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MECHANICAL AND MICROSTRUCTURAL CHANGES IN POST-FIRE RAW WOOD

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Abstract
Introduction: Today, the need for the neutralization of the environmental, economic, social, and other consequences of natural emergencies is becoming more and more urgent. One of such devastating disasters is forest fires, which are currently very widespread in the world. In most cases, after a fire, we are left with a forest that was partially exposed to fire. A burnt tree loses its immunity. As a result, an outbreak of various subcortical insect species, which infect healthy trees as well, occurs in these territories. Such a forest is subjected to sanitary cutting. **Purpose of the study:** We aimed to determine the residual mechanical properties of raw wood to be used as a structural material. **Methods:** In the course of the study, we used destructive and non-destructive testing methods in respect of the mechanical properties of the material. **Results:** It was established that changes in the microstructure of wood correlate with its strength properties. The maximum decrease in the strength properties of wood was observed at the top end of the tree and amounted to 22.7% as compared to the reference wood. The minimum decrease in the strength properties of post-fire wood was observed in the butt end of the tree and amounted up to 15.0%. In the middle part, a decrease in the strength properties of wood was up to 24.0%.

Keywords
Wood, fire, strength, microstructure, building structures.

Introduction

More and more consumers around the globe prefer wood in the design and construction of buildings. Wood is an environmentally friendly, renewable material, which is easy to use. However, wood resources are limited.

Forest fires are one of the most terrible and dangerous widespread natural disasters (Castillo et al., 2021; Interfax, 2021; Puntzukova, 2019; Ria, 2018; Soto et al., 2013; Yang et al., 2022). Every year, Russia witnesses thousands of forest, grass, and peat fires causing significant damage to the environment and economy (Nedkov et al., 2020; Veselkin et al., 2022). After a fire, there remains a burnt forest area, the nature of which depends on the type of forest that was there before the fire, the type of fire, its intensity, area, and duration.

As it is known, a burnt tree loses its immunity. Bark beetles get under the bark of such trees. However, they can also spread to healthy trees. The increasing length and severity of recent forest fire seasons annually cause widespread injury to millions of trees, facilitating the subsequent outbreak of various subcortical insect species infecting trees not affected by the fire (Arefyev, 2018; Kopylov et al., 2022). In burnt pine forest areas, the maximum abundance of insects can be observed in the fourth and fifth years after a fire (Ecologia, 2007; Kitchens et al., 2022). In small areas, the maximum abundance of insects can be observed in the second year after a fire. Forests are thinning due to forest cutting and parasite outbreaks. Burnt forests areas are subjected to sanitary cutting.

Within the implementation of the Ecology national project (National Projects of Russia, 2022) as well as the efficient use and saving of natural resources, the need for the sustainable use of wood shall be addressed.

We aimed to determine the residual strength properties of raw wood to be used as a structural material. Of particular research interest is post-fire raw wood, not older than 4–5 years from the fire, with a loss in the cross-section of up to 20%. The study of the strength properties and microstructure of such wood will make it possible to determine if such a material is suitable for structural use. It will also expand the scope of application for burnt wood (including as a structural material).

Thus, the study of wood with reduced physical and mechanical properties (including post-fire wood) is an important step toward the sustainable and rational use of natural resources.

Methods

Among other things, it is suggested to use post-fire wood in wooden building structures, including as lamellae in glued elements (Ayansola et al., 2022; Koshcheev et al., 2022; Lisyatnikov et al., 2022; Nippon Steel, 2005; Sergeev et al., 2022). Wooden structures are made mainly from coniferous wood (pine, spruce), therefore, the studies were performed with the use of pine wood samples (Chernyh and Moskalyev, 2020; Lisyatnikov, 2022; Noren, 1983; Sergeev, 2022).

Destructive and non-destructive testing methods were adopted to study the physical and mechanical properties of post-fire wood (Berwart et al., 2022; Jaworski et al., 2021; Roshchina et al., 2022).

