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IDENTIFYING PATTERNS IN THE RESISTANCE OF THERMALLY MODIFIED ASH WOOD TO WEATHERING

Oleksandra Horbachova
Corresponding author
PhD, Associate Professor*
E-mail: gorbachova.sasha@ukr.net

Serhii Mazurchuk
PhD, Associate Professor*

Vasyl Lomaha
PhD, Assistant*

Nataliia Buiskykh
PhD, Senior Lecturer*

Andrii Matviichuk
PhD
V. I. Vernadsky National Library of Ukraine
Holosiivskyi ave., 3, Kyiv, Ukraine, 03039

Nataliia Marchenko
PhD, Associate Professor
Technical Committee TC-18 "Forest Resources"
Lisodoslidna str., 2, Boyarka, Kyiv region, Ukraine, 08150

*Department of Technology and Design of Wood Products
National University of Life
and Environmental Sciences of Ukraine
Heroiv Oborony str., 15, Kyiv, Ukraine, 03041

Weathering of thermally modified wood negatively affects both the appearance of structures and their physical-mechanical characteristics, which further determines their service life. Given this, the object of the study was the resistance of ash wood varying degrees modification to abiotic environmental factors. It was found that the color stability of thermally modified wood samples is higher compared to untreated ones. A decrease in the value of the coordinate L from 68.4 to 33.6 indicates a decrease in lightness, that is darkening of the wood. Analysis of dimensional changes revealed increased swelling for untreated wood and amounted to 7.49 %, and for modified at a temperature of 200 °C – 1.75 %. The difference in shrinkage rates is much smaller – 2.09 % for wood of group III, which is 2 times less than untreated wood. The results confirm that thermal modification makes wood cell walls more hydrophobic by eliminating hydrophilic and hydroxyl groups of hemicelluloses. A linear dependence ($R^2 \approx 1$) of change in the physical characteristics of wood depending on its density due to the degree of modification has been established. Analysis of mechanical properties revealed that thermal modification increases the resistance of wood to compressive across the fibers by 2 times. Therefore, a comprehensive approach to analyzing the impact of weathering on the aesthetic, physical, and mechanical properties of thermally modified wood makes it possible to identify the principles of material stability depending on the treatment schedule. The identified mechanisms of transformation of material parameters contribute to the establishment of optimal parameters of thermal modification, which improve its characteristics. This creates the prerequisites for implementing new technological solutions focused on environmental friendliness and energy efficiency in production

Keywords: wood, ash, degree of thermal modification, weathering, moisture removal, drying cracks, strength

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1. Introduction

Wood aging is a natural process that significantly affects its mechanical and physical properties. The effect of aging on wood can lead to a deterioration of its characteristics, which in turn can cause problems in the construction and operation of wooden structures. Aging also affects the mechanical properties of wood, among which important indicators are strength, stiffness, and toughness. For example, shear or bending strength could decrease due to cellulose decomposition, resulting in structures losing their ability to withstand loads [1]. Over time, wood loses its ability to deform without breaking, which is a particularly dangerous phenomenon in structures where various types of loads act. Under modern conditions, when using a set of control and management tools, it is possible to influence plant productivity [2] and wood growth; in particular, the drying technology with the selection of effective process parameters [3] remains unchanged. After all, humidity is one of the key factors that affect the aging process of wood. High humidity levels could initiate the development of fungal diseases, which in turn leads to wood rotting. The durability of wooden structures could be partially improved by changing the properties of wood through thermal modification or acetylation [4]. These processes change its chemical structure, reducing hygroscopicity, improving biostability, and maintaining mechanical stability. As a result, wood as a material becomes ideal for use in outdoor structures.

Therefore, research into the impact of the operating environment on the degree of wood aging is relevant. The results will allow us to assess what processes occur and what solutions could be proposed to compensate for the negative consequences.

2. Literature review and problem statement

The study of changes in wood properties under the influence of UV radiation is important since the destruction of the wood surface by light could lead to color changes and a decrease in mechanical characteristics. This has significant consequences for the durability and aesthetics of wooden products. Thus, in work [5], a new instrumental setup was used to perform UV irradiation under the EGA-MS and Py-GCMS mode with *in situ* derivatization of fir and chestnut wood. The effect of ultraviolet irradiation was assessed by thermal stability and pyrolysate content. The results showed that UV degradation of the samples was mainly associated with the lignin fraction, and significant differences were observed between the two species. A qualitative comparison of EGA-MS profiles and semi-quantitative analysis of the composition of pyrolysates revealed that these methods could be used as a rapid monitoring tool to assess the UV destruction of wood. However, the study did not take into account the effect of photodegradation on the mechanical properties of materials.

