sampled for the chemical, physical and mechanical testing. The results of this study showed that the poor quality of wood resulted from the logs affected by oak decline at the final stage (five grade of infestation level) could not be used for furniture and other wooden products manufacturing.

Key words: *pedunculate oak; oak decline; physical properties; mechanical properties.*

INTRODUCTION

The evidence of genus *Quercus L.* including over 200 oak species was found to date since the Cretaceous. About 19% of the total forest in Romania is represented by the following species: pedunculate oak (*Quercus robur L.* or *Quercus pedunculata*), sessile oak (*Quercus petraea*), Austrian oak (*Quercus cerris*), gray oak (*Quercus pedunculiflora*), pubescent oak (*Quercus pubenscens*) and Italian oak (*Quercus frainetto*) trees. Decline of oak trees has been first reported in alluvial regions of the Sava and Drava rivers of Slovenia in 1878. The main cause was the disturbance of natural balance of biocenoses because of mass oak exploitation, climate and water pollution, followed by diseases and pest attacks (Čater et al. 2008). Another documented oak decline episode occurred in the 1920s in UK. The symptom of the affected trees was the defoliation by caterpillars of the oak leaf roller moth (*Tortrix viridana*) and the damage caused by oak mildew fungus (*Erysiphe alphitoides*) (Gibbs 1999). Constant degradation of the forest ecosystems afterwards, as a combined effect of several factors, caused massive oak decline in the 1980s across Europe and eastern North America. The phenomenon has been described as a complex interaction of stressors that contribute to tree death (Brasier and Scott 1994; Jung et al. 2000; Lynch et al. 2014). The consequences can still be seen even today. Since 1910, oak decline has been a serious and frequently occurring disease of Romanian oak forests. Being an episodic phenomenon first, affecting the Western Romanian woodlands covered by oak trees, oak decline was going on since the beginning of the 1930s. The phenomenon was reported in 1938 in the Southern Carpathians oak forests of Romania, and in the Southern Transylvania in 1943, affecting at that time more than 35 000 hectares of oak forests. The flood of the main river streams and the excess of water in the woodlands, the extreme temperatures of the 1940s and of the 1950s played a key role in oak decline at that time. Acute oak decline was reported between 1955 and 1961, in all woodlands covered by oak trees, except the Central and Eastern part of Romania. In 1970, around 25% of the woodlands of Romania were damaged, and 1.2 million hectares of them were reported to be covered by oak trees. Nowadays, more than 50% of the oaks are affected by oak decline in various stages of disease. Pedunculate oak (*Quercus robur L.)* and sessile oak (*Quercus petraea*) are considered to be more susceptible to oak decline than the other *Quercus* species (Alexe 1984; Denman et al. 2010). The evidence of the actual severe disorder is the oak decline in case of *Quercus* species, which are more resistant and stable to environmental changes, such as *Quercus pedunculiflora* and *Quercus Pubescens.* Practically, since the beginning of the twentieth century, oak decline has been a severe disease of European oak forests (Delatour 1983; Badea 1991; Kandler 1992; Brasier and Scott 1994; Jung *et al*. 2000; Thomas *et al*. 2002; Balcì and Halmschlager 2003a, 2003b; Moreira and Martins 2005). The symptoms include wilting, yellowing and shrinking of leaves, bark lesions followed by death of small branches and thinning of the entire crown, and finally death of the whole tree (Jung et al. 2000; Jönsson et al. 2005). On one hand, the causal agents discussed by the researchers include abiotic factors, such as air or water pollution (Farmer *et al*. 1991; Newsham *et al*. 1992), climate change (Tainter *et al*. 1990; Pearson and Stewart 1993; Chappelka and Samuelson 1998; Saxe *et al*. 2001; Pautasso *et al*. 2010; Sturrock *et al*. 2011), extreme temperatures (Thomas and Ahlers 1999), excess or lack of water, drought (Siwkcki and Ufnalski 1998**)**, geographical particularities. On the other hand, researchers found biotic agents to be responsible for the disorder, such as insects (Spruce e*t al*. 2011), fungal pathogens (Balcì and Halmschlager 2003a, 2003b; Jönsson *et al*. 2003; Jönsson 2004; Marçais and Bréda 2006; Lynch *et al*. 2014), bacteria and viruses. Unlike biotic and abiotic agents, silvicultural mismanagement, regional problems and inappropriate harvesting seems to be important in the occurrence of oak dieback (Jung *et al*. 2000; Čater *et al*. 2008; Sturrock *et al*. 2011). This disorder is finally the effect of the combination of several damaging agents from those mentioned before (Jung *et al*. 2000; Thomas *et al*. 2002; Camy *et al*. 2003; Jönsson *et al*. 2005; Lynch *et al*. 2014). Studies conducted in our country led to identification of species *Ophiostoma (Ceratocystis),* such as *C.roboris, O.valachica* and *Ceratostomella querci* and a new form of *Chalara (Endoconidiophora),* which are involved in the phenomenon of oak decline (Şimonca and Tăut 2010). Defoliators of oak forests like *Lymantria dispar* L. and *Apethymus abdominalis* are also responsible for tree death, but they have registered in the last years reduced outbreaks, showing only insignificant infestations in the oak forests from the Southern part of the country (Ciornei et al. 2004).

