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Abrasion resistance of sessile oak in the direction of primary tree growth and in the opposite direction on radial and tangential sections

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Abstract

The primary goal of this paper was to determine if there is a difference in the intensity of abrasive wear on the radial and tangential sections of sessile oak (*Quercus petraea*) in the direction that matches or opposes the primary growth direction of the tree. The resistance to abrasion was tested on the samples using the standard 'dry sand–rubber wheel' method in both directions and on both sections. Owing to the heterogeneity of the wood structure, the abraded mass was recalculated to the abraded volume. It was found that changing the direction of abrasion relative to the primary growth direction significantly affects the abraded volume on both sections, particularly on the radial section. Abrasion was more intense when the direction of wear opposed the primary growth direction in both sections. The smallest abraded volume was measured on the radial section in the primary growth direction, and the largest was measured on the same section in the opposite direction. The distribution of results was analyzed using the Weibull distribution, with less dispersion observed in the radial section compared to the tangential section in both wear directions. The total volume loss from abrasive wear in both directions was only 3.7% greater in the tangential section compared to the radial section. These results are attributed to the complex and highly oriented microstructure of oak wood, but still not fully understood.

Keywords Wear, Abrasion, Anisotropy, Sessile oak wood

Introduction

Throughout the entire history of human civilization, wood has undoubtedly been one of the most important structural materials. Although a wide range of highly advanced construction materials with superior mechanical properties have been developed over the last century, wood is still widely used in both its natural and modified

forms. Wood is primarily a natural, renewable, fully recyclable, and technically versatile material. In construction, its high specific strength and stiffness in the axial direction stand out, with values that are comparable to, or even exceed, those of some aluminium alloys and low-carbon structural steels [1]. In certain applications, wear resistance, particularly against abrasion, is crucial. Numerous examples exist where wood's high abrasion resistance is required, such as parquet floors, staircases, and pallets.

According to the ASTM G40-21a:2021 standard, abrasion resistance can be defined as the ability to resist mechanical wear caused by hard particles moving along a solid surface [2]. This property is difficult to define precisely as it depends on numerous internal and external

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factors, including the wood species, chemical composition, and structure at the molecular to macro levels [3–5]. Due to its highly oriented structure, significant variations in properties are present between different wood species, as well as within the same tree depending on the position of the sample relative to the three characteristic axes (longitudinal, radial, and tangential) and three sections (C-cross, R-radial, and T-tangential), Fig. 1. Mechanical and tribological properties, including abrasion resistance, can vary significantly within the same species and even within the same tree, depending on the position of the test sample relative to these characteristic axes [6, 7]. The direction of wear relative to the wood fibers and growth rings also influences the wear intensity. Abrading parallel to the fibers shows lower wear intensity than abrading perpendicular to the fibers. A similar trend is observed in cross-sections, where the wear intensity is lower when abrasion occurs parallel to the growth rings than in the perpendicular direction [8].

The intensity of abrasive wear correlates with density, hardness, and the yield strength of wood, as well as the earlywood/latewood ratio, but it is not possible to establish a completely unambiguous quantitative relationship between these properties [3, 9–14]. The yield strength of the counterface material during a three-body abrasion test also affects the wear intensity [15].

Aging of the wood and the degree of degradation of the wood structure also affect abrasion resistance [7, 9]. Research conducted on recent pedunculate oak wood and six subfossil pedunculate oak samples revealed that recent oak has the highest abrasion resistance. Additionally, a very strong negative linear relationship between the age of subfossil oak and its abrasion volume loss was observed. A moderate negative linear correlation was also found between the abrasion resistance and the

degree of degradation of lignin and cellulose in subfossil oak samples [9]. Oaks (genus *Quercus*) are represented by a total of 17 taxa in Croatia [16] and are generally among the most commercially exploited tree species. The most economically important species are the pedunculate oak (*Q. robur*) and sessile oak (*Q. petraea*). Both species grow throughout Europe up to Asia Minor, but they do not occupy the same ecological areas.

The intensity of abrasive wear is also influenced by the size of abrasive particles. When testing abrasion resistance with different abrasive sizes, the phenomenon of a critical abrasive grain size is often observed [6, 7]. As the size of the abrasive grains increases up to the critical size, the volume loss from abrasion increases linearly. Once this critical value is reached, further increases in grain size result in either the volume loss remaining constant or decreasing or increasing but at a lower rate. This phenomenon is observed in both metal and other technical materials [17].

The testing methodologies (two-body and three-body abrasion tests) and the applied surface pressures also affect the values of abrasion resistance [18, 19].

The research was carried out on sessile oak, a specific wood species for which there are no similar studies on abrasion wear in the recent literature. Oak wood, due to its good mechanical properties (especially high strength and hardness), is important as a building and construction wood for housing and bridge construction. It is also highly desirable for the production of veneers, parquet, joinery, furniture, barrels, wooden tools and other parts that require high wear resistance [20]. In luxury interiors in the aviation and automotive industries, wear resistance can be key to the durability and aesthetics of the material. The aim of this study was to determine if there is a difference in the intensity of abrasive wear when hard quartz sand particles abrade the surface in the direction that matches the tree's primary growth direction (the tree's height growth) and when the wear occurs in the opposite direction. In both cases, the wear direction was parallel to the fibers. The research was conducted on two sections of the sessile oak and its radial and tangential section. This hypothesis was based on the fact that the basic biological function of wood tissue is the flow of water with dissolved minerals directed from bottom to top and that this must be reflected in the abrasive properties.