Preservation of wood strength indicators in structures, in particular, is a critically important task that was solved in work [6]. The authors evaluated the effect of UV radiation on the elastic and viscoelastic properties of wood by the Lamb wave propagation method on samples of fir, poplar, oak, and alder wood exposed to UV radiation of different durations. In parallel with the Lamb wave propagation, mechanical three-point bending was performed to determine the modulus of elasticity (MOE), storage and loss moduli, as well as the loss coefficient. The difference in the values of the elastic modulus estimated by both methods was less than 4 %. In general, it was found that the action of UV radiation affected the decrease in the modulus of elasticity and the storage modulus of wood samples and led to an increase in their loss coefficient. Given this, the stiffness of the wood of the studied samples decreased and the viscoelasticity increased. However, it would be worthwhile to analyze the mechanical characteristics of structural elements with the transformation of structural wood elements.

Changes in the structure of wood caused by the action of physical and chemical factors in external structures were studied in [7]. Freshly cut dried pine wood was compared with samples obtained from floor beams in Safranbolu. A decrease in the compressive strength perpendicular to the fibers of the used wood was found, for which the indicator was almost 27 % lower compared to the control samples. However, it is important to understand the influence of each environmental factor on the durability and physical characteristics of the material at the microstructural level.

Therefore, in [8], the effect of water and moisture on the stability of archaeological wood was studied. It was established that the significant factor in the destruction of the main components – lignin and cellulose – was the ambient temperature. These transformations contribute to an increase in hygroscopicity, which also leads to a decrease in dimensional stability and resistance to decay. It is shrinkage and swelling that make it difficult to ensure optimal operation and durability of old wooden elements in structures.

A likely option to overcome the difficulties is to use thermal modification. This type of treatment is applied to improve the characteristics of wood under different environmental conditions. In [9], the sorption mechanism and water states of thermally modified wood under conditions of variable relative humidity were investigated. The results showed that TM inhibits monolayer and multilayer moisture sorption with increasing modification temperatures depending on the air moisture saturation. The obtained sorption isotherms indicate an increase in the hygroscopic stability of wood with increasing modification temperature. It was also worth investigating the change in the linear dimensions and geometric shape of the samples, which is important for the reliability of operation of wood products in an environment with high humidity. This makes the study incomplete.

Thermally treated wood is a relatively new material with improved properties. It is important to know the effect of sunlight on degradation processes during weathering. Therefore, the authors of [10] studied the degradation processes on samples of untreated and thermally modified wood of different species, exposing them to artificial and natural sunlight. Using SEM analysis, the features of degradation of the middle lamellae were established and the state of the cell wall was assessed. FTIR spectra indicated specific changes in surface chemistry during irradiation. It was found that ultraviolet light from natural or artificial sources primarily leads to lignin degradation. Such structural changes affect the wetting of the surface, which would need to be investigated to understand the behavior of the structure during operation under conditions of variable humidity.

This is the approach used in [11]. The authors used the Fox method to study the energy characteristics of the surface, which takes into account interphase interactions at the solid-liquid interface. It was found that the process of thermal modification of wood contributes to an increase in the resistance of its surface to wetting by reducing the polarity by 1.68 times with an increase in the duration of modification to 30 min. Analyzing the contact angle of wetting, a certain dependence on the free energy of the surface was revealed. Thus, for samples modified at 300 °C for 5 min, it is 64.5 mJ/m^2, and for 30 min – 24.1 mJ/m^2. It has not been investigated whether the obtained values change during cyclic moistening-drying, which accompanies wooden structures during operation.

However, in [12], the dimensional stability of thermally modified beech, poplar, and spruce wood, which was subjected to several wetting-drying cycles, was analyzed. The authors studied beech, poplar, and spruce. Additional extracts formed as a result of thermal modification were washed out during wetting cycles. During wetting cycles, additional extracts formed as a result of thermal modification were washed out. A positive effect of thermal modification on the dimensional stability of all groups of samples was noted. An improvement in dimensional stability was found to be up to 24–30 % during mild modification and by 26–54 % under high-temperature exposure. The effective dimensional stability of thermally modified wood was reduced compared to the initial efficiency after the first wetting cycle. After numerous soaking cycles, extractives and hemicelluloses formed as a result of thermal destruction are washed out of the samples. However, one should not ignore the influence of biotic factors, for the development of which increased humidity and temperature are favorable conditions.