Five grades of infestation levels of oak trees were established for the study, depending on the symptoms of the infested trees: thinning of the crown, branches dieback, "stag-headed" appearance of the trees. The 5th grade of infestation level corresponds to the more affected trees by oak decline. Trees corresponding to all grades of infestation levels were randomly selected and harvested for trunk sampling. They were cut into standard specimens for the determination of chemical, physical and mechanical properties of the wood.

The reference work on this subject (Latham and Armstrong 1934) was conducted on healthy oak tree and two other infested trees with different levels of infestation: an incipient phase, and a final stage of oak dieback. The results showed that the properties of the more affected oak tree were reduced by 32% compared with the healthy wood.

OBJECTIVES

The present paper investigates the physical and mechanical properties of oak wood (*Quercus robur*) affected by oak decline at different grades of infestation levels compared with healthy wood. Cellulose and lignin content, moisture content, linear shrinkage starting with fibre saturation moisture content, density, and permeability to water were determined as physical properties and MOE, MOR for static stresses, tensile strength perpendicular to the grains, shearing strength and Janka hardness perpendicular to the grains were investigated as representative mechanical properties. The result of the investigation aims to establish the manufacturing potential of infested wood in applications such as furniture and other wooden products.

METHOD, MATERIALS AND EQUIPMENT

A survey of the oak decline in Romania was made in 1999 for 11 oak stands on a range of different sites all over the country, by the Research Institute and Silvicultural Planning (I.C.A.S. Romania).

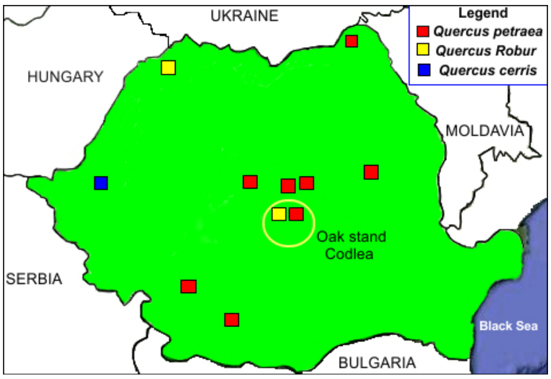

Fig. 1.
Map of Romania showing the location of the oak stands surveyed and the location of oak stand Codlea, from where the investigated oak wood (Querqus Robur L.) affected by oak decline was exploited.

The oak stands (Fig. 1) were representatives mainly for *Quercus robur* and *Quercus petraea*. The stands are located in different climatic zones, with various sources of pollution and industrial possibilities of processing the wood. Investigated wood (*Quercus robur*) affected by oak decline was exploited from the stand "Codlea", which is placed in the central part of the country. The pollution in this site is low. The atmosphere contains small concentration of chemical constituents such as SO_2, NO, No_2, NO_x, CO, O_3, Pb, PM10, PM2.5, NH_3 and C_6H_6. The measured emissions of those chemical constituents are situated under the standard limits of the legal norms, all year long.

Research Institute and Silvicultural Planning (I.C.A.S. Romania) has established five grades of infestation levels in case of trees affected by oak decline. This classification was based on the deterioration in the appearance of the foliage of affected trees (in %), linked by the amount of dead branches. This classification appears as the percentages of crown defoliation of oak trees and their correspondence to the grade of infestation level (Table 1).