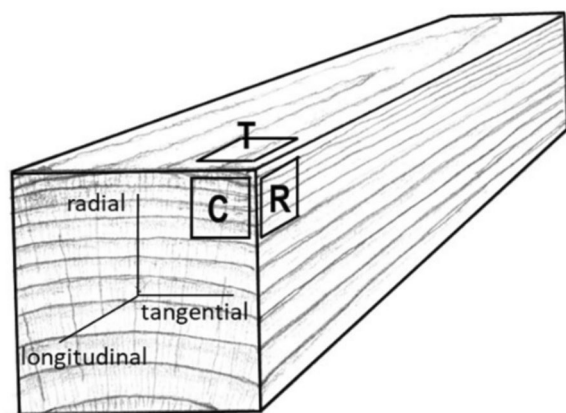


Fig. 1 The characteristic axes and sections of wood. C cross section, R radial section, T tangential section

Materials and methods

The samples were cut from heartwood of the butt part of sessile oak tree from the Gospić area (Lika, Croatia), where this oak species predominates climatically. The age of the tree at the time of cutting was estimated at over 50 years, based on the number of visible growth rings. The diameter of the trunk was about 50 cm.

Figure 2 shows the microstructure of sessile oak wood in the cross-sectional, radial, and tangential views. Sessile oak wood is characterized by a ring-porous organization with a very distinct dendritic arrangement of latewood vessels. The pores of earlywood (ep) are clearly visible to the naked eye and appear in 1 to 3 rows, while the pores of latewood (lp) are very dense, small, and numerous. Tyloses are common in large pores. Thick-walled fibers (f) are libriform and come in irregular patches. The rays come in two types: uniseriate rays (ur), which can be up to 20 cells high, and multiseriate rays (mr), which can be up to 1 mm wide and 10 mm high. Both types of rays are homogeneous. Apotracheal parenchyma is usually diffuse and is found in latewood in short tangential bands [21].

From the beam shown in Fig. 3, three series of samples (I, II, and III) were cut to analyze the effect of the radial distance of the samples from the pith on the intensity of abrasive wear. The third series of samples was positioned near the outer edge of the heartwood so that the curvature of the growth rings was minimized. In each series, 7 samples were cut, each positioned one above the other in the longitudinal direction. A total of 21 samples were prepared.

The samples were shaped into regular quadrilateral prisms with dimensions of 25 mm × 25 mm × 76 mm. Each sample was marked with the direction of primary growth. Two side surfaces of the samples, measuring 25 mm × 76 mm, corresponded to the radial section, and the other two corresponded to the tangential section. Abrasion resistance was tested on these surfaces. On one surface of each section (radial and tangential), the wear direction corresponded with the primary growth direction, and on the other surface of the same section, the wear direction was opposite, as illustrated in Fig. 4. A total of 84 measurements were conducted. During the entire test, the temperature in the laboratory was 22 °C and the relative moisture content was 46%.

Abrasion resistance testing was carried out using the standard 'dry sand–rubber wheel' method according to ASTM G65-16:2021 [22]. A schematic of the method is shown in Fig. 5. This method is primarily designed for



Fig. 3 Position of sample sets (I, II, and III) in the cross section of the beam. *hw* heartwood, *sw* sapwood

testing the abrasion resistance of metallic materials [23, 24], but in this study, it was applied for wood testing due to the research objective. The force with which the sample was pressed onto the rubber wheel was achieved using weights and was 45 N. The wheel rotation speed was 200 rpm, and the peripheral speed was 2.33 m/s. The wheel performed 200 rotations per testing cycle. The surfaces of the samples were abraded by quartz grain sand B35S (Kema, Puconci, Slovenia) with a particle size between 0.063 and 0.355 mm. Before testing on the 'dry sand–rubber wheel' device (Faculty of Mechanical Engineering and Naval Architecture, Croatia), all test surfaces were ground with sandpaper of the same quality (sandpaper quality P500) and brushed. The mass of the samples was measured before and after each wear cycle using a Mettler B5C 1000 (Mettler Toledo, Zurich, Switzerland) scale. Based on the measurement results, the abraded mass for all tested surfaces was calculated. The heterogeneity of the wood structure is one of its fundamental characteristics, so abrasion resistance is expressed as volume loss, accounting for differences in sample density.

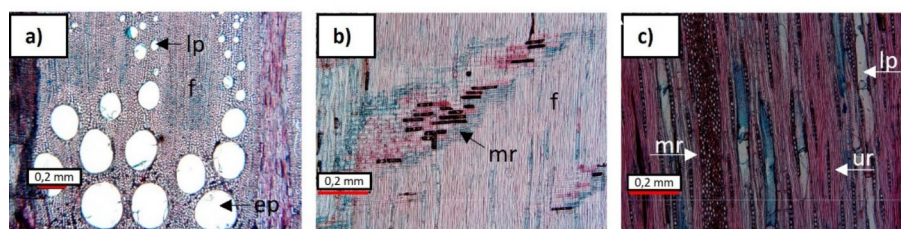


Fig. 2 Microstructure of sessile oak wood—cross (a), radial (b) and tangential (c) section. (Courtesy of Matea Hofer). *ep* earlywood pores, *lp* latewood pores, *ur* uniseriate ray, *mr* multiseriate ray, *f* fiber