Biological destruction could act separately or in combination with other types of degradation, so it is difficult to predict the degree of damage. In work [13], a modeling of the destruction process was carried out based on experimental data in order to approximate the prediction of biodamage. It was noted that for thermally modified wood, intensive biodegradation begins on day 40 and the specific density of the sample decreases to 530 kg/m^3, the value of the parameter χ ($\chi=\Delta\rho/\psi$) is 36.3 days. As a result of the research, a mathematical model of the process of biodegradation of wood by microorganisms was built, the fraction of destroyed material was determined, and the dynamics of biodegradation were simulated, which takes into account the degree of thermal modification of wood. However, the issues related to the development of targeted methods for the effective preservation of wooden structures remain unresolved. The likely reason is objective difficulties associated with the inability to reproduce operating conditions in a wider range of variation. After all, some species of wood-destroying fungi have even adapted to the decomposition of wood under the extreme conditions of the Arctic and Antarctic.

By studying archaeological wood under extreme conditions [14, 15], scientists were able not only to distinguish species by anatomical characteristics but also to identify the causative agents of the damage. The types of decay present and the degree of damage were determined by microscopic examination of cross-sections. Soft rot was identified as the dominant type of decay at 84 %; brown rot was found in 42 % of the samples, but the dominant type of decay was only in 13 % of the samples. The degree of degradation was generally high, with 62 % of the samples in the late stage of decay. However, the rate at which soft rot decay occurs has not yet been established. There is a potential risk that, as environmental conditions change, these wood-destroying fungi will become more active and may cause even greater losses in the future.

While reviewing the literature [5, 9–13], it was found that thermal modification somewhat improves the properties of wood and provides an increase in possible areas of use. However, the effect of moisture, UV radiation, and other environmental factors negatively affects the surface of wood, that is, weathering processes occur. All this allows us to state that it is advisable to conduct a study on the stability of properties of thermally modified wood against the action of variable environmental conditions. This could become the basis for expanding consumer interest in the material and extending the service life of finished products.

3. The aim and objectives of the study

The aim of our study is to identify the patterns of resistance of thermally modified wood against abiotic environmental factors. This will make it possible to develop optimal regime parameters for thermal modification and effectively use the material with an increase in the service life of the product.

To achieve the goal, the following tasks were set:

– to investigate the influence of operating conditions in the natural environment of ash wood of various degrees of processing on visual surface characteristics;

– to determine the level of influence of thermal modification of wood on its physical properties during weathering;

– to determine the effectiveness of thermal modification of ash wood on compressive strength indicators in the natural environment.

4. The study materials and methods

4. 1. The study hypothesis

The object of our study is the influence of the operating environment of wooden structural elements under natural conditions on the change in the surface and physical-mechanical properties of ash wood of various degrees of modification. The scientific hypothesis assumes a comprehensive approach to studying the transformation processes of untreated and thermally modified wood during aging in a natural environment to determine the optimal processing modes. It is evident that the variation of temperature during the day, the difference in humidity and mechanical wear reduce the protective properties of wood, which could lead to its faster degradation. Therefore, understanding the processes of environmental influence will contribute to the development of measures to improve the characteristics of the material and increase its service life.

4. 2. Tested materials and equipment used in the experiment

To assess the influence of environmental conditions on the physical-mechanical properties of wood, samples of untreated (control) and thermally modified ash were used. Samples measuring 20×20×30 mm were tested (Fig. 1). Thermal modification was carried out in a convection chamber without forced air circulation; the process took place in three stages. First, ash wood dried to 8 % was heated at a temperature of 105 °C for 1 hour. The second stage – thermal modification – lasted 10 hours at temperatures of 180 and 200 °C, respectively. The process was completed in a closed chamber by spontaneous cooling.

a *b* *c*

Fig. 1. Groups of experimental samples of ash wood: *a* — untreated; *b* — thermally modified at a temperature of 180 °C; *c* — thermally modified at a temperature of 200 °C

In total, 20 samples were tested in each group. Group I – untreated ash wood with an average density of 792 kg/m^3, Group II – thermally modified at a temperature of 180 °C, 729 kg/m^3, Group III – thermally modified at a temperature of 200 °C, 714 kg/m^3.

