Measuring Radial Variation in Basic Density of Pendulate Oak: Comparing Increment Core Samples with the IML Power Drill

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Abstract: To determine the appropriate final use of wood from a particular tree species, it is first necessary to know its properties. Methods that use wood samples taken directly from the trunk of a growing or felled tree are very time-consuming and require a great deal of manual work. Non-destructive methods may be more effective and much faster, thanks to the use of advanced technologies. The resistance drilling can be used to determine the variation in wood density along the radius of the stem. The main aim of the present study was to determine the basic density of the wood on a cross-section of the trunk of oak trees and to investigate the correlation of the results with those obtained by drilling the same trees with the IML RESI-PD 400. The results of Spearman’s correlation test showed strong positive correlations between all examined properties. We observed a trend whereby the density of the wood and Resi amplitude increased in direct proportion to the width of the annual rings. The results of linear regression show a strong relationship between examined properties. This study provide evidence that the Resi is an appropriate tool for non-destructive determination of wood density.

Keywords: wood properties; drilling resistance; IML RESI-PD; micro-resistance drilling; Quercus robur; annual ring; resistograph amplitude; Resi

1. Introduction

The proper management of forest resources can contribute to sustainable forest management. To determine the appropriate final use of wood from a particular tree species, it is first necessary to know its properties. The most important determinants of wood quality are the physical properties of the wood [1,2]. The density of wood is considered to be the most important indicator determining its mechanical and other physical properties, regardless of tree species or wood type. Several methods are used to determine this property. In general, we distinguish between destructive methods, which interfere with the trunk structure, and non-destructive methods [3].

Methods that use wood samples taken directly from the trunk of a growing or felled tree include the displacement method and the volumetric method [4]. In this case, a Pressler drill is usually used to collect wood samples. These methods are very time-consuming and require a great deal of manual work, including weighing, drying and measuring the samples.

Non-destructive methods may be more effective and much faster, thanks to the use of advanced technologies. Various devices can be used to perform analysis by non-destructive methods, including X-ray devices [5–7], the Pilodyn instrument [8–11] and the resistance drill (RD) [12–17]. Non-destructive methods allow the mechanical and physical properties of the wood to be determined without causing permanent damage that might affect the end-use of the material tested [18,19].

The resistance drill was developed in 1984 by German engineers. Initially, measurements made with this device often gave erroneous results; this was because the drilling
technology was not adapted to the heterogeneous structure of wood [20]. After refining the device, in 1990 the company Rinntech patented a device under the name "Resistograph®" (Rinntech, Heidelberg, Germany; www.rinntech.com, accessed on 1 March 2022). This tool measured the resistance of the drilled material based on the energy input when drilling at a constant speed [20,21]. Since then, the RD has been used as a tool to diagnose the health of the woody tissue of a single tree. The device is drilled into a cross-section of a tree at any height, using a thin needle (drill) that is a few millimetres in diameter. However, resistance drill’s results depend on many variables such as moisture content [22,23], air temperature as well as drill bit flexion, speed, friction and RPM [24–26], angle of drilling [27] and species [26,28,29]. It is important to eliminate or at least limit the variability generated by these factors before and during Resi measurements.

Moisture content is strongly correlated with wood density. The volume of dry wood (oven-dried) regulates the quantity of water wood cells can absorb [30,31]. When it comes to drilling resistance most authors reported minor effect of moisture content on RD results (e.g., [32]); however, Sharapov et al. [23,26] noticed that the effect of MC on RD, depends on RPM and feed rate (FR). The feed speed and RPM of the drill can be adjusted to the diameter of the tree and the tree species being examined [33]. This device allows a quick and accurate check for wood defects (e.g., decay) on the cross-section of the trunk, which can cause weakening of the tree tissue [32,34]. In addition, the resistance drill can be used to determine the variation in wood density along the radius of the stem [9,11,28,35]. A major advantage of using an RD is that it allows measurements to be made without additional preparation of the tree—such as stripping of the bark, as is necessary when the Pilodyn is used—and it is possible to make measurements from the bark surface to the core of the tree or even across the entire cross-section of the trunk [3]. To date, resistance drilling testing has mainly been used for urban tree diagnostics—for decay detection and as a complement to comprehensive tree condition assessments [34,36]—and less frequently for determining wood density for scientific or industrial purposes [15–17,27,37].

The aim of this study was to determine the basic density (BD) of wood on a cross-section of the trunk of living oak trees, and to investigate the correlation of the results with those obtained by drilling the same trees with the IML RESI-PD 400.