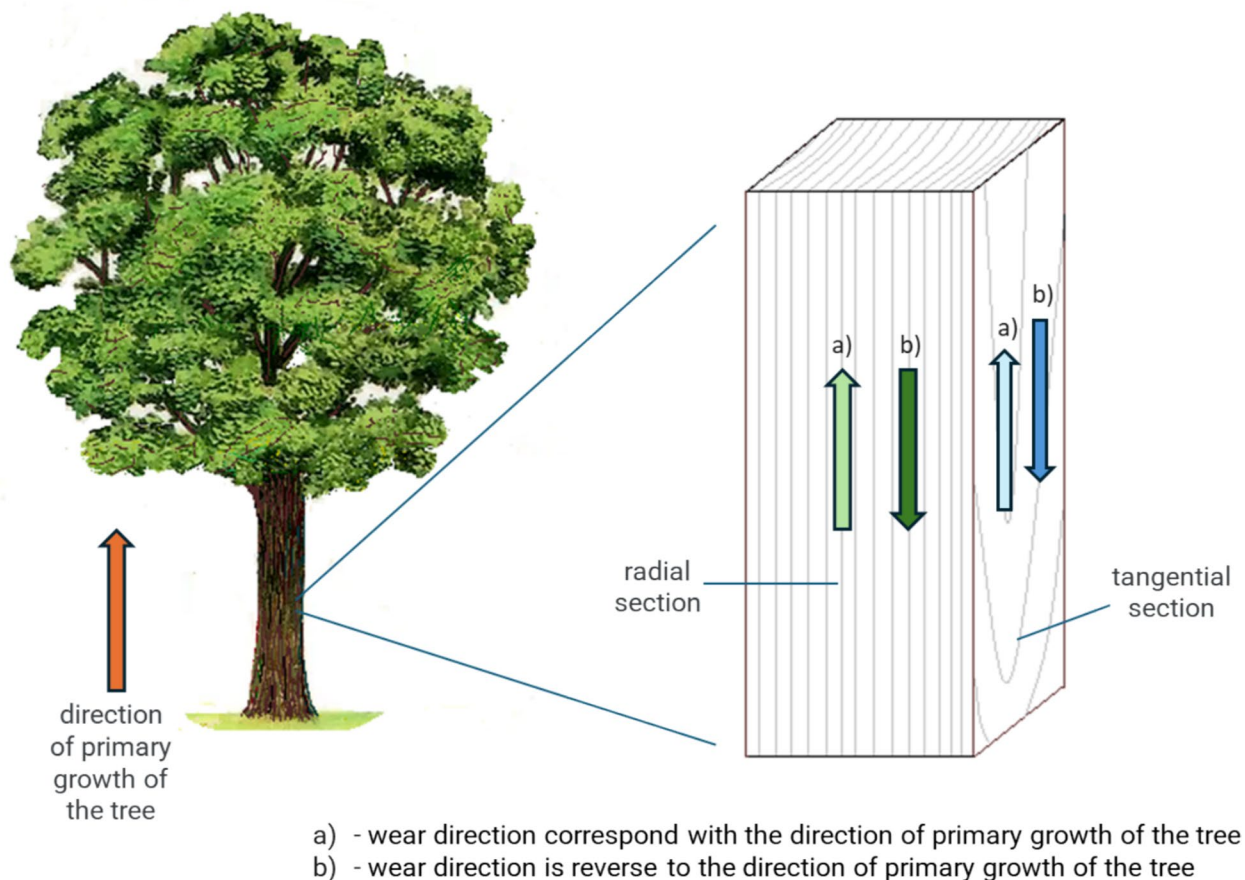


Fig. 4 Direction of wear in relation to the direction of primary tree growth

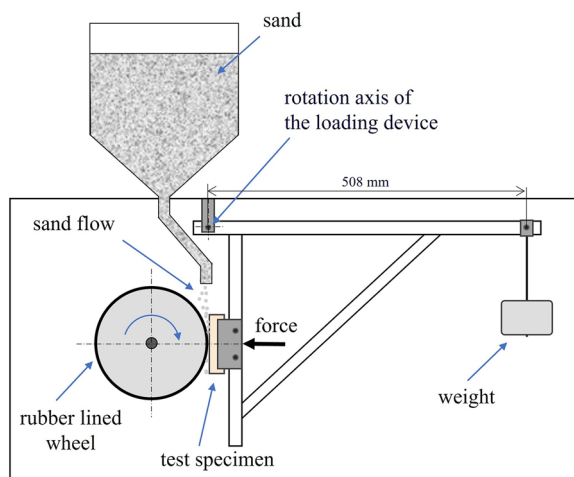


Fig. 5 Schematic presentation of the device for the dry sand rubber-wheel abrasion test

The variability of the results for the abraded volume of individual surfaces on the radial and tangential sections of the samples is described by the well-established Weibull distribution. This statistical method is widely

used to assess the reliability of various properties of heterogeneous materials, such as wood [25].

The hardness of the radial and tangential sections was tested using the Brinell method, on an HP250 (VEB WPM, Leipzig, Germany), in accordance with the EN 1534:2020 standard [26].

Results and discussion

Table 1 shows the samples density values for a moisture content of 12%. The highest measured density was 1020 kg/m^3 and the lowest was 954 kg/m^3 . The average density value was 984 kg/m^3 . The obtained density values are within the range reported in the literature for this oak species [20, 27].