In many wooden structures, wood resists compression, bearing, shear, bending as well as longitudinal and transverse tension (Lukina et al., 2022; Sergeev et al., 2021). In many cases, a complex stress-strain state is observed (compression with bending in arches, shear and bearing stresses in the supporting elements of structures, tension at an angle to the fibers and shear at the truss chord splices, etc.).

Earlier, we tested wood for compression and tension along the fibers as well as static bending. As a result, we established a decrease in the strength of the samples taken from the top end of the tree trunk. For instance, under static bending, the strength of the post-fire wood samples taken from the top end decreased by more than 20%, under compression along the fibers — by 28.8%, under tension — by 30.6%. The minimum decrease in strength in all three types of tests was observed in the samples taken from the butt end: under static bending, the decrease was almost 6.0%, under compression along the fibers — 15.0%, and under tension along the fibers — 8.4%.

To ensure a comprehensive study of the strength properties of post-fire raw wood, it is necessary to perform tests for shear along the fibers.

The samples were taken from post-fire trees (pine). Forest growing area: Yakutia, Russia. Intended use of the forest: commercial forest. Type of fire: creeping, independent, medium-scale. Damage to the forest stand from the fire: 10–15% by the cross-section. The bark of the trees is charred.

The samples were taken from the butt and top ends as well as the middle part. The samples were made from each slice, at different depths to the core part: in the center, at a depth of 0.5 radius (in the middle), and on the periphery (near the bark). Therefore, sap wood, the most commonly used wood in building structures, was studied. As a reference, samples of intact pine wood were taken.

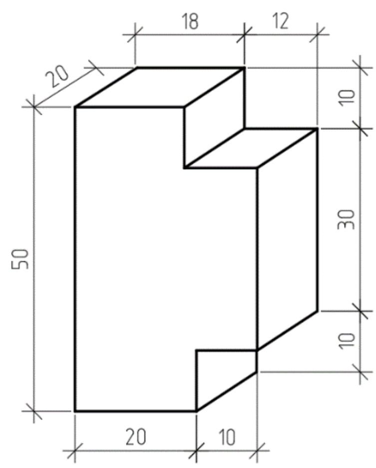
Strength depends on moisture. Before the tests, the samples were brought to a moisture close to the normalized one, followed by conversion to 12% moisture (Korolkov et al., 2021; Ye et al., 2022).

Before the tests, the samples were weighed, and the density of wood was determined. The density of the samples taken from the butt end was 454.3 kg/m^3, from the middle part — 403.6 kg/m^3, from the top end — 346.7 kg/m^3.

Determining the strength of wood weakened by fire under shear along the fibers

The samples were tested for shear along the fibers (Figure 1).

The studies were carried out using an REM-100-A-1 testing machine. The universal REM-100-A-1 testing machine meets the applicable requirements and is intended for mechanical tests



a)

b)

Figure 1. Testing of wood weakened by fire for shear along the fibers:
a) test sample shape; b) sample testing

involving the tension, compression, and bending of samples and items made of materials with a breaking strength not exceeding 100 kN.

The sample was loaded uniformly at a constant speed of the loading head. The speed of the loading head was 4 mm/min.

The obtained experimental data on the samples of wood weakened by fire were compared with those on the reference samples (Figure 2). Based on the test results, the statistical processing of the experimental data was performed.

Analysis of the post-fire raw wood microstructure

The strength properties of wood depend on the microstructure of the material. To clarify and confirm the results of the mechanical tests, the scanning electron microscopy and optical microscopy of the samples were carried out.

The scanning electron microscopy of the samples was performed using a Quanta 200 3D microscope (USA). With scanning electron microscopy, it is possible to study the micromorphology and fine structure of the sample surface using a focused electron beam scanning the sample surface (Cao et al., 2022; Labudin et al., 2022; Grünewald et al., 2012). Optical microscopy was performed using a Raztek MRX9-D digital optical microscope (Russia), which allows for the visual observation of the microstructure of opaque objects.

