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Measurements of wood density using X-ray computer tomography

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Abstract: The use of computer tomography enables non-invasive (non-destructive) determination of internal defects in wood. Studies aimed at determining the dependence between wood density and CT number were undertaken to identify the state of preservation of the internal parts of wooden objects without the need to interfere with their structure. Measurement of CT number allows quantitative determination of the degree of wood destruction by fungi and insects. An X-ray computer tomograph was used to measure the CT number for pine wood with varying density and based on the results, curves were plotted for dependence between CT number and wood density. The graph and equation describing the above dependency currently enable determining the local density of wood inside various objects, based on CT number. This method is particularly useful in the study of historic objects.

Keywords: computer tomography, CT number, wood, wood density,

INTRODUCTION

The density of wood determines many of its attributes and properties. In cases in which wood tissue is degraded by fungi or damaged as the result of the action of xylophagous insects it can be an indicator regarding the degree of destruction or preservation. For practical reasons, in the lumber or construction industries, as well in the preservation of historic objects various devices are used that allow to measure the density of wood or at least compare areas with higher or lower density and thus determine internal defects or degraded areas, that is those with lower durability. Usually methods involving indirect measurements are used, such as determining resilience based on the propagation of mechanical, acoustic or ultrasound waves in wood or measuring the frequency of transverse vibrations (Schad et al. 1996, Ross et al. 1997, Emerson et al. 1998, Wang et al. 2004). Direct density measurements are also made, using various types of densitometers that involve X or γ radiation. In most cases scans give a two-dimensional image that only approximately show the areas with lower density. A technique that is expensive but free from such limitations is computer tomography, which has already found practical use in the wood industry, e.g. in sawmills and plants producing particleboards or plywood. Besides the three-dimensional image of the interior of the studied object, which allows the localization of internal defects, it also enables measuring the CT number at any given point and consequent determination of the local density of wood.

So far, computer tomography has been used to reveal internal defects in wood, such as foci of degradation by fungi and insect-feeding (Schad et al. 1996, Schmoldt et al. 1997, Krajewski et al., 2005). The current study was aimed at determining the dependence between the CT number of wood and its density. The objective was to examine the usefulness of computer tomography for determining the density of wood. This could in further perspective allow the plotting of standard curves, enabling readings of local, internal densities of wood tissue in the examined objects and subsequent diagnosis of areas decomposed by fungi and attacked by insects. This would also make it possible to detect internal degradation foci and evaluate the state of preservation for recommendations for conservation or restoration activities.

The use of tomography studies to determine CT number – relative attenuation coefficient for radiation in wood

X-ray computer tomography is a costly but rapid method that allows analyzing the internal structure of wood and detecting its faults. It is non-destructive and non-invasive. A three-dimensional image of the interior of heterogeneous materials is formed as a result of the irradiation of the studied objects with ionizing radiation. The image is reconstructed based on calculations of attenuation coefficient of ionizing radiation (X-rays or γ radiation) passing through the layer of the examined object. In the most frequently used computer tomography this is visible on a tomogram in the form of an image of the transverse section made in any given plane of the studied object. A complete image is obtained when the object is moved parallel to its axis and the individual sections (scans) are combined. The obtained image allows studying the internal defects of the material. The individual layers reflect differences between areas with various radiation attenuating properties.

Attenuation of radiation passing through the object is the outcome of its absorption and scattering in the object. As the beam passes through the object each detector measures the value of relative linear attenuation coefficient. The linear measurements are used to calculate the relative linear attenuation coefficient for any given point (pixel) and to compare the attenuation of the beam passing through the examined material with given thickness to its attenuation when passing through water. The attenuation coefficient depends on the density of the studied material and its specific attenuation coefficient. The experimentally determined attenuation coefficient depends on the energy of the radiation source, moisture content of wood and the species of wood and ranges from about 0.1858 cm^2/g for air dried to 0.1797 cm^2/g for absolutely dry wood (Moschler and Douglas 1988, Malan and Marais 1992).

In the case of medical tomographs, with typical photon energy 73 keV, the relative linear attenuation coefficient for X-rays in the studied material compared to the attenuation coefficient in water, is called the CT number and is expressed in Hounsfield units [H].

$$\text{CT number} = (\mu s - \mu w)/ \mu w * 1000$$

μ_s – coefficient of relative attenuation of radiation in the studied material

μ_w – coefficient of relative attenuation of radiation in water

In medical computer tomography studies the CT number is in the range -1000 H for air, 0 H for water and +1000 for human bones.

In heterogeneous materials, such as wood, the attenuation coefficient depends on both the energy of the ionizing radiation and the chemical structure of the material. The obtained electronic record enables precise reading of differences in the density of material, which are particularly clear in the case of components with high atomic number. In view of the high dose of radiation energy and low atomic number of the components of wood, the phenomenon of radiation attenuation is in the main proportional to thickness of the material itself. Assuming that the density of wood matter in wood with moisture content 0% is 1500 kg/m^3, the differences in thickness observed in a tomogram reflect the presence of elements of anatomic structure as well as the presence of water in the walls and lumen of the cells.