According to the ISO 13061-1:2014 [28], the coefficient of variation for density measurements should not exceed 10, as also reported in the literature [29]. This indicates that the variation in the results from the density measurements is within acceptable limits.

Table 2 presents the statistical analysis results of the abraded mass measurements of all 84 abraded surfaces.

Table 1 Density values and statistical data of the measurements at a moisture content of 12%

Samples			ρ_{12} , kg/m ³		
Series I	Series II	Series III	Series I	Series II	Series III
1	8	15	1004	1008	1001
2	9	16	984	959	977
3	10	17	954	958	964
4	11	18	980	961	983
5	12	19	997	1011	985
6	13	10	980	1020	1003
7	14	21	987	985	975
Average			984	986	984
Arithmetic mean			985		
Standard deviation			18.52		
Standard deviation of the arithmetic mean			1.01		
Coefficient of variation, %			2		

The abraded mass was measured at a moisture content of 7.97% and recalculated for a moisture content of 12%.

Figure 6 shows the results of the abraded volume measurements for both directions on the tangential sections of all samples. Only in two of the 21 samples was the abraded volume slightly higher in the primary growth direction than in the opposite direction. In all other samples, the abraded volume was lower, and in most cases, much lower.

In the radial direction, the abraded volume was significantly higher in the opposite direction from the primary growth direction for all samples (Fig. 7).

It was found that the measured abraded volume for both sections and both directions follow the Weibull distribution. The Weibull shape parameter was higher for the radial direction. The determination coefficients (goodness of fit) were greater than 0.8 for each group of

data. Figure 8 presents the Weibull plots for both abraded sections and both wear directions.

Table 3 presents the results of the statistical analysis for the abraded volume (mm³), parameters of the Weibull function, and the determination coefficient for both sections and both wear directions.

The largest average abraded volume was obtained in the radial section when the wear direction was opposite to the primary growth direction. The smallest average abraded volume was also measured in the radial section when the wear direction matched the primary growth direction.

The highest standard deviation and coefficient of variation values were observed in the tangential section in the primary growth direction (T↑), and the lowest were in the radial section in the same direction (R↑).

The values of standard deviation for the wear direction opposite to the primary growth direction were similar in the radial (R↓) and tangential sections (T↓), while the coefficient of variation for the same direction was lower in the tangential section due to the higher average abraded volume.

The larger abraded volume in the direction opposite to the primary growth direction of wood in both sections is most probably a consequence of the wood structure and biological orientation. During the abrasion of wood tissue, the cell wall of wood cells is abraded. Most wood cells consist of vessels and wood fibers that are oriented longitudinally, with a smaller portion made up of parenchyma cells in wood rays, which are oriented radially. Vessels have thick cell walls and large lumens, and compared to wood fibers, they are relatively short. Wood fibers have thick cell walls and narrow lumens. While the tree is alive, the primary role of wood fibers is mechanical support, and the primary role of vessels is to conduct water with dissolved minerals, a process that occurs in

Table 2 Statistical analysis results for the measured abraded mass at 12% moisture content

	Series I				Series II				Series III			
	$m_{T\uparrow}$	$m_{T\downarrow}$	$m_{R\uparrow}$	$m_{R\downarrow}$	$m_{T\uparrow}$	$m_{T\downarrow}$	$m_{R\uparrow}$	$m_{R\downarrow}$	$m_{T\uparrow}$	$m_{T\downarrow}$	$m_{R\uparrow}$	$m_{R\downarrow}$
Min	0.153	0.235	0.168	0.292	0.161	0.250	0.173	0.308	0.160	0.174	0.158	0.212
Max	0.272	0.327	0.191	0.353	0.280	0.313	0.203	0.378	0.280	0.323	0.198	0.355
Average	0.210	0.273	0.180	0.321	0.214	0.276	0.186	0.331	0.218	0.265	0.183	0.309
SD	0.049	0.034	0.008	0.022	0.046	0.023	0.009	0.022	0.048	0.044	0.012	0.042
Var	0.0024	0.0011	0.0001	0.0005	0.0021	0.0005	0.0001	0.0005	0.0024	0.0020	0.0001	0.0018
CV, %	23.31	12.37	4.49	6.88	21.51	8.17	4.94	6.73	22.20	16.75	6.40	13.55

SD standard deviation, Var variance, CV coefficient of variation

$m_{T\uparrow}$ —abraded mass in grams for the tangential section in the wear direction that matches the primary growth direction of the wood, $m_{T\downarrow}$ —abraded mass in grams for the tangential section in the wear direction that is opposite to the primary growth direction of the wood, $m_{R\uparrow}$ —abraded mass in grams for the radial section in the wear direction that matches the primary growth direction of the wood, $m_{R\downarrow}$ —abraded mass in grams for the radial section in the wear direction that is opposite to the primary growth direction of the wood