The studies involved the samples that were selected for mechanical tests prior to the tests for shear along the fibers.

Results and discussion

Figure 2 shows the results of the mechanical tests of the samples for shear along the fibers. Under static load, the shear resistance of wood at first increases in proportion to the increase in the length / projection of the sample (Figure 2); then, as soon as the length of the projection reaches a value equal to 9*h,* shear resistance becomes constant — shear occurs.

The ultimate strength of wood under shear along the fibers is determined as follows:

$$\tau_w = \frac{P_{\max}}{b \cdot l}, \quad (1)$$

where P_{max} is the maximum load, kN; b is the sample thickness, mm; l is the shear length, mm.

The ultimate strength of wood under static bending is determined as follows:

$$\sigma_w = \frac{3F_{max}l}{2bh^2}, \quad (2)$$

where F_{max} is the maximum load, kN; l is the distance between the centers of the supports, mm; *b* is the actual width of the samples, mm; h is the actual height of the samples, mm.

The ultimate strength under compression along the fibers is determined as follows:

$$\sigma_w = \frac{P_{max}}{ab}, \quad (3)$$

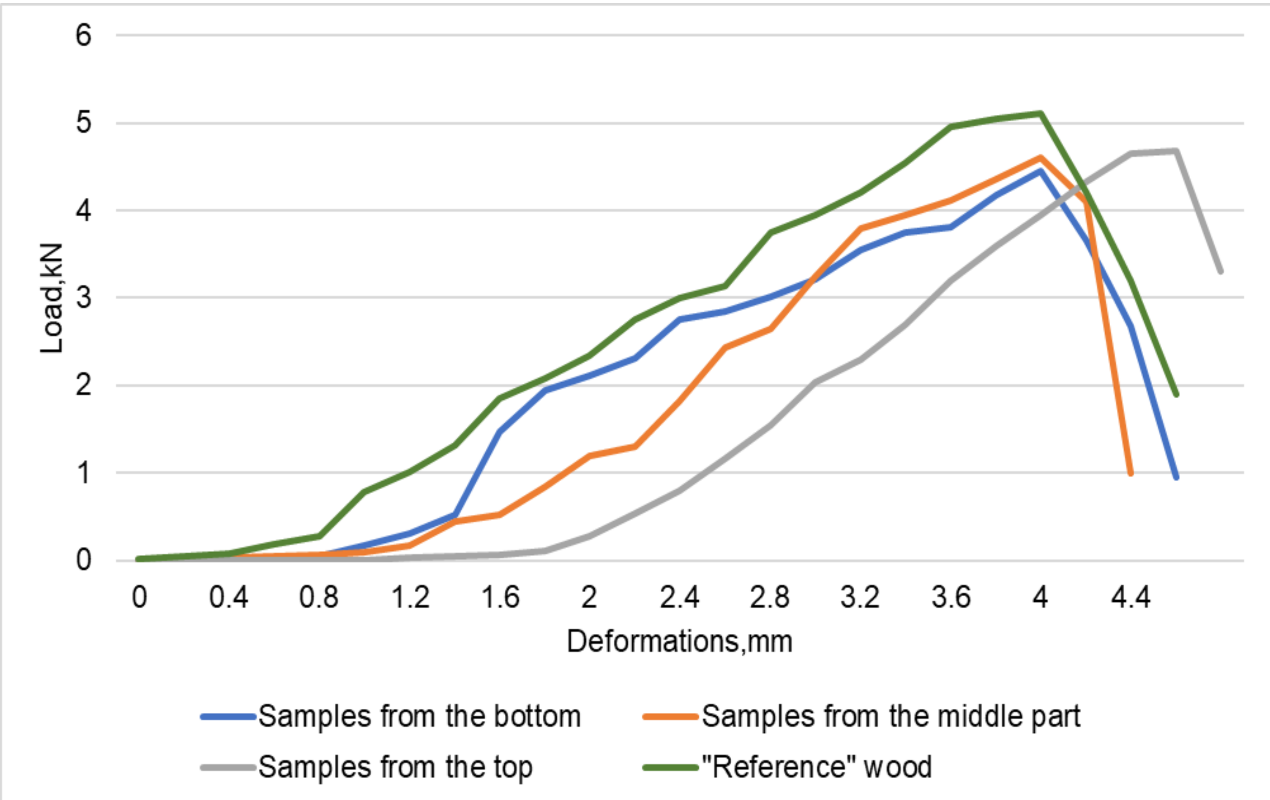


Figure 2. A load vs. deformations diagram for pine wood weakened by fire under shear along the fibers

