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DENSITY PROFILES OF SPRUCE WOOD CHANGED BY BROWN-ROT AND WHITE-ROT FUNGI

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ABSTRACT

In this paper the changes of density profiles of spruce samples 20x20x30 mm in individual stages of decay caused by the brown-rot fungi *Serpula lacrymans, Coniophora puteana* or *Gloeophyllum trabeum*, and by the white-rot fungus *Trametes versicolor* within the range from 4 to 24 weeks have been studied. The differences in density between the sound and the decayed wood were measured in two anatomical directions in the longitudinal-radial plane by means of the analyzer of density profiles using radioisotope ^{241}Am. The most pronounced decrease in wood density was caused by the white-rot fungus *T. versicolor*. The brown-rot fungi caused higher mass losses, however their effect on the drop of wood density was smaller because they decreased expressively the volume of decayed samples as well.

KEY WORDS: wood-destroying fungi, *Serpula lacrymans*, *Coniophora puteana, Gloeophyllum trabeum, Trametes versicolor*, spruce, density profiles, mass losses

INTRODUCTION

The great disadvantage of wood is its susceptibility to degradation by different abiotic and biotic factors. Its damage can be caused by wood-destroying fungi, insects, fire, wind, rain, and air pollution. Wood-destroying fungi are the most frequent biodegradation agents of logs, timber and wood products. Rotten wood has a lower density, worse mechanical properties and its physical properties are changed individually according to the kind of rot (brown, white or soft).

Presented article deals with the task of finding changes in the density profiles of spruce wood after its intentional degradation by the wood-destroying fungi *Serpula lacrymans, Coniophora puteana, Gloeophyllum trabeum* or *Trametes versicolor*. There are many methods for the detection or identification of the wood rot stages (Reinprecht 1996, Unger et al. 2001):

– direct methods are based on the analysis of the structural changes in wood, which occur during the degradation processes - macroscopic, microscopic and chemical analyses,

- indirect „destructive and semi-destructive“ methods are obviously based on the existence of some relations between the structure of decayed wood and its mechanical properties,
- indirect „non-destructive“ methods are still more important at the present time, especially in cases, when an objective requirement for a minimum defect on the wooden components during a test (listed buildings and objects, danger of a static erosion of a wood construction, etc.) is established; in research works and also in a practice are currently used acoustic (Arita et al. 1986, Wilcox 1988, Marčok et al. 1997), electrical (Kučera and Bucher 1988, Makovíny and Reinprecht 1990), colorimetric (Solár et al. 2006), and radiographic methods (Hlobil et al. 1997, Illman and Dowd 1997).

In the era of increasing automation and fast manufacturing process in the wood processing industries, which places great requirements on a comprehensive product quality control method, the significance of non-destructive wood testing methods in industrial applications has been increasing (Krzosek and Mańkowski 2001). Non-destructive methods are now often based on the principle of electromagnetic waves, and X-ray or radioactive radiation. We can simply say that these methods are based on the process of the radioscopy. Electromagnetic wave (radiation) radiated from the source represents the energy flow passing through substances which results in mutual interaction between the substances and radiation. Upon this principle is based CT (computer tomography) which has a wide range of applications in many different branches of wood science and practice (Habermehl and Ridder 1993, Marčok 1995, Lindberg et al. 1996, Kučerová and Lisý 1999).

Gamma-ray and X-ray tomography is obviously a very complex non-destructive method which requires expensive equipment but gives interesting data on micro-density for the analysis of the structure within rings and/or growth traits. With continuous measurement along the radius, it is possible to qualify grain and texture (Bailléres and Durand 2000). The main advantage of these techniques for wood bulk density determination is that it allows detection and quantification of heterogeneities and internal defects. At the sub-millimetric resolution level, it is possible to identify morphological and structural aspects of wood samples (Macedo et al. 2002). The X-ray microdensitometric analysis gives information about the variation of density in each annual ring of the wood specimen and it is a complementary methodological approach to the gravimetric method for determining the kinetics of wood degradation by fungi (Bucur et al. 1996). Comparison of bulk density determined by CT images with the values obtained by gravimetric methods presented a very good linear correlation coefficient /R^2 = 0.94/ (Macedo et al. 2002).

There are many research and development institutes concerned with the radioisotopic wood densitometry preferring the radioisotope ^{241}Am as a source of radiation (Divos et al. 1996, Gierlik and Dzbeński 1996, Tiitta et al. 1996, Mańkowski and Gierlik 2000).