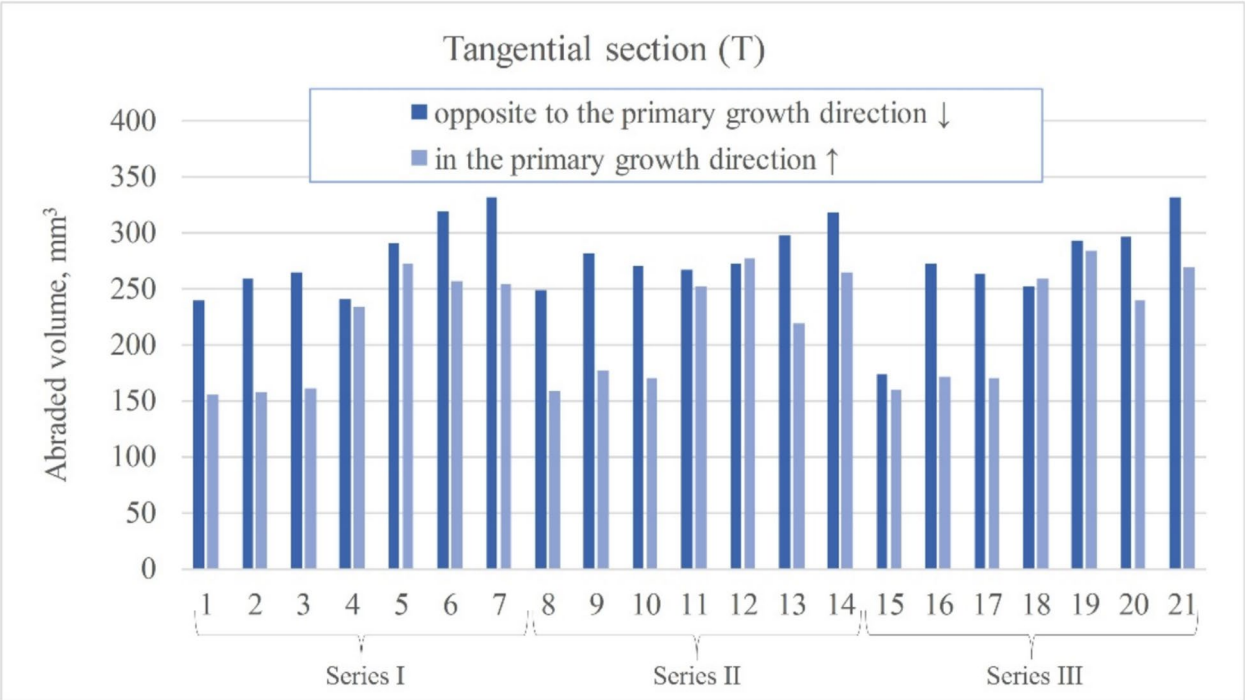


Fig. 6 Abraded volume on tangential section for both directions

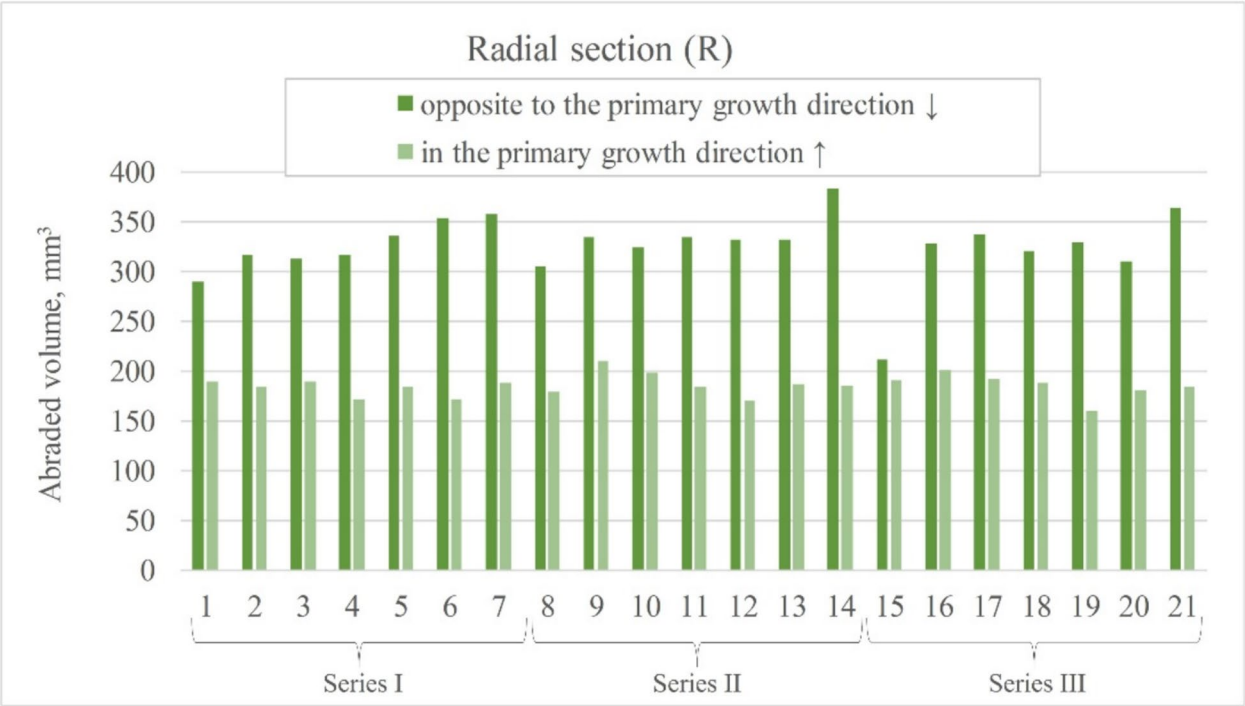


Fig. 7 Abraded volume on radial section for both directions

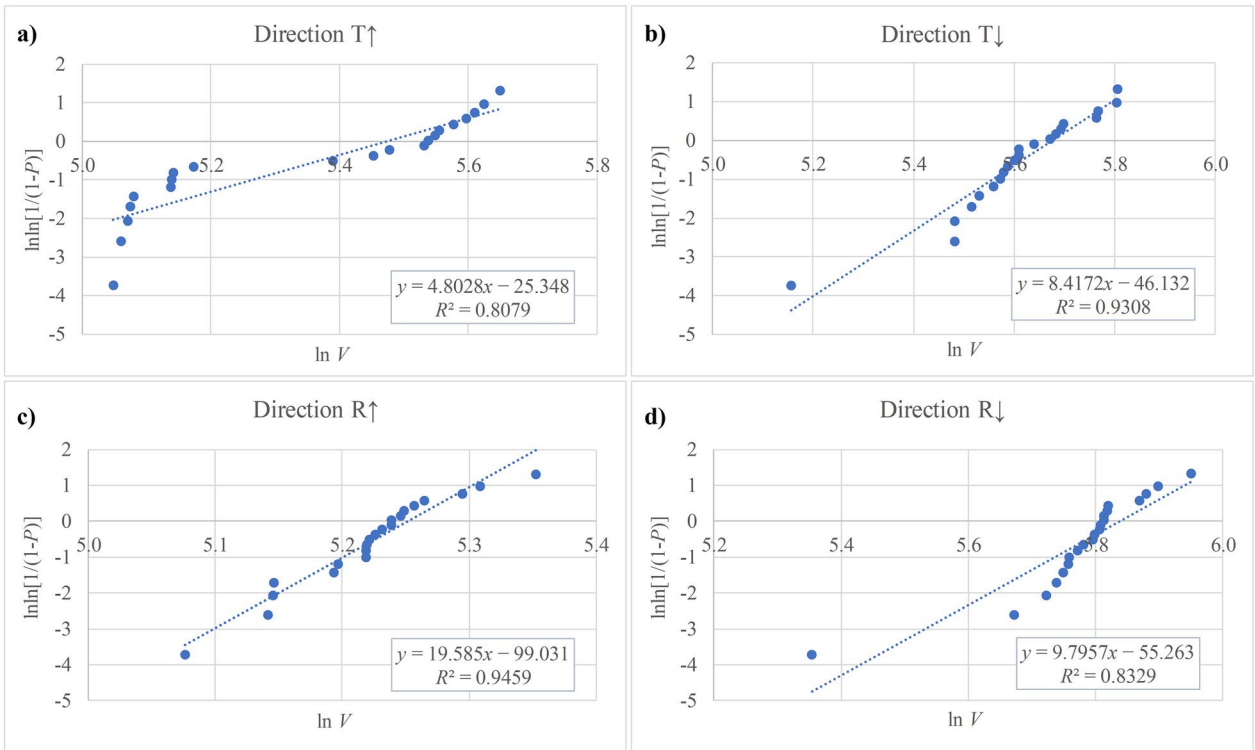


Fig. 8 Weibull plots for the abraded volume of different directions: **(a)** tangential section, in the direction of the primary growth of the wood; **(b)** tangential section, opposite to the direction of the primary growth of the wood; **(c)** radial section, in the direction of the primary growth of the wood; **(d)** radial section, opposite to the direction of the primary growth of the wood. P probability of failure, V abraded volume

Table 3 Statistical analysis results for the measured abraded volume, parameters of Weibull function and determination coefficient

	Orientation			
	T↑	T↓	R↑	R↓
Sample number	21	21	21	21
Minimum of abraded volume, mm ³	156	174	160	212
Maximum of abraded volume, mm ³	284	332	211	384
Average of abraded volume, mm ³	217	276	186	326
Standard deviation	47.85	35.44	11.08	32.70
Coefficient of variation, %	22.02	12.86	5.96	10.04
Weibull parameter	4.80	8.42	19.59	9.80
Coefficient of determination	0.81	0.93	0.95	0.83

T↑—tangential section, in the direction of the primary growth of the wood, T↓—tangential section, opposite to the direction of the primary growth of the wood, R↑—radial section, in the direction of the primary growth of the wood, R↓—radial section, opposite to the direction of the primary growth of the wood

the primary growth direction of the tree, from the roots to the top. However, in future studies, microscopic observations and nanostructural analyses of cell wall layers would be desirable in order to confirm our hypothesis that the biological orientation and anisotropic structure

are the factors influencing the observed differences in abrasion resistance.

The cause of the larger abraded volume in the direction opposite to the primary growth could also be the tapering of the trunk, but due to the relatively short samples, the effect of tapering can be neglected in this case.

Based on the average values of the abraded volume shown in Table 3, the differences between the two wear directions were calculated for the tangential $\Delta V(T\downarrow - T\uparrow)$ and radial sections $\Delta V(R\downarrow - R\uparrow)$. Figure 9 shows these differences for all three sets of samples. The difference in the radial section for all three sets is more than twice as large as the difference in the tangential section, indicating that the effect of wear direction is much greater in the radial section than in the tangential section. Considering the radial position of the sample, it is evident that series I and II show almost identical ΔV results both on the radial and tangential sections, with slightly lower values for the samples of series III which are furthest from the pith.