Table 1

Crown defoliation of trees affected by oak decline and their correspondence to the grade of infestation level

Grade of infestation level	Crown defoliation (%)	Wood quality class	Wood characteristics
1	0 – 10	I	No micro- and macro-structural modifications.
2	15 – 30	I	No micro- and macro-structural modifications.
3	35 -65	II	Incipient colour changes to the boundary between heartwood and sapwood.
4	70 -99	III	Macroscopic changes in both sapwood and heartwood with colorations, incipient rot and insect attack, cracks.
5	100 (with bark)	IV	Significant changes in the macroscopic and microscopic structures, colorations, rot, insect attack, disorder of the anatomic structure.

Oak trees corresponding to all grades of infestation levels were randomly selected from the site and marked. One tree for each infestation level was harvested for trunk sampling and cut into logs, according to SR ISO 4471-93. Two logs with a length of 1.50 m were cut from each tree, as follows: the first one was cut at a height of 1.30m from the ground, and the second one at a height of one third of the trunk length from the ground. Afterwards, the logs were cut into standard specimens for the determination of physical and mechanical properties of the wood, according to SR ISO 3129-93. Harvested oak trees (Fig. 2) were 115 years old, had a mean diameter of 34 cm and a height of 23m. As observed, the colour of the wood appeared darker with the increasing of infestation level.

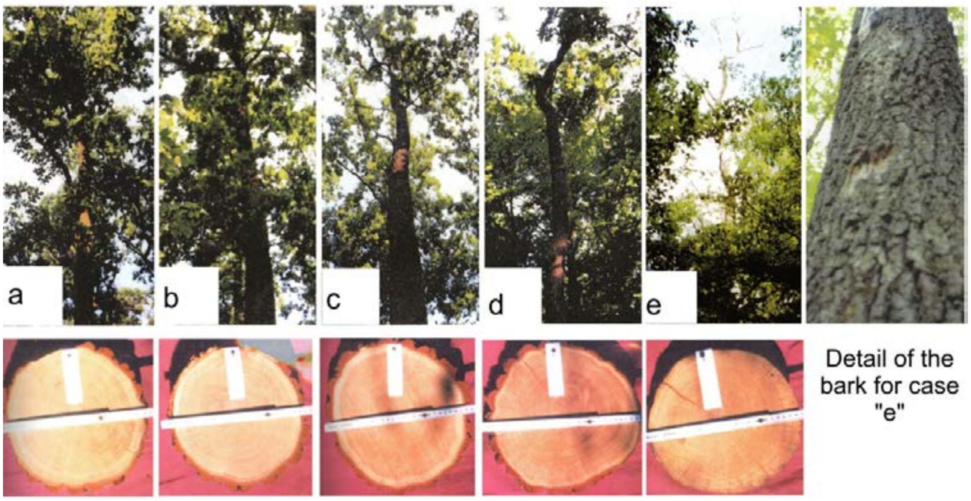

Fig. 2.

Selected and harvested oak trees affected by oak decline on different grades of infestation levels, and their corresponding crosscut sections; a) grade 1; b) grade 2; c) grade 3; d) grade 4; e) grade 5.

Cellulose and lignin content

The amounts of main chemical components of oak (*Quercus robur* L.) wood found in the literature are as follows: cellulose-45.08%, lignin-26.31% and pentosans-16.77% (Simionescu and Ştefănescu 1986). For present research, determination of cellulose content was done using the standard method of Cross and Bevan. The method is based on wood chlorinated by means of sodium hypochlorite in alkaline solution. The cellulose content was determined for 100 grams of oak wood, for the specimens corresponding to each infestation level of oak trees. Lignin's content for 100 grams of oak wood material was determined using Klason-Komarov method.

Physical properties

Moisture content (MC) at the moment of harvesting was determined on drill cores extracted by Pressler borer, according to STAS 83-89. The samples (24 pcs.) were weighed on analytical balance type MB-C-03/02 with the accuracy of 0.0002 grams. Volume was measured by the Breuil volumeter and the constant mass was obtained by drying in the oven at 103±2°C. Afterwards, the density (ρ) of the infested oak wood was determined according to STAS 84-87, using 36 samples.