4. 3. Methodology for a comprehensive assessment of the influence of environmental parameters on the physical-mechanical characteristics of wood

4. 3. 1. Weathering

Samples after conditioning at 65 % relative humidity and 20°C temperature and initial measurements were placed on a stand. The stand for natural weathering according to SIST EN 927-3:2019 was placed in an open, unshaded area facing south, the angle of inclination was 45°. The samples were exposed to natural conditions for 36 months, starting from

June 2021 to June 2024. Then, a set of studies of changes in material properties under natural weathering conditions was conducted with samples of three groups (Fig. 2).

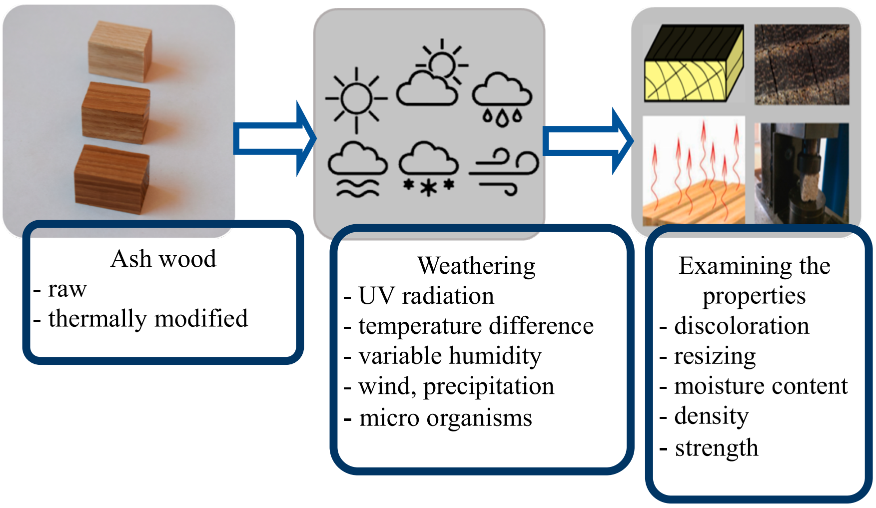


Fig. 2. Methodological scheme for assessing changes in indicators

4. 3. 2. Visual assessment of surface properties

The color of the wood samples was measured before and at the end of the weathering test on the tangential surface according to ISO/CIE 11664-4:2019. The color coordinates were determined according to the *CIELab* color space model. For each sample, the values were measured at 5 points and the average values were calculated. The *CIELab* system expresses color in the form of three components. L^* (brightness) – from 0 (black) to 100 (white), a^* coordinates from green ($-a$) to red ($+a$), b^* – from blue ($-b$) to yellow ($+b$) colors, respectively. The total color difference ΔE was determined as the square root of the sum of the squares of the differences of the corresponding coordinates [16].

The surface condition of the samples was also visually assessed for the presence of stains, delamination, and cracking.

4. 3. 3. Measurement of moisture removal and dimensional change

The equilibrium moisture content (EMC) of the samples was measured in a climatic chamber at 20 °C and a relative humidity of 65 %. The EMC of all samples was determined as the ratio of the difference in mass of the samples after equilibration in the climatic chamber for three weeks and the mass of the dried samples after weathering to the mass of the dried samples after weathering [17]. Control samples were also used as reference for determining the EMC before aging.

The moisture removal efficiency (MEE) of the samples was calculated as the ratio of the equilibrium moisture content of untreated and modified wood, respectively. Five replicates were used for each modification regime.

The linear shrinkage and swelling were determined according to the ISO 13061-13:2024 methodology. To determine the shrinkage, the samples were dried at a temperature of 100 °C to constant mass. To determine the swelling value, the samples were kept in an environment with a humidity of 96 % for 20 days. Measurements of dimensions were performed before and after drying or moistening with an accuracy of 0.1 mm. Shrinkage was calculated as the percentage decrease in size and volume due to moisture removal from the initial to the absolutely dry state. The swelling value was determined as the percentage increase in size and volume due to moistening from the absolutely dry state to the point of fiber saturation.

4. 3. 4. Density determination

According to the ISO 13061-2:2014 methodology, the following requirements were observed when measuring the samples. Measurements of the cross-sectional sides and the length of the test samples along the axes of symmetry were carried out with an accuracy of 0.1 mm. Weighing was carried out with an accuracy of ±0.2 %. Density was determined as the ratio of the mass of the sample to its volume.