When vessels and wood fibers are considered individually, given their tube-like shapes, there should be no difference in their abrasion resistance in the tangential and radial sections. However, since oak has a ring-porous structure, these wood cells are not homogeneously

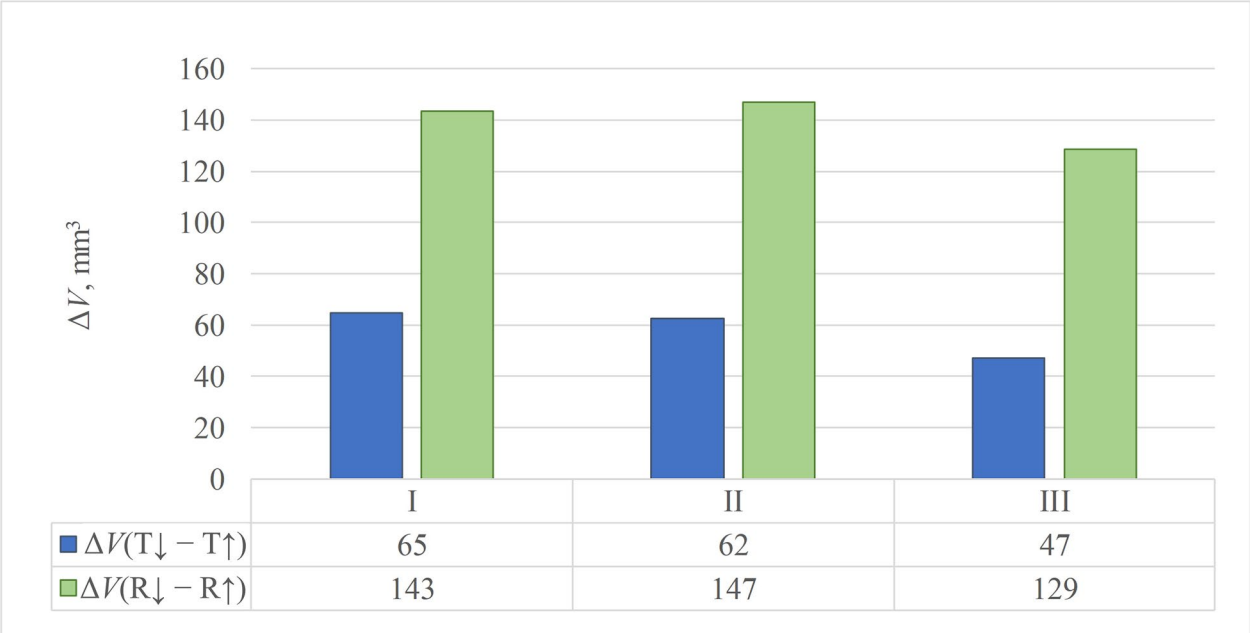


Fig. 9 Differences between the average values of abraded volume with respect to the wear direction in the tangential and radial sections

distributed. Each growth ring consists of an early part, which forms at the beginning of the growing season and is primarily made up of vessels, and a late part, which forms later and consists mostly of wood fibers and smaller vessels [21, 30]. These two layers alternate throughout the cross-section and concentrically arrange around the pith. The farther from the pith, the less curved these layers become, and the wood tissue can be viewed as a layered composite material. The thickness of individual layers can vary depending on the thickness of the annual growth. Density, hardness, stiffness, and strength are not the same in these two layers, and they are higher in the late part of the growth ring in all species, including oak [13, 31]. When testing abrasive wear using the ‘dry sand–rubber wheel’ method, the wear direction is perpendicular to the layers in the tangential section, and the wear gradually transitions from one layer to another. The proportion of the abraded surface in the early and late parts of the growth ring changes throughout the test. In the radial section, the proportions of the abraded surface in the early and late parts of the growth ring change much less during the test, which is why the variability in the results in the tangential section is much greater than in the radial section. This variability is especially pronounced during abrasion in the primary growth direction of the wood.

In addition to the mentioned layering, the difference between the structure of the radial and tangential

sections is also influenced by the radially oriented parenchyma cells of the wood rays. The longitudinal axis of these cells in the radial section is positioned at a 90° angle to the wear direction, and the cells are abraded longitudinally. In the tangential section, the cells of the wood rays are abraded transversely. It is known from the literature that wood cells generally offer the greatest resistance to abrasion in the transverse section [6, 7]. Compared with other wood species, oak has an above-average amount of wood rays in its structure. The numerous multiseriate rays could have a special influence on the amount of abraded volume when changing the abrasive section or wear direction [30].

The amount of abraded volume in the radial section in the primary growth direction (186 mm³) is about 14.4% less than the abraded volume in the tangential section in the same direction (217 mm³). By changing the abrasion direction, the abraded volume in the radial section (326 mm³) increased by about 18.2% compared to the abraded volume in the tangential section. (276 mm³).

It is difficult to answer unambiguously why the change in direction affects abrasion resistance in this way. The cause likely lies in the highly complex and strongly oriented wood structure, making it difficult to estimate how individual structural features interact to affect abrasion resistance.