In order to assess longitudinal (β_l), tangential (β_t) and radial (β_r) shrinkage of wood starting from the saturation grain moisture content value, according to STAS 85/2-1991, 30 specimens with sizes of 100x20x20mm were immersed into the water at a temperature of 20°C until constant dimensions were obtained. The dimensions have been afterwards measured on the radial, longitudinal and tangential grain directions of the wood with a digital calliper at 0.01mm accuracy.

Permeability of wood to water belongs to the physical properties significant to technological processes related to drying, surface coating and wood impregnation. It was determined according to STAS 8191-1982, using 18 samples for testing. The experimental permeability coefficients were calculated based on Darcy's low on the radial, longitudinal and tangential grain directions of wood, by the following formula:

$$K_{exp} = \frac{V \cdot \eta \cdot L}{S \cdot t \cdot \Delta p}$$

where: V is the volume of the flowing liquid, η – dynamic viscosity of water, L – specimen length, S – active surface, t – time of the flow duration, Δp – pressure difference.

The experiment was conducted using an apparatus where the water was introduced at a pressure of 1 atmosphere and a temperature of 20°C. Time of flow duration was of 300s.

Mechanical properties

Specimens (a total of 32 pcs.) with sizes of 300x20x20mm were subjected to static bending test on the universal testing machine. Static flexural strength (MOR) and modulus of elasticity (MOE) were determined according to STAS 337/1-1988 and STAS 337/2-1989. The force was applied to the middle of specimens, radially to the tree rings. The maximum force was registered, and MOE and MOR were calculated for a wood moisture content of 12%. MOE, MOR, tensile strength perpendicular to fibres (TS), shear strength (SS) and Janka hardness perpendicular to fibres (JH) were investigated on the universal testing machine VDM type, at a testing speed of 6mm/min. The tensile strength perpendicular to fibres (TS) was determined according to STAS 6291-89, using 24 specimens with sizes of 50x20x20mm for the tests. The shear strength (SS) was determined according to STAS 1651-1983, using 24 specimens of 50x20x20mm for testing. The Janka hardness perpendicular to fibres (JH) was determined according to STAS 2417/1-1987 on 24 specimens with sizes of 50x50x50mm. The number of specimens was determined for each type of infestation level of the wood. The sizes and the shapes of the specimens were imposed by corresponding technical standards for each type of mechanical test.

RESULTS AND DISCUSSIONS

Cellulose and lignin content

These chemical components were determined both for the logs cut at a height of 1.30m from the ground, and for those cut at a height of one third of the trunk length from the ground. Duplicate samples were used for each determination applied to the wood affected by the five oak decline grades of infestation level.

Percentage of cellulose experimentally determined (Fig. 3) was observed to decrease with increasing wood damages due to oak decline phenomena, whilst the amount of lignin increase with a reduction of tree health. Cellulose content of declining wood experimentally determined is close to that found in the literature (Simionescu and Ştefănescu 1986). Instead, lignin amount was found to be significant lower compared with healthy wood (Fig. 3).

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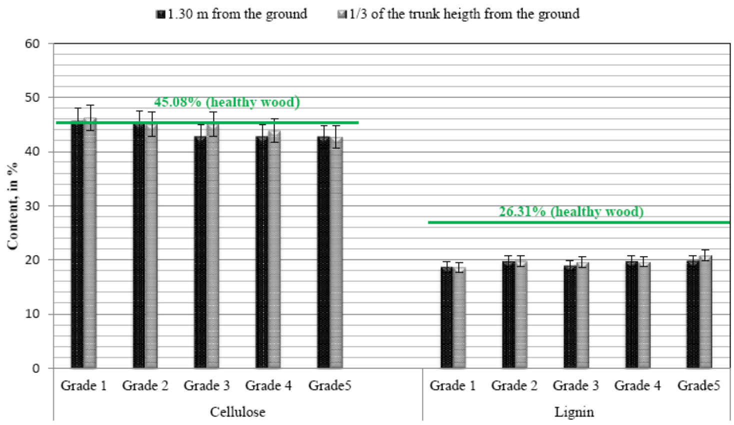

Fig. 3.
Cellulose and lignin content compared with healthy wood.