In this experiment and also in our previous works we used the analyzer of density profiles which is based on measurement of the absorption coefficient of attenuation of the gama-radiation passing through the sample. As a source of the gamma-radiation is used radioisotope ^{241}Am with the energy of 59.5 keV. The above mentioned apparatus was constructed by the Department of Mechanical Technology of Wood in cooperation with the Department of Physics and Applied Mechanics, Faculty of Wood Sciences and Technology, Technical University in Zvolen (Bahýl 1992). Now it is used especially for measurement of the density profiles of the composite materials (Štefka et al. 1993, Štefka 1996). By using this apparatus

we also monitored the density profiles of the sound and the decayed wood. In the previous work, Novotná et al. (2004) after degradation of Norway spruce samples with a diameter of 50 mm and a thickness of 4 mm (in the longitudinal and also in the radial direction) by the fungi *Serpula lacrymans* or *Trametes versicolor* stated an apparent decrease of their density profiles in the oven dry state (e.g. Fig. 1).

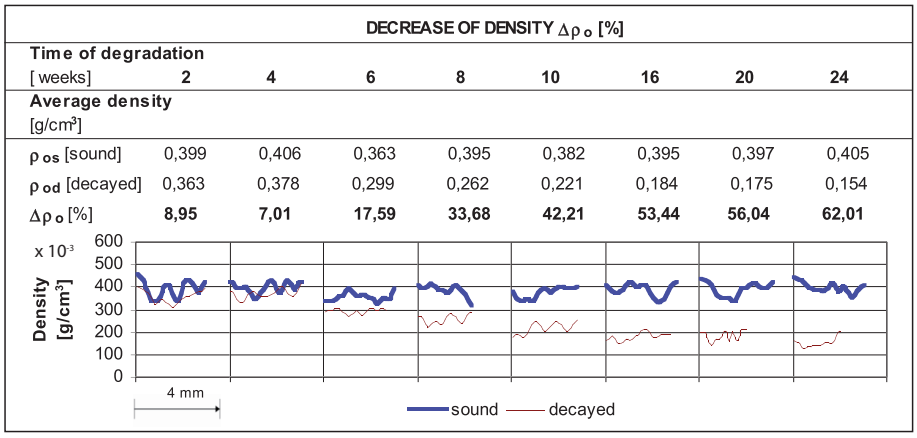


Fig. 1: Profiles of the density of spruce samples with a thickness of 4 mm in longitudinal direction (and also the average density decrease $\Delta\rho_o$) after their degradation caused by the wood-destroying fungus Trametes versicolor lasting 2, 4, 6, 8, 10, 16, 20 or 24 weeks (Novotná et al. 2004)

MATERIAL AND METHODS

Samples of the Norway spruce wood *(Picea abies (L.) H. Karst.*) with the dimensions of 20 x 20 x 30 mm (longitudinal x radial x tangential) have been manufactured from one sound log. The experiment was carried out according to the working scheme illustrated in the Figure 2.

- Measuring of the sound spruce samples by the analyzer of density profiles
- Degradation of samples by wood-destroying fungi during 4, 8, 12, 16, 20 or 24 weeks
- Calculation of the mass losses of the decayed samples
- Measuring of the decayed spruce samples by the analyzer of density profiles
- Calculation of the average density decreases of the decayed samples in the line of gamma beam

Fig. 2: Scheme of the experiment with spruce samples 20x20x30 mm (LxRxT)

Degradation of wood samples by the wood-destroying fungi

Samples of spruce wood have been attacked by the brown-rot fungi *Serpula lacrymans* (Wulfen) J. Schröt, *Coniophora puteana* (Schumach.) P. Karst., and *Gloeophyllum trabeum* (Persoon) Murrill, and by the white-rot fungus *Trametes versicolor* (L.) Pilát, from a collection of the wood-destroying fungi cultures of our mycological laboratory.

Before the degradation process the sound samples were dried at a temperature of 103 ± 2 °C, weighed in the oven dry state (m_o), conditioned to the moisture content of 8 %, and then the density profile was measured. After that the samples were dipped in the distilled water for 15 minutes and placed into 1 l Kolle's flasks with mycelium of the chosen wood-destroying fungus expanded on the malt agar soil. During all those processes the sterile conditions were kept. The degradation period in individual series of samples was 4, 8, 12, 16, 20 or 24 weeks.