4. 3. 5. Strength under compressive loading conditions

Strength indicators were determined according to ISO 13061-5:2020 and ISO 13061-17:2017. The maximum load under compressive conditions perpendicular or parallel to the fiber was determined on a PM-5 tensile machine with a maximum possible force of 50,000 N. An increasing compressive force was applied to the corresponding surface of the test specimen at a speed of 4.5 mm/min until the moment of failure and the value was recorded with an accuracy of 0.01 N. The tensile strength was calculated as the ratio of the destructive load to the area of application of the compressive force.

5. Results of investigating the patterns of changes in the characteristics of ash wood modified under different regimes under the influence of weathering

5. 1. Analysis of the transformation of aesthetic characteristics of ash wood under operating conditions

In this study, ash wood samples were subjected to experimental exposure by aging for 36 months (from June 2021 to June 2024) under natural conditions of a moderately continental climate. The city of Kyiv was chosen as the place of the experiment, which is characterized by an average annual air temperature of +7–9 °C, an average relative humidity of 75–85 %, and seasonal fluctuations in climatic parameters. Such conditions allowed us to obtain data on the behavior of wood under conditions that are as close as possible to real ones (Table 1).

Under the influence of UV radiation, changes in the color of the surface of the samples occurred, visible to the naked eye (Table 2). At the beginning of the study, the color varied from light yellow to dark chocolate' after exposure, the surfaces of all groups of samples lost their color and turned gray. The color was evaluated in the CIE Lab color coordinate system.

It is clearly visible that during exposure to natural conditions, the color of wood changes depending on the modification parameters. The coordinate L decreases for all groups of samples – from 1.25 times (thermally modified at 200 °C) to 1.5 times (untreated). That is, we could speak of some stability of the color of thermally modified wood. As for a and b, the nature of their change has a similar trend – an increase in the difference is observed for untreated wood (the smallest value is 1.96 and 2.2 times, respectively) in comparison with modified at a temperature of 200 °C (3.1 and 4.8 times). If we talk about the total color difference ΔE, then this value increases from 18.9 to 37.5 – a difference of about 50 % in each group. The results indicate a darkening of the surface, which also coincides with the visual assessment.

The results of mechanical wear and a decrease in the protective ability of the surface are shown in Fig. 3.

The best results were demonstrated by wood samples with a higher degree of modification (under high-temperature conditions) (Fig. 3, *c*). Drying cracks were barely noticeable on the end sections of some samples, and a small proportion of the layers of late wood became looser on the longitudinal sections. Ash of group II showed less resistance to operating conditions (Fig. 3, *b*). On the tangential surface, in the place of the late layer, surface destruction of the wood was detected, and on the radial surface, microcracks in this area. These samples are more susceptible to the negative impact of temperature drops since the number of shrinkage cracks on the cross-section increased and they could be seen with the naked eye. Untreated ash wood underwent the greatest changes under weathering conditions (Fig. 3, *a*). In addition to clearly expressed cracks on all sections, there is delamination of early wood. The surface became dirty gray, and black marks were visible at the point of contact with the base on which the samples were placed.

5. 2. Determining the physical properties of thermally modified wood during weathering

Evaluating changes in physical characteristics due to degradation, a comparative analysis of the results was carried out (Table 3). The mass loss was from 0.5 % to 3 %, depending on the degree of processing.

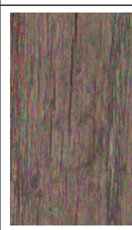
Table 1

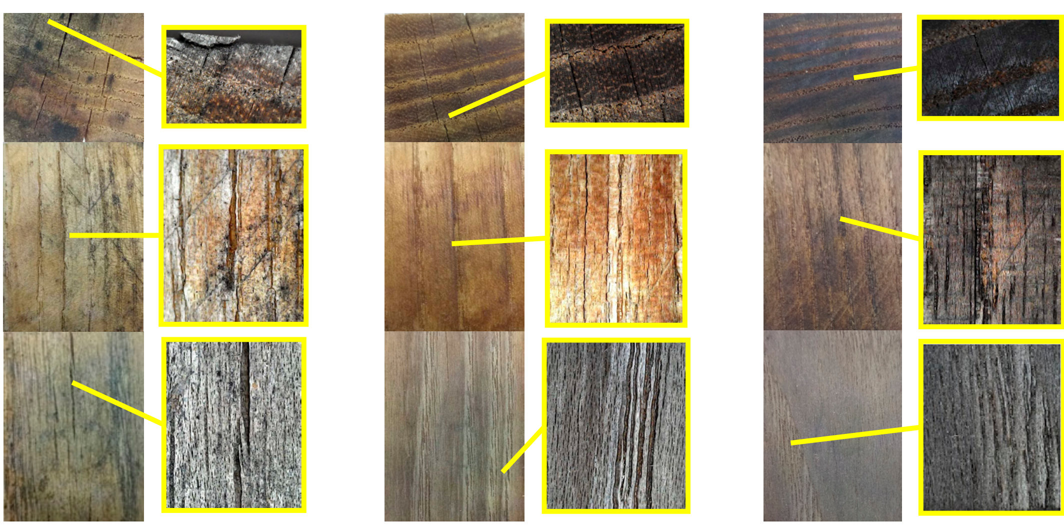
Hydrometeorological indicators of the sample exposure environment