Physical properties

Moisture content (MC) was measured on 24 specimens for each infestation level of declining oak wood. The test was conducted according to STAS 83-89. Specimens of 300x20x20mm were cut for measuring the density (ρ_{12}) of infested oak wood, a. The specimens were collected from the logs cut at a height of one third of the length from the ground. Density was measured on 36 specimens for each grade of infestation level according to STAS 84-87. Shrinkage of wood (β_l, β_t, βr), determined according to STAS 85/2-1991, was measured on 10 samples each, and 18 samples were used for the determination of experimental permeability coefficient (K_{exp}) on each grain direction of wood, according to STAS 8191-1982.

The results reported (Table 2) are the mean values of the measurements conducted on all specimens.

Table 2

Physical properties of oak wood affected by oak decline

Physical properties/ Grade of infestation level	Healthy wood*	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Moisture content at the moment of harvesting the trees, MC, in %	-	74.93	69.36	61.95	52.35	48.40
Density at a moisture content of 12%, ρ_{12}, in kg/m^3	620-740	706	691	671	671	611
Maximum longitudinal shrinkage, β_l, in %, determined from the fibre saturation moisture content	0.1-0.4	0.17^a 0.15^b	0.20^a 0.19^b	0.26^a 0.24^b	0.30^a 0.29^b	0.32^a 0.34^b
Maximum tangential shrinkage, β_t, in %, determined from the fibre saturation moisture content	7.8-10	9.10^a 9.00^b	9.10^a 8.90^b	8.10^a 8.00^b	8.30^a 8.20^b	5.10^a 5.20^b
Maximum radial shrinkage, βr, in %, determined from the fibre saturation moisture content	4-6.4	5.20^a 5.00^b	4.70^a 4.50^b	4.30^a 3.90^b	3.50^a 3.50^b	3.20^a 3.00^b
Experimental permeability coefficient, *Kexp(l)*, on longitudinal grain direction, in m^2/Pa·s	-	9.442^a 11.051^b	8.426^a 12.019^b	7.634^a 9.195^b	6.237^a 8.700^b	3.159^a 6.608^b
Experimental permeability coefficient, *Kexp(t)*, on tangential grain direction, in m^2/Pa·s	-	0.476^a 0.628^b	0.332^a 0.594^b	0.312^a 0.498^b	0.303^a 0.376^b	0.269^a 0.282^b
Experimental permeability coefficient, *Kexp(r)*, on radial grain direction, in m^2/Pa·s	-	0.323^a 0.532^b	0.151^a 0.494^b	0.170^a 0.389^b	0.205^a 0.273^b	0.092^a 0.114^b

[a] *Values corresponding to sampling at a height of 1.30 m from the ground*
[b] *Values corresponding to sampling at a height of one third of the length from the ground*
** Source: Filipovici 1964a*
☐ *Values outside the range of values of healthy wood*

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The results (Table 2) show that the moisture content of wood decreased with increasing infestation level. This trend was also observed for density of wood, permeability coefficient to water and linear wood shrinkage, except longitudinal shrinkage. For declining oak wood of grade 5, the experimental density proved to be lower than the values found in the literature. For declining oak wood of grades 5, 4 and 3, maximum tangential and radial shrinkage proved to be out of range. For damaged wood of grades 1 and 2, investigated physical properties are similar to those found in literature for healthy wood.

Mechanical properties

Sampling for MOE and MOR for static bending stresses was done from the logs which were cut at a height of 1.30m from the ground.