After the elapse of the exact time of degradation the samples were taken out of the Kolle's flasks and cleaned from the fungi mycelia. Then the samples were subjected to a two-phase drying to reach the oven dry state (m_{od}). The first phase – air seasoning was carried out under milder conditions when t = 20–25 °C, φ = 60–70%, τ = 100 h. The second phase – kiln seasoning was performed in three steps when t_1 = 60 °C, τ_1 = 1 h; t_2 = 80 °C, τ_2 = 1 h; t_3 = 103 ± 2 °C, τ_3 = 4 h. The aim was to avoid or minimize formation of cracks and deformations and to prevent the wood-destroying fungi from their further activity. The mass losses (Δm) of decayed samples caused by the selected wood-destroying fungi (Fig. 4a) were determined by the relation:

$$\Delta m = [(m_o - m_{od})/m_o] .100 \ [\%]$$

Testing of the wood samples by the analyzer of density profiles

The density profiles have been tested for spruce samples at a moisture content of w ≅ approximately 8 %, both in the longitudinal "L" direction and in the radial "R" direction (i.e. in the longitudinal-radial plane – Fig. 3b), prior to bio-degradation of samples (sound state - $\rho_{w(L)}$, $\rho_{w(R)}$) and also after their degradation with fungi (decayed state - $\rho_{wd(L)}$, $\rho_{wd(R)}$). The percentage changes of the average density of decayed spruce samples in the line of gamma beam ($\Delta\rho_{w(L)}$, $\Delta\rho_{w(R)}$) were calculated as well (Fig. 6 and 7), together with their arithmetic mean value -$\Delta\rho_w$ (Fig. 4b):

$$\Delta\rho_{w(L)} = [(\rho_{w(L)} - \rho_{wd(L)})/\rho_{w(L)}] .100 \ [\%]$$
$$\Delta\rho_{w(R)} = [(\rho_{w(R)} - \rho_{wd(R)})/\rho_{w(R)}] .100 \ [\%]$$
$$\Delta\rho_w = (\Delta\rho_{w(L)} + \Delta\rho_{w(R)}) / 2 \ [\%]$$

Block diagram of the density profile analyzer is given in the Figure 3. The sound samples, and subsequently the same ones subjected to decay, were inserted into the apparatus in the same position which was secured by small cuts on their edges. A series of six samples was placed into the apparatus at once, so the result of the measurement was the diagram with the density profiles of all the six samples (Fig. 6 and 7).

The analyzer of density profiles has made use of the connection between the density of wooden material and an attenuation of the narrow beam of the low-energy gamma radiance passing through the material. Each series of the six spruce samples was put into the moving electrical car of the apparatus (Fig.3a). The moving electrical car was set in the initial position and the cover of the emitter was removed. The source of the radiation was the emitter on the basis of radioisotope ^{241}Am with the energy of 59.5 keV and the power of 5.0 GBq. The beam of the gamma-rays was passing through each sample in one plane of the transition by two slots sized

0.3 x 10 mm in the lead shading plates. The samples were shifted by the stepping electromotor in front of the slot, at which the shift of the samples was after each 0.2 mm. The analyzer of density profiles scanned the density of the respective sample in that plane (Fig 3b). The intensity of the radiation after crossing the slots was evaluated by the NaJ (TI) detector which was attached to the single-channel spectral analyzer made by the firm STADOS Prague. Measurements of the density profiles for each sample were carried out in the same "longitudinal-radial" plane (sound samples = 20 x 20 mm, decayed samples → changed dimensions) located in their centre (sound samples = 15 mm from the surface in the tangential direction) – (Fig. 3b).