where P_{max} is the maximum load, kN; *a, b* are the cross-sectional dimensions of the sample, mm.

Based on the test results, the statistical processing of the experimental data was performed.

The accuracy figure *P* (%) is determined using the following equation:

$$P = \pm \frac{m}{V} \cdot 100\%, \quad (4)$$

where m is the standard error of the mean; V is the coefficient of variation.

Based on the results of the tests, Table 1 was compiled in addition to the tests performed earlier.

Table 1. Comparative data on the mechanical properties of post-fire wood throughout the trunk height in comparison with reference wood

Type of test	Breaking load P_{max}, kN / Accuracy figure P, %				Stress σ, MPa / Strength decrease, %			
	Butt end	Medium part	Top end	Reference wood	Butt end	Medium end	Top end	Reference wood
Shear along the fibers	4.45 / ±1.41	4.61 / ±1.46	3.95 / ±1.25	5.11 / ±1.62	7.42 / 12.92	7.68 / 9.78	6.58 / 22.70	8.52
Static bending	1.12 / ±0.36	1.05 / ±0.33	0.95 / ±0.32	1.19 / ±0.38	32.26 / –5.84	30,24 / –11,76	27.36 / –20.16	34.27
Compression along the fibers	10.34 / ±3.27	9.88 / ±3.12	8.68 / ±2.75	12.12 / ±3.83	25.86 / –14,99	24,76 / –18,31	21.67 / –28.81	30.43
Tension along the fibers	6.57 / ±2.08	5.81 / ±1.84	4.91 / ±1,55	7.84 / ±2.47	82.17 / –8.39	72.63 / –23.58	61.51 / –30.61	98.11

The microstructure of pine was determined using scanning electron microscopy in the cross-section of the samples since this method is considered suitable for studying the structure of wood at the molecular level. The results of this study contribute to a better understanding of changes in the microstructure of wood throughout the trunk height and the mechanism of changes in the strength properties of post-fire wood.

The microscopic analysis of pine wood was performed to determine the number and diameter of tracheids, the thickness of their walls, and some other changes in the structure of wood. The study of tracheids was carried out both for post-fire and intact wood samples.

Figure 3 shows a significant post-fire increase in the number of tracheids as a result of fire in comparison with the reference samples. The largest increase in the number of tracheids is characteristic of the butt end.

Signs of a post-fire increase in the average diameter of tracheids were observed. Using a microscope, the resin channels in the reference and post-fire wood samples were calculated.

Changes in the density of the resin channels (the number of the resin channels per 1 cm^2) are characterized by the following pattern: in the top end, it decreases, and in the butt end, it increases, taking on a more rounded shape. This observation is confirmed by a number of studies (Kuroda et al., 2022; Park et al., 2022). Resin from the top layers runs down to the butt end of the trunk, which explains a sharp increase in the density of this area right after the fire, before wood is affected by a fungal disease (Kiseleva et al., 2020).

The microscopic analysis of post-fire wood showed that the wood cells are “empty” and the samples are quite light as compared to the reference ones. The analysis of density demonstrated the following: a decrease in density in the butt end as compared to reference wood was 10%, in the middle part — 24%, and in the top end — 44%.

Figure 4 shows the results of the analysis of the wood samples in the longitudinal section using optical microscopy.

Optical microscopy shows partial breaks and cracks along the fibers. The development of such cracks is associated with internal stresses that occur as a result of sudden temperature and moisture fluctuations. Wood begins to shrink. Its outer layers become drier than its inner layers.