2. Materials and Methods

2.1. Site Description and Trees Selection

The study was carried out in November 2021. Trees analyzed in this study were located on a forest plot, situated in the western part of Poland (51°51’13.631” N; 16°26’8.844” E), which is in the central part of the European range of pedunculate oak (Quercus robur L.). Selected trees were of similar age, estimated to be between 90 and 110 years. The research plot was located in an area of mixed forest habitat type. The height and diameter at breast height were measured for all trees in the sample plot classified as pedunculate oak. Then, nine trees were selected from the set of all measured trees (Table 1). The trees were characterized by regular crown build and did not have any visible symptoms of pathogens or wood defects affecting the health of the xylem.

| Number of Tree | Height (m) | Mean Diameter (cm) |
|---------------|------------|--------------------|
| 1             | 27.0       | 52.5               |
| 2             | 29.0       | 51.0               |
| 3             | 27.5       | 65.0               |
| 4             | 24.0       | 54.5               |
| 5             | 23.5       | 56.0               |
| 6             | 30.0       | 72.5               |
| 7             | 27.5       | 56.5               |
| 8             | 32.0       | 58.0               |
| 9             | 24.0       | 54.5               |
| Mean          | 27.2       | 58.0               |

Table 1. Characteristics of selected trees.
2.2. Estimating Basic Density by Dimensional Method

From each selected tree, an increment core was drilled at breast height in the N–S direction from the bark to the pith, using a Pressler drill. Each collected increment core was divided into sections, each containing 10 annual rings. In total, 87 samples were labelled. Immediately after the division, each sample was weighed to an accuracy of 0.001 g using a Steinberg laboratory scale (Steinberg Systems SBS-LW-200A, Berlin, Germany). After weighing, the length of each sample was measured to an accuracy of 0.01 mm using a certified Vogel calliper (Vogel Germany GmbH & Co. KG, Kevelaer, Germany). The diameter of each sample was determined to be 5.15 mm, according to the information supplied by the drill manufacturer. In accordance with the dimensional methodology described by Pérez-Harguindeguy et al. [4], the volume of each sample was calculated by Equation (1):

\[ V = \pi \times (0.5D)^2 \times L \] (cm³) (1)

where \( V \) is volume, \( D \) is the diameter of the sample (5.15 mm), and \( L \) is the length of the sample.

Based on the length of each sample, the average annual ring width where wider rings have a higher percent latewood (ARW) was calculated using Equation (2):

\[ \text{ARW} = \frac{L}{\text{AR}} \] (2)

where \( L \) is the length of the sample and \( \text{AR} \) is the number of annual rings in the sample.

In the next stage of the study, samples were transported to a laboratory, where they were dried for 24 h at 105 °C in a laboratory dryer. After reaching 0% water content and constant mass, the samples were placed in a desiccator until cooled. Next, each sample was weighed and measured by the same procedure that had been used for samples in fresh condition. The basic density was calculated using Equation (3):

\[ \text{BD} = \frac{m_s}{v_m} \] (g/cm³) (3)

where \( m_s \) is the mass of an oven-dried sample, and \( v_m \) is the volume of the fresh sample.

The moisture content was calculated using Equation (4):

\[ \text{MC} = \frac{(m_w - m_s)}{m_w} \times 100 \] (%) (4)

where \( m_w \) is mass of fresh sample.

2.3. Estimating Wood Resistance by IML RESI PD400

Immediately following the collection of each increment core, a resistance drilling test was performed. In our study, we used the IML RESI PowerDrill 400. Using a 400 mm drill with a drilling speed of 50 cm/min and 1500 RPM, the resistance in the north–south (N–S) direction was measured directly under the hole made by drilling using a Pressler drill at breast height (Figure 1). The feed and drill speed can be adjusted to from 15 to 200 cm/min and from 1500 rpm to 5000 rpm. Each drilling location was free of visible defects in the wood, such as knots or cracks. The main variable investigated using the resistance drilling was Resi amplitude (RA%), which quantifies the resistance that the wood presents to a drill bit moving at a specified constant speed, examined at 0.1 mm increments from 0 to 100%. The \( \text{RA}_{\text{max}} \) and \( \text{RA}_{\text{min}} \) data were then extracted using dedicated software. The software used to analyse the Resi data was PD-Tools PRO. The data were then exported to a text file and prepared in Microsoft Excel for statistical analysis.
2.4. Comparing Data from Resi and Basic Density of Each Sample

Based on the length (mm), an appropriate number of Resi measurements were fitted to each sampled wood. The results of the Resi tests represented the values $R_{A\text{max}}$ (for late wood) and $R_{A\text{min}}$ (for early wood). From these two values and the number of measurements within one sample, $R_{A\text{mean}}$ was calculated for each sample. For further statistical analyses, the $R_{A\text{mean}}$ value of each sample was used.