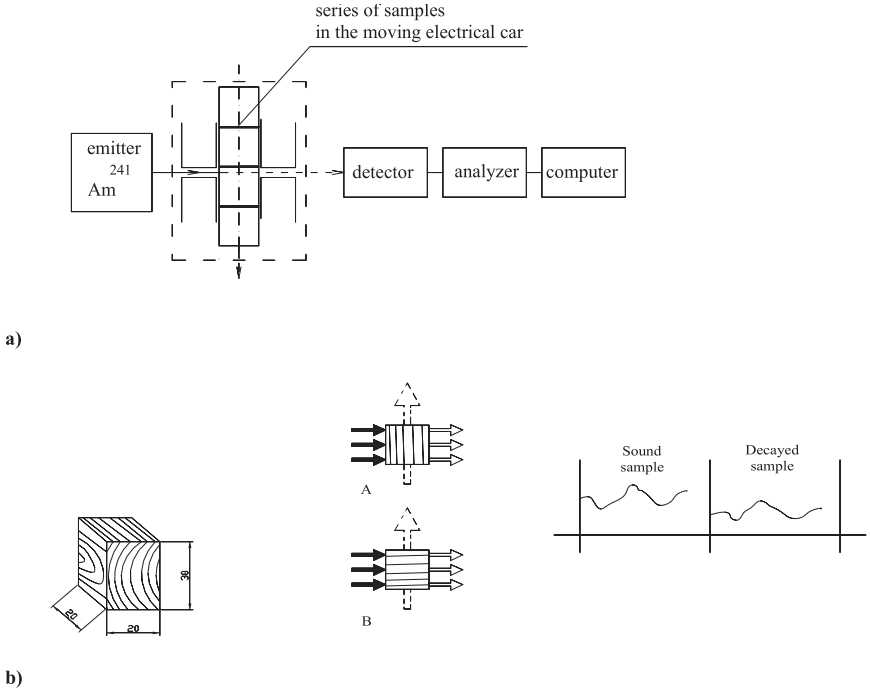


Fig. 3: Block diagram of the analyzer of density profiles (a), and scanning positions of the wood sample 20x20x30 mm (LxRxT) in the apparatus "A = gamma beam in the radial direction" or "B = gamma beam in the longitudinal direction" with final recordings of the density profile of sound and decayed sample in the "longitudinal-radial" plane (b)

Note:
A – the line of gamma beam oriented in the radial direction and the specimen movement in the longitudinal direction, i.e. the densities of early and late wood were accumulated, and due to this fact they could not be separately identified (Fig. 7).
B – the line of gamma beam oriented in the longitudinal direction and the specimen movement in the radial direction, i.e. the different densities of early and late wood could be well identified (Fig. 6).

RESULTS AND DISCUSSION

The mass losses (Δm) and the arithmetic mean density decreases determined in the longitudinal-radial plane of the decayed spruce samples ($\Delta\rho_w$) are presented in the Figure 4. At brown-rot the mass losses of spruce wood were higher than the density decreases. On the other hand, the white rot fungus *Trametes versicolor* caused similar mass losses and density decreases. Shape changes of decayed samples are presented in the Fig. 5.

- *S. lacrymans*, *C. puteana* and *G. trabeum* – decreased volume of the samples markedly, reduced their size and deformed their shape, mainly since the 8th or 16th week of their degradation.
- *T. versicolor* – did not change or only slightly increased the volume of the samples up to the 24th week of their degradation.

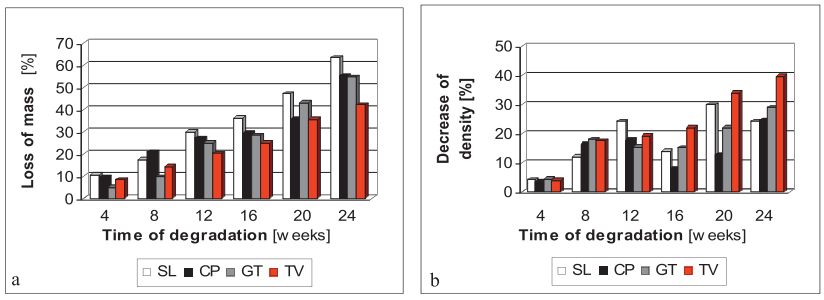


Fig. 4: The mass losses (Δm) and the density decreases in the longitudinal-radial plane ($\Delta\rho_w$) of spruce samples during their degradation by the wood-destroying fungi S. lacrymans (SL), C. puteana (CP), G. trabeum (GT) or T. versicolor (TV) in the time periods from 4 to 24 weeks