Measurement of radiation attenuation allows calculating the attenuation coefficient (CT number) for local values of the density of the studied material and reconstructing its internal image. Tomograms are formed as a result of calculations of local CT number and are reconstructions arising from data obtained for superimposed consecutive measurements at different angles. The attenuation coefficient (CT number) calculated for each pixel is reflected on a gray or color scale and depicted as an image of the transverse section of the studied object. Each area with the same density is evaluated statistically and reflected by the same color or the same level of gray. This affords the possibility of quantitatively determining differences between the density of individual areas of wood, observation of internal defects and heterogeneity, differences in moisture content and its distribution in the element. The resolution of the image depends on beam width and the distances between rays in the beam.

A decrease in cellulose content and increased participation of lignin in the wood, resulting from differences in the chemical composition of wood, its anatomic composition or degradation, may also bring about a lowering of the attenuation coefficient. This is caused by differences in its value for the individual main chemical components of wood. According to Lindgren (1991) the attenuation coefficient for cellulose is 0.2634, for hemicellulose 0.2655 and for lignin 0.2608.

Determination of CT number for wood

Tomography studies aimed at measuring CT number depending on known wood density were carried out using a 4th generation General Electrics medical computer X-ray tube with focus size 07 x 04 mm, voltage 140 kV and current 200 mA, and a 685 channel detector. The studies embraced healthy wood of the Scots pine (*Pinus sylvestris* L) with moisture content 6%. Approximately 140 samples of wood with density in the 380 kg/m^3 to 580 kg/m^3 range were examined.

Every sample consisted of 5 scans, each 10 mm thick. The tomograms were used to read the CT number for a whole single scan, which ranged from -580H to -385H. The results were used to calculate the dependence between the CT number of healthy wood and its density at moisture content of the wood 6%. A clear-cut dependence between CT number and density of wood ρ_6 (at 6% moisture content; Fig. 1) described by rectilinear regression equation, was obtained:

$$\text{CT number} = 1.0118\rho_6 - 1018$$

at determination coefficient $R^2 = 0.95$.

or dependence between density and CT number, described by the equation:

$$\rho_6 = 0.9883CT + 1006$$

On this basis a curve for the dependence between CT number and wood density was plotted, which in further practice may enable reading the local moisture content of wood based on CT number measurement. It seems that the results obtained for wood with moisture content 6% may be more useful for practical purposes that those obtained in Lindgren's studies (1991), who arrived at the dependence between the density of absolutely dry wood and CT number described by the equation:

$$\rho_0 = 1.052CT + 1053$$

and for fresh cut wood, without prior determination of its moisture content, by the equation:

$$\rho_u = 0.993CT + 1015$$

in the latter case the precise measurement is not given since the moisture content of fresh cut wood can fluctuate within a broad range.

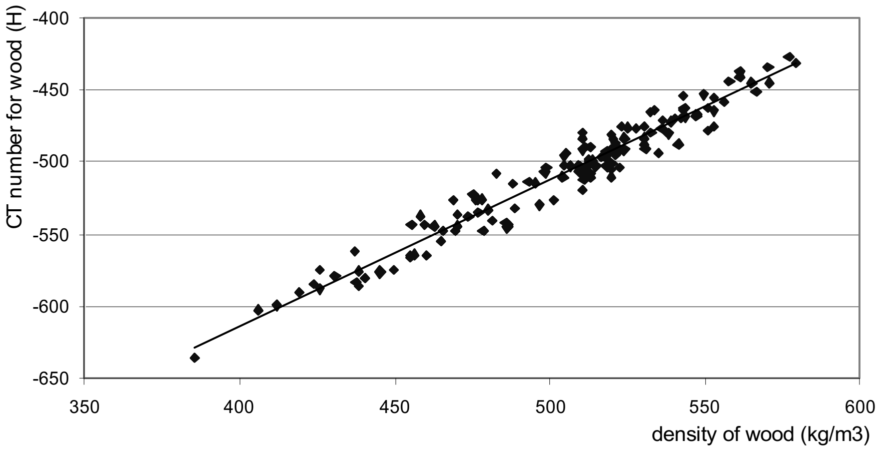

Fig. 1 Dependence between CT number and density of pine wood

CONCLUSIONS

The results obtained by us allow drawing the following conclusions:

Determination of the density of healthy wood based on determination of CT number measured by X-ray computer tomography holds significant promise for evaluating the degree of preservation of internal areas of wood in studied objects, especially in historical monuments.

As a result of determining the dependence between CT number and density of wood it is possible to measure the density of this material under humidity conditions inside closed quarters, especially in museums.

As much as 94% of CT number variation for wood is attributed to its density.

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Streszczenie: *Pomiar gęstości drewna metodą rentgenowskiej tomografii komputerowej.* Zastosowanie tomografii komputerowej umożliwia w sposób nieinwazyjny (nieniszczący) określanie wewnętrznych wad drewna. Badania wyznaczenia zależności gęstości drewna od liczby CT podjęto w celu oznaczania stanu zachowania wewnętrznych partii obiektów drewnianych bez konieczności naruszania ich struktury. Pomiar liczby CT pozwala w sposób ilościowy oznaczać stopień zniszczenia drewna przez grzyby i wady. Na rentgenowskim tomografie komputerowym dokonano pomiaru liczby CT drewna sosnowego o różnej gęstości. Na tej podstawie wyznaczono krzywe zależności liczby CT od gęstości drewna. Wykres i wzór opisujący powyższą zależność umożliwia obecnie wyznaczanie lokalnej gęstości drewna wewnątrz obiektów na podstawie pomiaru liczby CT. Szczególne zastosowanie powyższej metody ma miejsce podczas badań obiektów zabytkowych.

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