2.5. Statistical Analysis

To verify the distribution of the data, the Shapiro–Wilk test was performed. The data for BD and $R_{A\text{mean}}$ met the requirements of normality, while the test on ARW data led to rejection of the normal distribution hypothesis. To compare data between samples on a cross-section of the trunk, the ANOVA test was performed. When significant differences were detected, a post hoc Tukey’s HSD test was performed. Statistical inference was performed at the significance level $\alpha = 0.05$. Coefficients of determination ($R^2$) were calculated using linear regression to test the relationship between examined properties. The RStudio program and the R package 4.0.5 (R Core Team 2021, Vienna, Austria) were used for the calculations.

3. Results

3.1. Mean Basic Density, Moisture Content and Average Annual Ring Width

Mean values of examined properties and distribution on cross-section of all selected trees were calculated. The mean value of basic density in our study was 0.540 g/cm$^3$. As regards the distribution on the trunk cross-section, the largest density values were obtained closest to the pith (0.699 g/cm$^3$); then, a decrease was observed in the direction of the bark (0.404 g/cm$^3$). The results of the Tukey’s HSD test indicated significant differences between wood samples, especially between the outermost samples (Figure 2). For the results obtained using a Resi, we observed a similar trend in $R_{A\text{mean}}$ values as in the case of BD, although we observed more significant differences between samples along the cross-section of the trunk (Figure 3). The mean value of $R_{A\text{mean}}$ was approximately 22.0%. All samples have MC level above the maximum saturation point ranging from approximately 68 to 123%. The mean moisture content of the examined samples was 89.13%. The results of the Tukey’s HSD tests presented statistically significant differences on the cross-section of the trunk (Figure 4). The widest annual rings were observed closest to the pith (6.17 mm), while the narrowest near the bark (1.03 mm); the average annual ring width in the studied cores was calculated at 2.48 mm. The Tukey HSD test showed significant differences between each sample from the first six decades and those from the last five (Figure 5).
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Figure 2. Distribution of basic density (g/cm$^3$) on the cross-section of the trunk from bark (section I) to the pith (sections X/XI) with marked * significant and ** highly significant differences between wood samples using Tukey’s HSD test. Whiskers corresponding to minimum and maximum values, boxes represent the 1st and 3rd quartile values, midlines indicate the median.

Figure 3. Distribution of mean Resi amplitude (%) on the cross-section of the trunk from bark (section I) to the pith (sections X/XI) with marked * significant and ** highly significant differences between wood samples using Tukey’s HSD test. Whiskers correspond to minimum and maximum values, boxes represent the 1st and 3rd quartile values, midlines indicate the median.
Figure 4. Changes of moisture content (%) on cross-section of the trunk from bark (section I) to pith (sections X/XI) with marked * significant and ** highly significant differences between wood samples using Tukey’s HSD test. Whiskers correspond to minimum and maximum values, boxes represent the 1st and 3rd quartile values, midlines indicate the median.

Figure 5. Changes of average annual ring width (mm) on cross-section of the trunk from bark (section I) to pith (sections X/XI) with marked * significant and ** highly significant differences between wood samples using HSD Tukey test. Description: whiskers represent minimum and maximum values, boxes—1st and 3rd quartile values, midlines—median.

3.2. Spearman Correlation between Examined Properties and Modelling Basic Density in Relation to Residual Amplitude

The results of the Spearman correlation show a strong positive correlation between each two pairs of properties. The strongest relationships were observed between BD and ARW (0.70) and between RAmean and BD (0.68). According to the observed trends, as the
3.2. Spearman Correlation between Examined Properties and Modelling Basic Density in Relation to Resi Amplitude

The results of the Spearman correlation show a strong positive correlation between each two pairs of properties. The strongest relationships were observed between BD and ARW (0.70) and between RA\text{mean} and BD (0.68). According to the observed trends, as the value of one of the examined properties increases, the value of each of the other properties also increases. Negative correlation was found between RA\text{mean} and MC (−0.31) and BD and MC (−0.53). In this case, as moisture content increases, resistance drilling and basic density decreases.

Coefficients of determination (R\textsuperscript{2}) were calculated for the relationships between BD and RA\text{mean}, using linear regression. Significant relationships between examined properties were observed. The adjusted R\textsuperscript{2} for the pair BD–RA\text{mean} was 0.40 (Figure 6).

![Figure 6. Relationship between mean Resi amplitude (%) and basic density (g/cm\textsuperscript{3}) calculated using linear regression with 50 cm/min drilling speed and 1500 RPM.](image)

4. Discussion

In our study we estimated and compared basic density, mean Resi amplitude and average annual ring width for pedunculate oak wood, using destructive and non-destructive methods. This oak is classified as a ring-porous wood species. This kind of wood is characterized by visible differences between annual rings and a borderline between early and late wood. The density of oak wood depends on many factors, including species, habitat and growth conditions and sample location [38–43]. The mean basic density obtained in this study was lower than the results reported by other authors [38,43]. Analysis of the distribution of density on a cross-section of the trunk showed that BD increased in a direction from bark to pith. This trend is confirmed by other authors who have studied oak wood [41–44]. When it comes to distribution on the cross-section of the trunk, we observed similar changes of examined properties. In the first five sections (i.e., first five decades of growth) from the pith we noticed higher values of BD and RA than in the rest of the sections (last six decades of growth). This phenomenon can be caused by wider annual rings, which were also noticed in the section closest to the pith. In ring-porous tree species
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(including Oak) the density of wood is highly correlated with annual ring width (high late wood zone), which was also confirmed in our study.