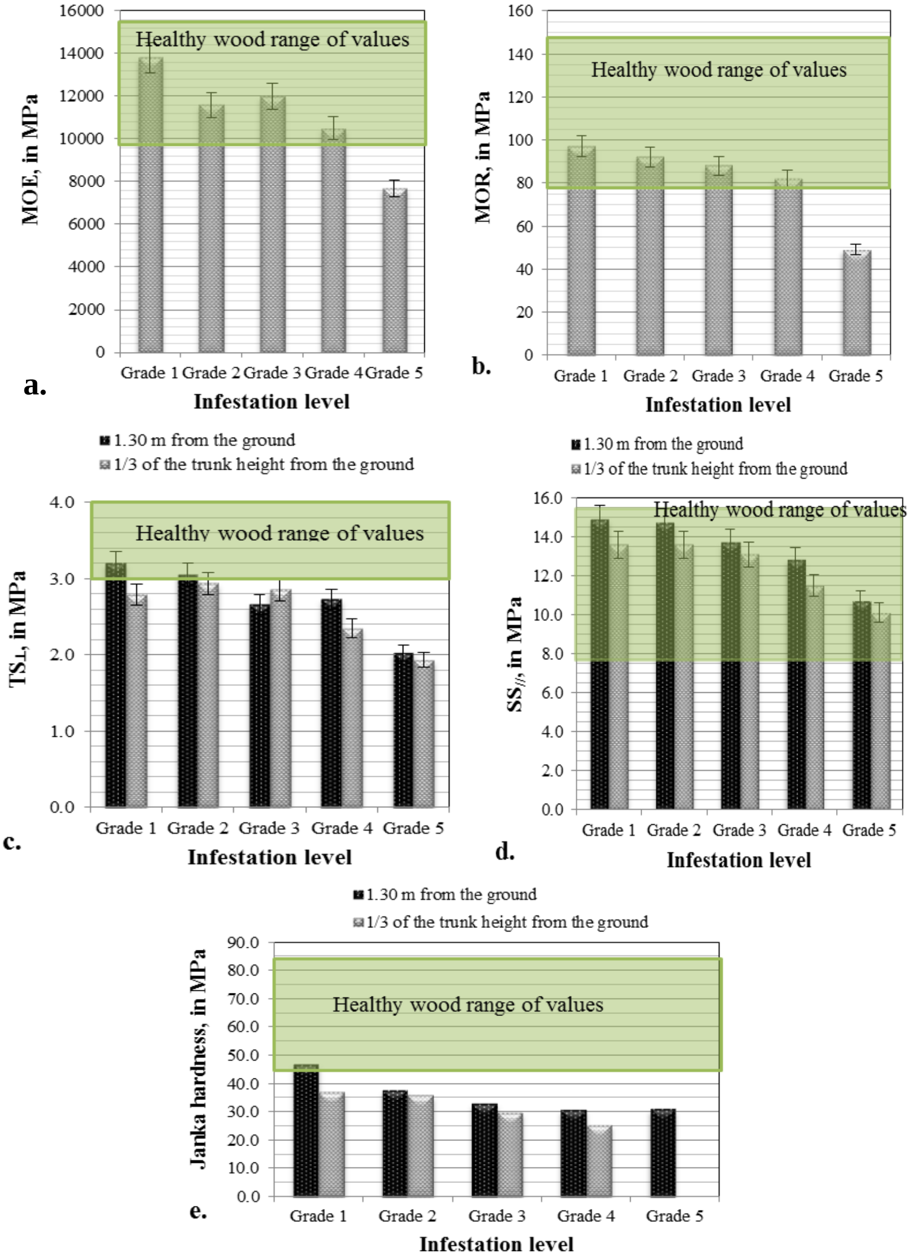

Fig. 4.
Mechanical properties of infested oak wood compared with healthy wood; a. modulus of elasticity (MOE); b. static flexural strength (MOR); c. tensile strength perpendicular to the grain direction ($TS_{\perp}$); d. Shear strength on longitudinal grain direction ($SS_{//}$); e. Janka hardness perpendicular to the grains direction.

An amount of 32 specimens (300x20x20mm) for each infestation level of declining oak wood was subjected to bending strains using the universal testing machine, according to STAS 337/1-1988 and STAS 337/2-1989. Another 24 specimens (50x20x20mm) were cut from the same logs for tensile strength (TS) testing perpendicular to the wood grains direction according to STAS 6291-89 and other 24 specimens (50x20x20mm) for the longitudinal shear strength ($SS_{//}$) determination, according to STAS 1651-1983. For Janka hardness perpendicular to the grains testing (JH), according to STAS 2417/1-1987, 24 specimens with sizes of 50x50x50mm were cut from the logs obtained at a height of 1.30 m from the ground. Mean values of the measurements were considered (Fig. 4). Mechanical properties, such as TS, $SS_{//}$ and JH were determined on radial section of the wood.

The experimental results (Fig. 4) were compared with the values found in the literature for healthy wood (Filipovici 1964a, 1964b). Wood affected by oak decline in the first grade of infestation level did not suffer damages of mechanical properties, as observed from diagrams in Fig. 4. The best values were reported for the specimens obtained from the logs cut at a height of 1.30m from the ground.