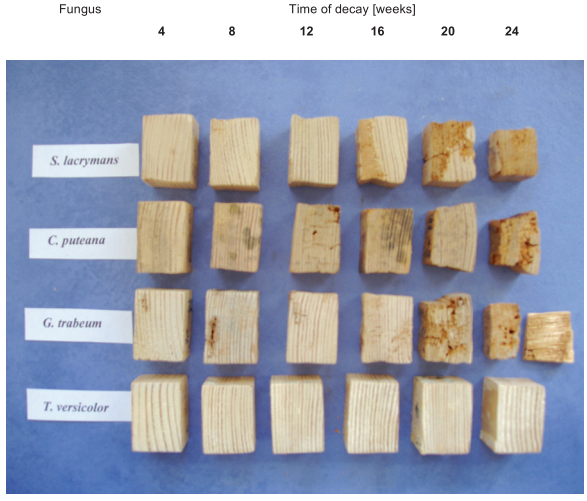
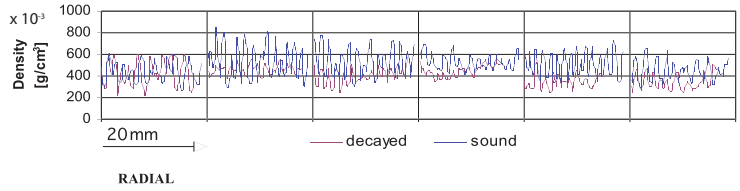


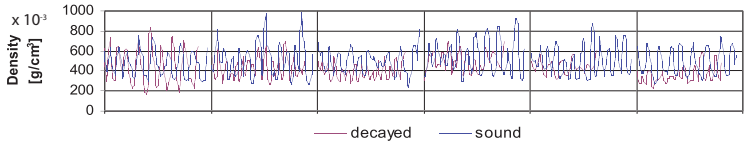
Fig. 5: Shape changes of spruce samples after rot-processes caused by the wood-destroying fungi S. lacrymans, C. puteana, G. trabeum or T. versicolor in the time periods from 4 to 24 weeks
Note: At brown rot, the wood was more obviously damaged under a thin surface layer (radial-tangential plane), e.g. due to S. lacrymans acting for 16 and 20 weeks.

DENSITY PROFILES OF SPRUCE WOOD – "GAMMA BEAM IN LONGITUDINAL DIRECTION (L)"

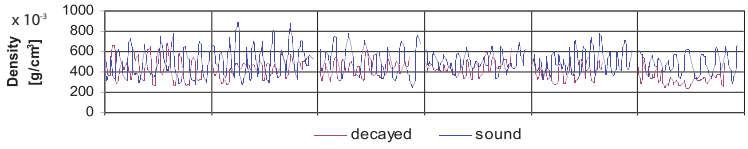
Time of decay [weeks]	4	8	12	16	20	24
Serpula lacrymans						
Average density in the line of gamma beam [g/cm^3]						
$\rho_{w\,(L)}$ [sound]	0.436	0.537	0.526	0.529	0.502	0.445
$\rho_{wd\,(L)}$ [decayed]	0.428	0.466	0.401	0.450	0.346	0.345
Decrease of density [%]						
$\Delta\rho_{w\,(L)}$	**1.83**	**13.22**	**23.76**	**14.93**	**31.08**	**22.47**



Coniophora puteana						
Average density in the line of gamma beam [g/cm^3]						
$\rho_{w\,(L)}$ [sound]]	0.469	0.514	0.491	0.552	0.496	0.488
$\rho_{wd\,(L)}$ [decayed]	0.446	0.435	0.401	0.493	0.442	0.360
Decrease of density [%]						
$\Delta\rho_{w\,(L)}$	**4.90**	**15.18**	**18.33**	**10.69**	**10.89**	**26.23**



Gloeophyllum trabeum						
Average density in the line of gamma beam [g/cm^3]						
$\rho_{w\,(L)}$ [sound]	0.462	0.530	0.509	0.501	0.508	0.479
$\rho_{wd\,(L)}$ [decayed]	0.444	0.436	0.434	0.443	0.400	0.338
Decrease of density [%]						
$\Delta\rho_{w\,(L)}$	**3.90**	**17.74**	**14.73**	**11.58**	**21.26**	**29.44**



Trametes versicolor						
Average density in the line of gamma beam [g/cm^3]						
$\rho_{w\,(L)}$ [sound]	0.465	0.512	0.503	0.507	0.497	0.472
$\rho_{wd\,(L)}$ [decayed]	0.439	0.417	0.409	0.390	0.331	0.282
Decrease of density [%]						
$\Delta\rho_{w\,(L)}$	**5.59**	**18.55**	**18.69**	**23.08**	**33.40**	**40.25**