Feed rate and RPM are an important factors, which can have an impact on RD results. Similar findings where obtained by Sharapov et al. [23,26] who examined the effect of MC and three different feed rates of resistance drilling on different species i.e., oak (Q. robur L.). In our study, drilling speed was set at 50 cm/min, with 1500 revolutions per minute and 89% mean MC. The average RA<sub>mean</sub> of all selected trees was 22%, and the distribution trend was similar as in the case of basic density. We observed a very low value of RA<sub>mean</sub> in the first section. According to Gendvilas et al. [25] this phenomenon can be caused by drilling friction. Most current studies on the determination of Resi amplitude were carried out on tropical and coniferous species e.g., [14,16,29,37,45] and European broadleaved tree species [26,28].

The results of Spearman’s correlation test showed strong positive correlations between all examined properties. We observed a trend whereby the density of the wood increased in direct proportion to the resiampplitude. The width of the annual rings has an indirect effect on RA, because ARW is strongly correlated with BD. Similar trends in wood density and annual ring width have been observed by other authors [40,44,46]. Changes in Resigraph amplitude have been used for determining the characteristics and structure of annual rings [13,47] but not in the context of density changes on a cross-section of the trunk.

The results of the linear regression show a significant relationship between RA<sub>mean</sub> and BD. However, the values we obtained are lower compared to other studies on European tree species, especially hardwoods. In this case, a lower R<sup>2</sup> can be caused by the needle friction. Gendvilas et al. [25] showed that Resi can underpredict BD on the first few centimeters of drilling. However, this issue can be eliminated by using non-linear friction correlation. It is also important to take into account that most of reported studies were carried out in a laboratory under a controlled environment and using a stabilized device. In our study, measurements were carried out directly in the forest where human error may have had an impact on drilling consistency. Acuna et al. [28] reported high adjusted R<sup>2</sup> values (>0.80) between density and RA<sub>mean</sub> for Q. robur and five other wood species with 30 cm/min FR and 1500 RPM, while Sharapov et al. [26] obtained relationship ranging between 0.58 and 0.87 for three different feed rates on water saturated samples. Da Silva et al. [29] computed various R<sup>2</sup> values on tropical tree species, ranging from 0.55 to 0.97, and observed that the correlation between the properties was stronger in the case of higher-density wood species; however, the authors did not specify feed speed and RPM. In contrast, Karlinasari et al. [48] reported a lower correlation (R<sup>2</sup> = 0.25) between Resi amplitude and wood density in the case of agarwood with 1000 RPM.

5. Conclusions

The results obtained in this study provide evidence that the Resi is an appropriate tool for non-destructive determination of wood density. Moreover, we observed a strong significant correlation between annual ring width and basic density. This means that AWR has an indirect impact on wood resistance. In the case of oak wood, these results may be related to a higher proportion of late wood in wider rings, although this hypothesis should be confirmed in future studies. We created a linear model to calculate the relationships between resistance drilling results, basic density and annual ring width, but the adjusted R<sup>2</sup> values obtained were small (0.40). According to the literature, it is possible to improve this relationship by using appropriate correction models or by carrying out the study under more stable conditions. Wood has a heterogenous structure, therefore we cannot know whether the needle is moving exactly in the radial direction. Nevertheless, the relationship between the examined properties was significant. This study was carried out only in one stand and one species, on a small number of selected trees and samples. Therefore, in further studies, consideration should be given to increasing the number of samples and plots to attempt to create a more accurate model.
Author Contributions: Conceptualization: K.T. and A.T.; methodology: K.T., A.T. and T.J.; formal analysis: K.T. and A.T.; data curation: K.T.; writing—original draft preparation: K.T., A.T. and T.J.; writing—review and editing: K.T. and A.T.; visualization: K.T.; supervision: A.T. All authors have read and agreed to the published version of the manuscript.

Funding: Publication was co-financed within the framework of the Polish Ministry of Science and Higher Education’s program: “Regional Initiative Excellence” in the years 2019–2022 (No. 005/RID/2018/19”), financing amount 12 000 00 PLN.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Acknowledgments: The authors would like to thank the staff of the Włoszakowice Forest District for their help with the experiment.

Conflicts of Interest: The authors declare no conflict of interest.

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