High temperature during a fire has a destructive effect on the structure of wood. This type of cell wall destruction can be explained by the fact that under the influence of high temperatures, free moisture in the tube cavities boiled off, and that, in turn, led to an increase in the excess pressure of the vapor-air mixture, which contributed to the destruction of

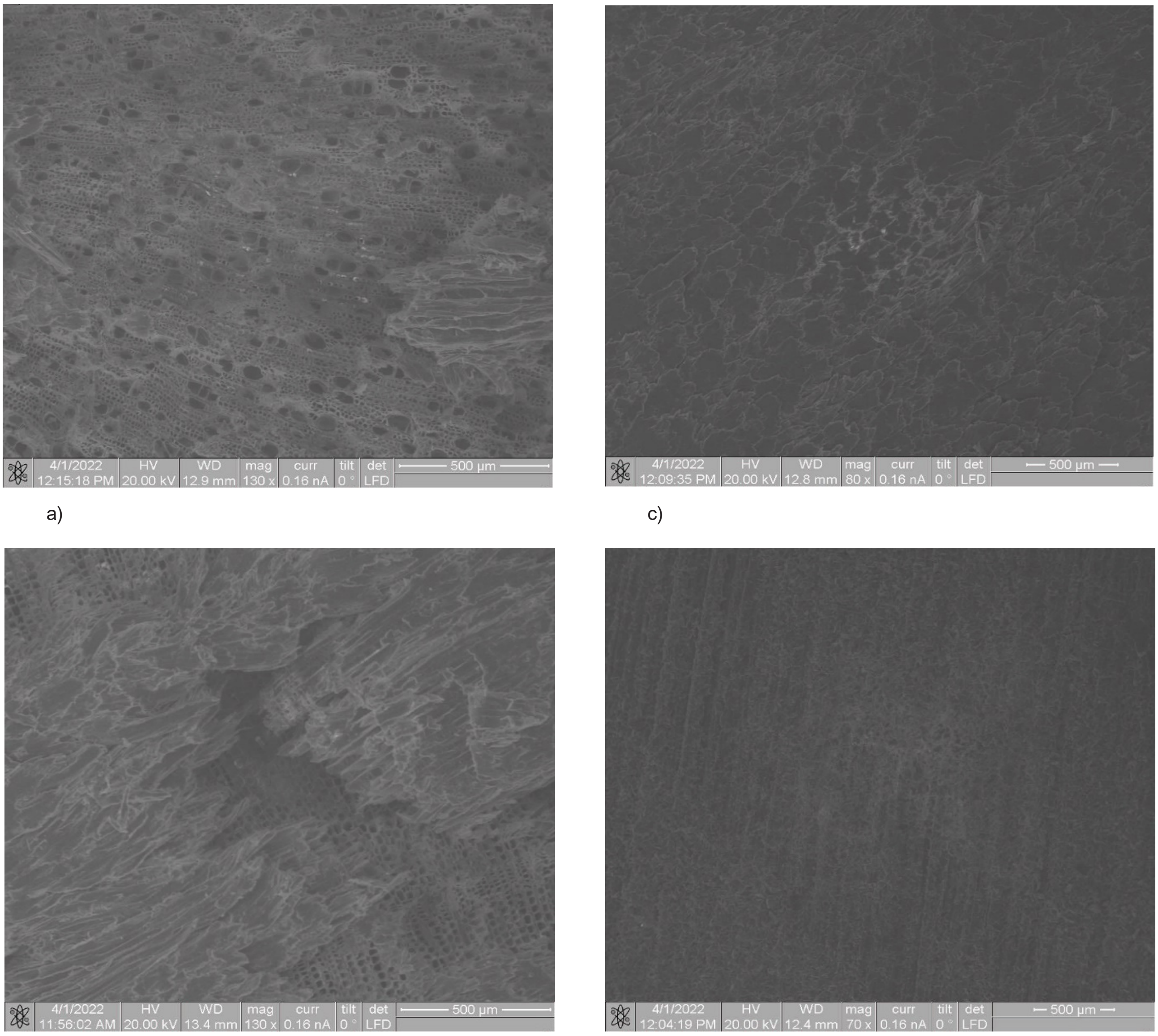


Figure 3. Analysis of the wood samples in the cross-section using scanning electron microscopy:
a) the butt end weakened by fire; b) the middle part weakened by fire;
c) the top end weakened by fire; d) the reference samples