Figure 10 shows the average value of the total abraded volume in both wear directions for the tangential

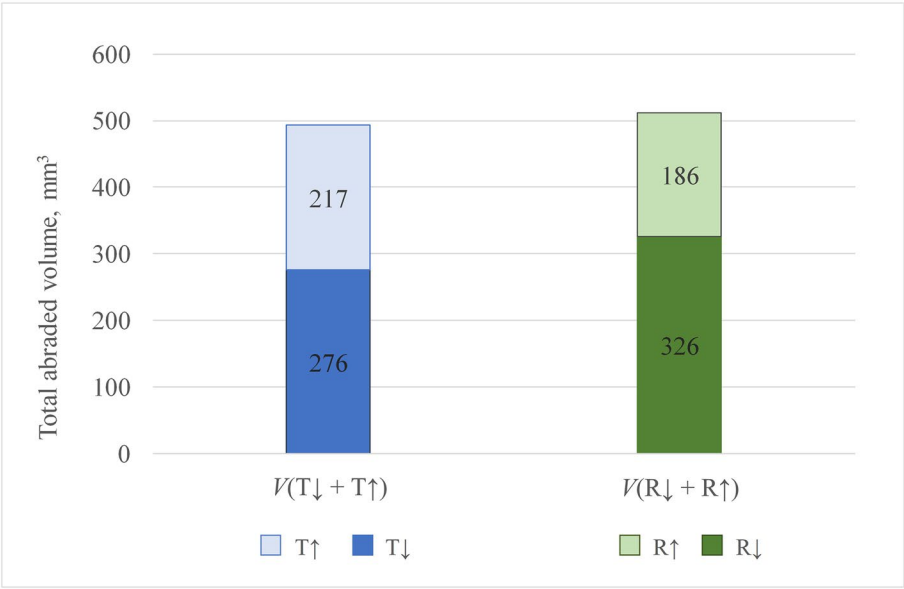


Fig. 10 Average values of the total abraded volume in both directions in the tangential and radial sections

Table 4 Results of HB hardness measurements

	Tangential section	Radial section
Average hardness	15.14	14.51
Standard deviation	1.59	1.48
Coefficient of variation, %	10.52	10.20

$V(T\downarrow + T\uparrow)$ and radial sections $V(R\downarrow + R\uparrow)$. The values of the total abraded volume for both sections are roughly equal. Compared with the tangential section, the radial section has slightly lower abrasion resistance, about 3.7%. This aligns with some previous studies on abrasion resistance in other wood species, conducted using different testing methods [7, 8, 32].

Table 4 presents the mean values of the measured hardness, standard deviation, and coefficient of variation for the radial and tangential sections.

The mean measured hardness of the tangential section is 4.34% higher than that of the radial section. The coefficient of variation for both sections is less than 17%, which is within the limits prescribed by the ISO 13061–1:2014 standard [28].

By comparing the mean values of the measured hardness on the radial and tangential sections with the average values of the total abraded volume in both directions shown in Fig. 10, it can be seen that the tangential section has a higher hardness and a lower value of $V(T\downarrow + T\uparrow)$, signifying a higher resistance to abrasive wear. If, however, individual sections and different wear directions are observed, then no correlation can be established between

hardness and abrasion resistance. For the same hardness, the resistance to abrasive wear changes significantly if the wear direction is changed. This was observed on both sections and was particularly pronounced on the radial section where the abraded volume increased by 75% by changing the wear direction. From this, it could be concluded that biological orientation has a dominant influence on the resistance to abrasive wear.

Conclusions

The following conclusions can be drawn from the obtained results:

- The direction of wear, in relation to the primary growth direction of the tree, influences the amount of abraded volume in the radial and tangential sections of sessile oak wood. Both sections experience greater wear in the direction opposite to the primary growth direction of the wood.
- The largest abraded volume was measured in the radial section in the direction opposite to the primary growth direction of the wood, while the smallest was in the same section in the primary growth direction. This shows that the influence of the wear direction is more pronounced in the radial section than in the tangential section.
- The radial position of the samples within the trunk has no significant influence on the differences between abraded volume with respect to the wear direction in the tangential and radial sections.

- The parameters of the Weibull function are higher for the radial section than for the tangential section in both directions. The determination coefficients were greater than 0.8 for both sections and both directions.
- The smallest variation in results was obtained in the radial section in the direction that coincides with the primary growth direction, while the largest variation was observed in the tangential section in the same direction.
- When abraded in the direction of the primary growth, the abraded volume in the radial section is about 14.4% smaller than the abraded volume in the tangential section, while in the opposite direction, the abraded volume in the radial section is 18.2% greater than in the tangential section.
- Although the individual average abraded volumes in the tangential and radial sections differ significantly for different wear directions, the total abraded volumes for both wear directions and both sections are similar. The radial section has about 3.7% greater total abraded volume compared to the tangential section. A lower hardness value was obtained in the radial cross-section, with a similar percentage difference.
- Since no data on research concerning the influence of the wear direction relative to the primary growth of wood has been found in the literature, and given the complex and varied anatomical structures of different wood species, additional research is necessary on other construction wood species with the aim to deepen knowledge about this scientific issue.

Abbreviations

ep	earlywood pores
lp	latewood pores
ur	uniseriate ray
mr	multiseriate ray
f	fiber

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Not applicable.

Author contributions

Conceptualization, V.R. and S.E.; methodology, V.R. and I.O.; software, H.L. and I.O.; validation, V.R., S.E. and D.Č.; formal analysis, H.L. and I.O.; investigation, I.O. and V.R.; resources, I.O. and D.Č.; data curation, D.Č. and H.L.; writing—original draft preparation, V.R., S.E. and H.L.; writing—review and editing, V.R., S.E., H.L., D.Č. and I.O.; visualization, V.R., S.E., H.L., D.Č. and I.O.; supervision, V.R. and S.E. All authors read and approved the final manuscript.

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Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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