Poor quality of wood affected by oak decline at final stage (grade 5) was finally proved by mechanical test results for the determination of MOE, MOR on static stresses, tensile strength perpendicular to the grains and Janka hardness perpendicular to the grains.

Experimental results of testing declining oak compared with healthy oak have shown that the oak affected by oak decline at the incipient phase (grade 1) preserves the quality of healthy wood in terms of physical and mechanical properties. This is the reason that justifies the further analysis of declining oak wood of grades 2 to 5 against the declining oak wood of grade 1.

CONCLUSIONS

The quality and potential value of lumber sawn from oak wood stands affected by oak decline is most easily understood by examining the significant properties of damaged wood with impact on it's valorization.

As main components of wood, cellulose and lignin affect mechanical properties, shrinkage of wood, and its permeability to water. Percentage of cellulose was observed to increase tensile strength in both *P. Pinaster* and *C. Sativa* (Genet *et al*. 2005). Other researchers concluded that tensile strength perpendicular to the grains and elongation of single fibers increased with a reduction in the amount of lignin (Zhang *et al*. 2013). Our experimental research found the same trend of decreasing the tensile strength perpendicular to the grains with the increasing of lignin content. Thus, the amount of lignin for declining oak wood of grade 5 increased with 9.16% compared with that of grade 1, whilst the tensile strength perpendicular to wood grain direction for the same damaged oak wood decreased with 29% compared with infested wood of grade 1. Moisture content of declining oak wood of grade 5 at the moment of harvesting was found to be of 64.6% of the moisture content of declining oak wood of grade 1. For declining wood of grade 2, the percentage was of 92.6%, for grade 3 it was of 82.7%, and for grade 4 it was of 69.9%.

Density of damaged oak wood affected by oak decline at the final stage (grade 5) was found to be lower than normal values of healthy oak wood and it represents 86.5% of the density of declining oak wood of grade 1. In the same time, as seen in Fig. 3, the lignin content increases with the increasing of infestation level of the tree, and the moisture content decreases (Table 2). This is explained by the fact that, with the increasing of infestation level, the wood vessels are blocked and the water is not conducted efficiently to the upper part of the tree, reducing thus the growth of the tree. This phenomenon is associated in the same time with an increased deposition of lignin.

Mechanical properties, such as MOE and MOR for static stresses are significant factors in assessment of potential wood quality. As experimental results show, MOE and MOR for static stresses in case of infested oak of grade 5 are not in the range of healthy oak values, and they represents 55.8% and 50.5% respectively of the values of declining oak of grade 1. While shear strength testing results appeared within the range of healthy wood values, tensile strength perpendicular to wood grains testing brought bad results for grades 3, 4 and 5 of the infested oak wood. The tensile strength perpendicular to the grains values for grades 3 and 4 represented 85% of the value reported for grade 1, and for grade 5 it dropped to 63-69%. Better results were obtained for specimens obtained from the logs cut at a height of 1.30m from the ground, fact that gives information on the evolution of wood degradation in case of oak decline, which starts with the upper part of the stem. Bad results were also obtained for Janka hardness perpendicular to the grains testing, where all grades of damaged wood (except grade 1) recorded much reduced values: with 20% for grade 2, up to 35% for grade 5.

Comparing the experimental results obtained in the present research with previous conclusion of the research on this subject (Latham and Armstrong 1934), which asserted that the properties of the more affected oak tree were reduced by 32% compared with the healthy wood, we can enhance this assertion by the results of reduction the tensile strength perpendicular to the grains (with 31%), shear strength (with 29%) and Janka hardness perpendicular to the grains (with 35%). In addition, values for MOE and MOR for static stresses dropped for the more affected wood to 55.8% and 50.5%. Declining oak of grade 1 was considered healthy wood, according to the recorded results.

As final conclusion, except grade 5, with 100% crown defoliation, all trees affected by oak decline can be harvested for timber production and can be used for furniture or other wooden products manufacturing, except those that require increased hardness.

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STAS 337/1 -88: Lemn. Incercarea la încovoiere statică (in Romanian Language)/ Wood. Determination of static bending strength.

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