the cell walls in the groups of tubes (Kantieva et al., 2021; Scandelli et al., 2021).

The study of the wood samples using scanning electron microscopy showed that in the case of creeping fires, up the trunk, fire damage is less.

Therefore, as a result of high temperatures, the mechanical properties of wood change: wood becomes brittle, thus, its shock resistance decreases. Qualitative changes in the microstructure of wood are also represented by changes in strength properties. The following pattern can be observed: post-fire wood is characterized by reduced strength properties. The maximum decrease in strength properties is observed in the top end and amounts to 22.7%; in the middle part and butt end, a decrease in strength under shear is 10–12%.

Conclusions

Thus, we can draw the following conclusions in respect of changes in the microstructure of raw wood under the influence of forest fires:

1. Fires cause changes in the anatomical structure of tubes and fiber tracheids. Anatomical changes in raw wood occur throughout the entire height of the trunk. The following pattern is observed: the shape and number of tracheids in the annual ring change. The butt end is characterized by a higher density of resin channels.

2. Fires cause changes in the number of tracheids. Quantitative changes are accompanied by qualitative changes represented by changes in strength properties. Anatomical changes correlate with changes in the strength properties of wood. The maximum decrease in strength properties is observed at the top end and amounts to 22.7% as compared to the reference wood. The minimum decrease in the strength properties of post-fire wood