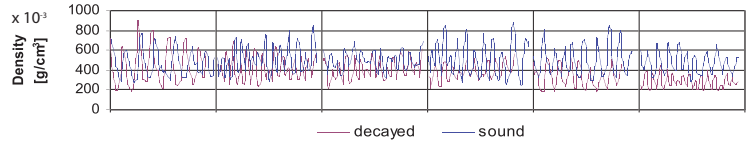


Fig. 6: Profiles of the density of spruce samples before and after degradation by the wood-destroying fungi S. lacrymans, C. puteana, G. trabeum, or T. versicolor which lasted 4, 8, 12, 16, 20 or 24 weeks, if the gamma beam was oriented in the longitudinal direction (Fig. 3b)

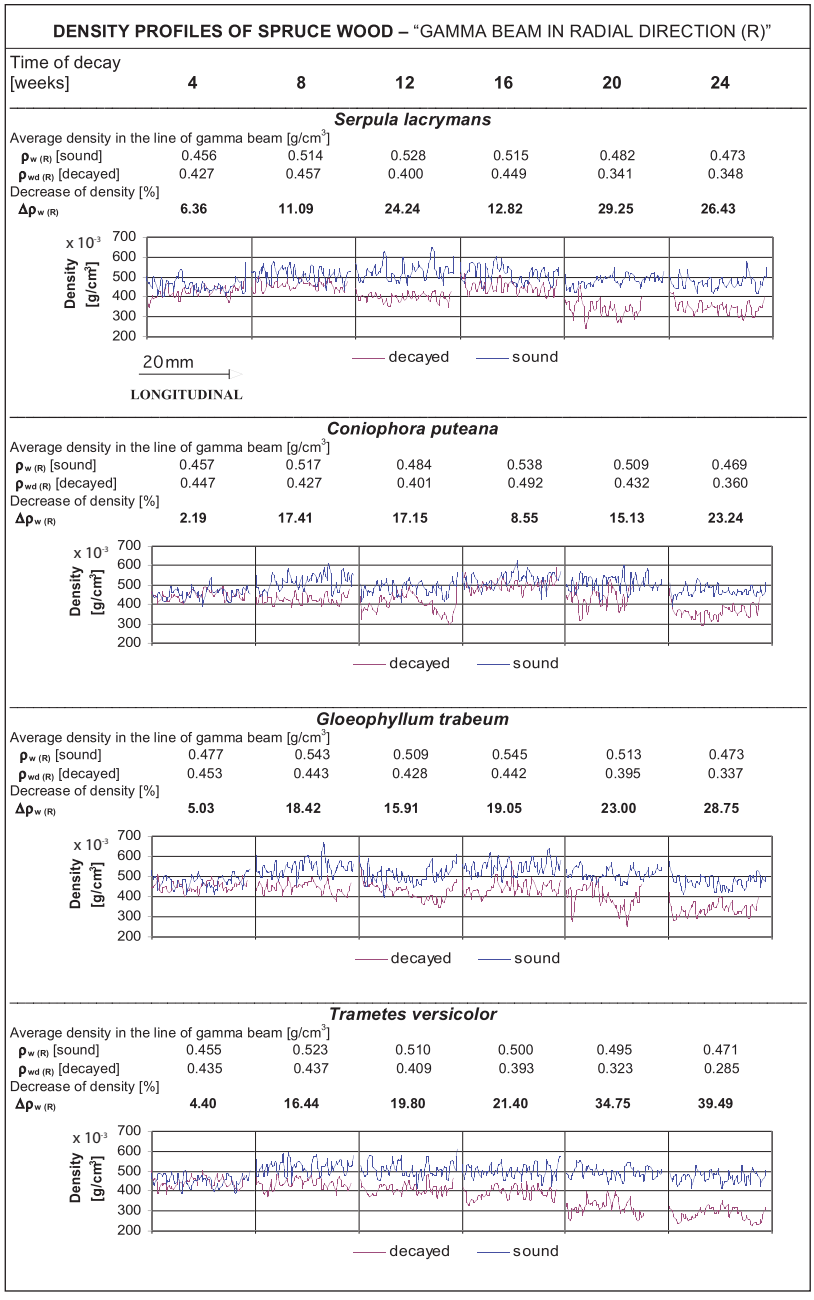


Fig. 7: Profiles of the density of spruce samples before and after degradation by the wood-destroying fungi S. lacrymans, C. puteana, G. trabeum, or T. versicolor which lasted 4, 8, 12, 16, 20 or 24 weeks, if the gamma beam was oriented in the radial direction (Fig. 3b)