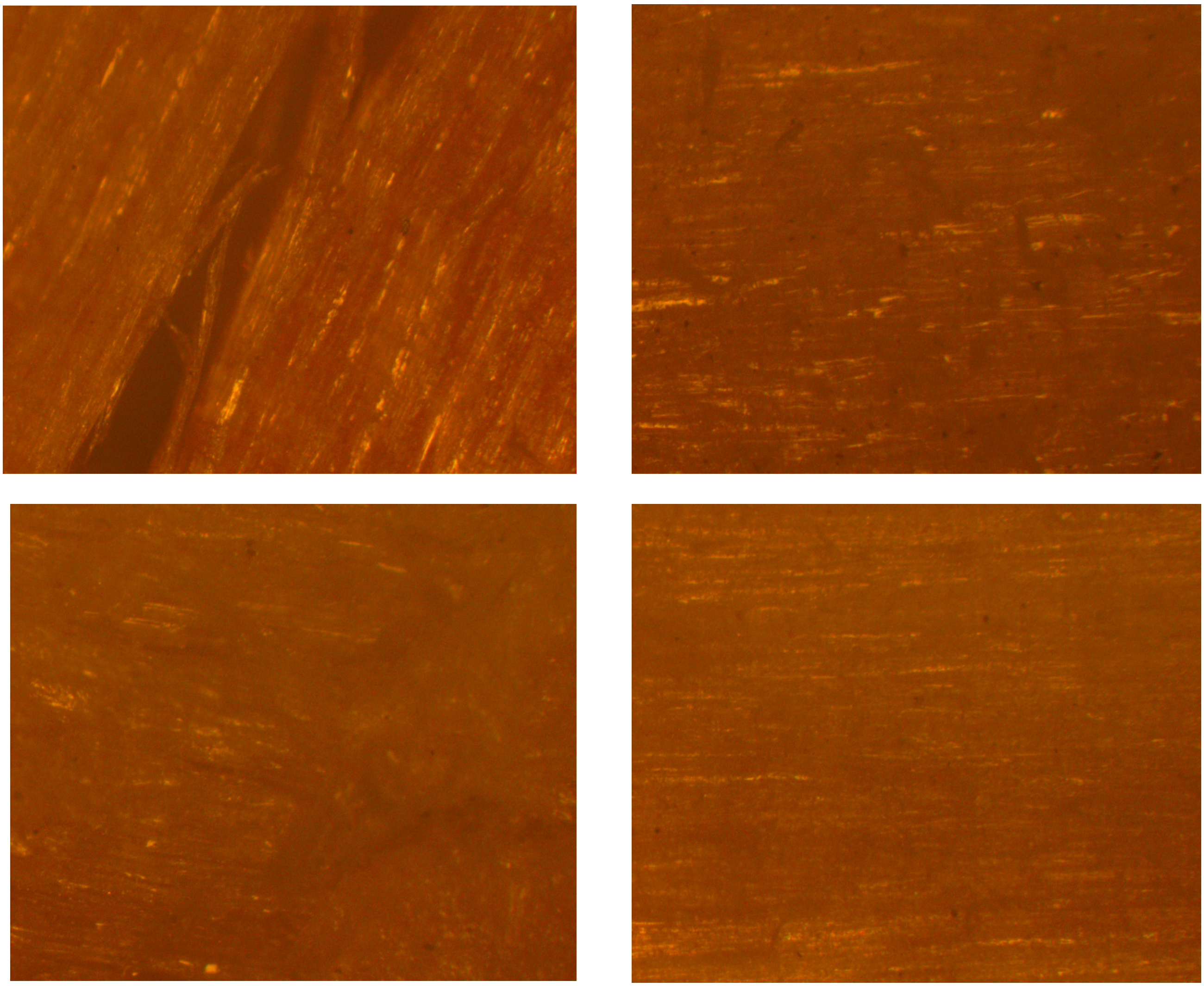


Figure 4. Analysis of the wood samples in the longitudinal section using optical microscopy:
a) the butt end weakened by fire; b) the middle part weakened by fire;
c) the top end weakened by fire; d) the reference samples

is observed in the butt end.

3. Post-fire wood is characterized by high resinosis in the butt end, higher density, and, therefore, higher strength properties. The peformed mechanical tests for static bending, compression along the fibers, tension along the fibers, and shear along the fibers show that the total strength decrease amounts to 6.0–15.0%.

4. Taking into account the strength properties of post-fire raw wood can help in solving a practical problem: is it always necessary to urgently cut down burnt trees that are still alive?

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МЕХАНИЧЕСКИЕ И МИКРОСТРУКТУРНЫЕ ИЗМЕНЕНИЯ СЫРЬЕВОЙ ДРЕВЕСИНЫ, ПОДВЕРЖЕННОЙ ОГНЕВОМУ ВОЗДЕЙСТВИЮ

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Аннотация
Нивелирование экологических, экономических, социальных и других последствий чрезвычайных ситуаций природного характера становятся сегодня все более актуальным. Одним из разрушительных бедствий являются лесные пожары, которые широко распространены в мире. На местах после пожара остается лес, который зачастую частично подвергается огневому воздействию. Обожженное дерево теряет иммунитет, поэтому на этих территориях происходит вспышка различных подкорковых видов насекомых-вредителей, которые заражают в том числе и здоровые деревья. Такой лес подвергается санитарной вырубке. **Целью работы** является определение остаточных механических свойств сырьевой древесины для использования в качестве конструкционного материала. Использованы **методы:** разрушающего и неразрушающего методов контроля механических характеристик материала. В **результате** установлено, что изменение микроструктуры древесины коррелируется с прочностными свойствами. Максимальное снижение прочностных свойств наблюдается в вершинной части дерева и составляет 22.7% по сравнению с эталонной древесиной. Минимальное снижение прочностных свойств древесины, подведённой огневому воздействию, наблюдается в комлевой части – до 15.0%. В срединной части снижение прочности составляет до 24.0%.

Ключевые слова
Древесина, пожар, прочность, микроструктура, строительные конструкции.