Changes in the density profiles of the decayed samples in relation to the sound ones are recorded in the Figures 6 and 7. In these figures are also presented the average densities of the sound ($\rho_{w(L)}$, $\rho_{w(R)}$) and the decayed ($\rho_{wd(L)}$, $\rho_{wd(R)}$) samples measured by the gamma-radiation method at a moisture content of $w \cong 8$ %, together with their percentage changes – decreases ($\Delta\rho_{w(L)}$, $\Delta\rho_{w(R)}$). The average density values were determined from the records of the density profiles for individual sound and decayed samples by using the planimetric method (Fig. 6 and 7 – see numerical data).

From the resultant profiles of density across the spruce samples having a thickness of 20 mm in the radial direction and also in the longitudinal direction (Fig. 3) are obvious differences in their densities between:

- *earlywood and latewood*, mainly if the gamma-beam was directed in the longitudinal direction (i.e., if the samples in the moving car of apparatus have been moved in the radial direction – Fig. 6),
- *individual stages of rot "weeks of decay"*, at both methods of experiment – Fig. 6 and 7 (more illustratively if the gamma-beam was directed in the radial direction – i.e., if the samples in the moving car of apparatus have been moved in the longitudinal direction – Fig. 7).

The changes in density between the sound and the decayed wood were more noticeable due to the effect of the white-rot fungus *T. versicolor* than that of the brown-rot fungi *S. lacrymans*, *C. puteana* and *G. trabeum* (Fig. 6 and 7).

The achieved results demonstrated that identification of the degree of the brown-rot by measurement of the density profiles is less sensitive in comparison with its determination by the mass losses. For example, the mass losses of spruce samples continually increased with the time of decay (Fig. 4a), however their percentage decreases of density in the longitudinal-radial plane measured in the line of gamma-beam ($\Delta\rho_{w(L)}$, $\Delta\rho_{w(R)} \rightarrow \Delta\rho_{w}$) changed heterogenously and were sometimes more apparent at shorter times of decay (Fig. 4b, 6 and 7). This result can be explained by unexpected deformations of decayed samples connected also with local unanticipated changes of their volume – e.g. in the measured longitudinal-radial plane (Fig. 5).

Theoretically, the average densities of spruce samples in the longitudinal-radial plane should be identical for the both measurements in the longitudinal and radial directions:

$$\rho_{w(L)} = \rho_{w(R)}$$
$$\rho_{wd(L)} = \rho_{wd(R)}$$

However, smaller or higher differences were achieved in the experiments, i.e., if the individual values in the Fig. 6 and 7 are compared – e.g. for decayed samples deteriorated 24 weeks:

Serpula lacrymans	$\rho_{wd(L)}$	$= 0.345 \neq \rho_{wd(R)}$	$= 0.348$
Coniophora puteana	$\rho_{wd(L)}$	$= 0.360 = \rho_{wd(R)}$	$= 0.360$
Gloeophyllum trabeum	$\rho_{wd(L)}$	$= 0.338 \neq \rho_{wd(R)}$	$= 0.337$
Trametes versicolor	$\rho_{wd(L)}$	$= 0.282 \neq \rho_{wd(R)}$	$= 0.285$

This result can be explained by some mistakes during the measurement of samples and also at the planimetric evaluation of individual density profiles.

By means of the graphically recorded density profiles of tested wood can be studied in detail the development of the changes in its density between the sound and degraded state, e.g., if the

decrease of density after decay process is higher on the surface or inside of wood, or if the density drops more in the early wood or in the late wood.

The results of our study confirmed that it seems to be suitable to use the narrow-beam gamma absorption method or fine X-ray densitometric analysis for determining the density of wood in local degradations caused by individual wood-destroying fungi. Bucur et al. (1996) and Tiitta et al. (1996) in their studies used similar X-ray densitometric analyses for detection of the differences between degradation kinetics of some types of wood products with specific wood-destroying fungi.

CONCLUSIONS

The developed equipment based on the narrow-beam gamma absorption method is easy to use and comparatively good results can be achieved in detecting density changes in wood samples after biodegradation process. The gamma-ray densitometric analysis provides a non-destructive answer to the problems related to the nature and kinetics of wood degradation. By using the achieved experimental measurement results it is possible to determine and compare the brown-rot and white-rot in wood species in the individual stages of their degradation.

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