Air quality indicator	Parameter value
Annual precipitation, mm	469.4–515.7
Maximum temperature in summer, °C	34.4–40.9
Number of freeze-thaw cycles, times/year	30–60
Minimum temperature in winter, °C	–12.8–(–26.2)
UV index, winter/summer	3–5/7–8
Average number of rainy days, days/year	146
Relative humidity, % autumn/winter/spring/summer	68–86/82–88/65–80/60–68

Table 2

Quantitative assessment of the change in surface color of samples

Parameter	Status of samples of different groups					
	Initial			After weathering		
	I	II	III	I	II	III
Visual result						
L	68.4	50.0	42.0	44.6	38.6	33.6
a	9.8	13.4	11.8	5.0	5.6	3.8
b	15.6	18.0	14.4	7.0	7.0	3.0
ΔE	–	18.9	26.5	25.8	31.4	37.5



a *b* *c*

Fig. 3. Surface texture of cross-sections of ash wood samples: *a* – untreated; *b* – thermally modified at a temperature of 180 °C; *c* – thermally modified at a temperature of 200 °C

Table 3

Changes in the physical characteristics of untreated and thermally modified ash wood

Parameter	Condition of ash wood samples								
	Group I			Group II			Group III		
	At the beginning of the study	After weathering	In a completely dry state	At the beginning of the study	After weathering	In a completely dry state	At the beginning of the study	After weathering	In a completely dry state
Determined									
Weight, g	10.80	11.42	10.50	9.11	9.58	9.00	8.93	9.35	8.89
Width, mm	21.70	22.58	22.08	19.85	20.20	19.78	20.88	21.10	20.88
Thickness, mm	20.05	20.60	20.23	20.10	20.30	20.08	20.08	20.23	20.03
Length, mm	31.33	31.50	31.48	31.30	31.38	31.33	29.83	29.80	29.80
Calculated									
Moisture absorption, %	5.74			5.12			4.65		
Swelling, %	7.49			3.04			1.75		
Equilibrium moisture content, %	2.91			1.27			0.45		
Shrinkage, %	4.24			3.47			2.09		
Moisture removal efficiency, %	–			56.17			84.50		
Density in absolutely dry state, kg/m^3	747			723			713		

The level of moisture absorption for all groups of samples has approximately the same value – 5 %. But the swelling is different. Thus, for untreated wood, it is 7.49 %, modified at a temperature of 200 °C – 1.75 % to the initial dimensions. The difference in shrinkage indicators is much smaller – 2.09 % for wood of a higher degree of modification, which is 2 times less compared to untreated. Thermally modified wood, depending on the degree of processing, had a correspondingly lower equilibrium moisture content than untreated wood, and the best moisture removal efficiency – 84.4% – was observed under conditions of exposure to a temperature of 200 °C.

Changes in the size of the samples led to a slight decrease in density – a maximum of 6 % in untreated wood.

Analysis of the change in the main physical parameters of the studied groups of ash wood of different degrees of thermal modification due to weathering in the natural environment from the initial values is shown in Fig. 4. The plots are based on the values from Table 3 calculated taking into account the determined parameters at the beginning of the study, after weathering, and in a completely dry state. The variation of the values is displayed relative to the average density of the wood in each group of samples.

A linear dependence of change in the physical characteristics of wood depending on its density due to the degree of modification has been established. The significance of the relationship is evidenced by correlation coefficients approaching 1. The dependence is somewhat smaller for the value of shrinkage – R^2=0.8514 (Fig. 4, *d*), but it should also be assessed as a strong correlation.

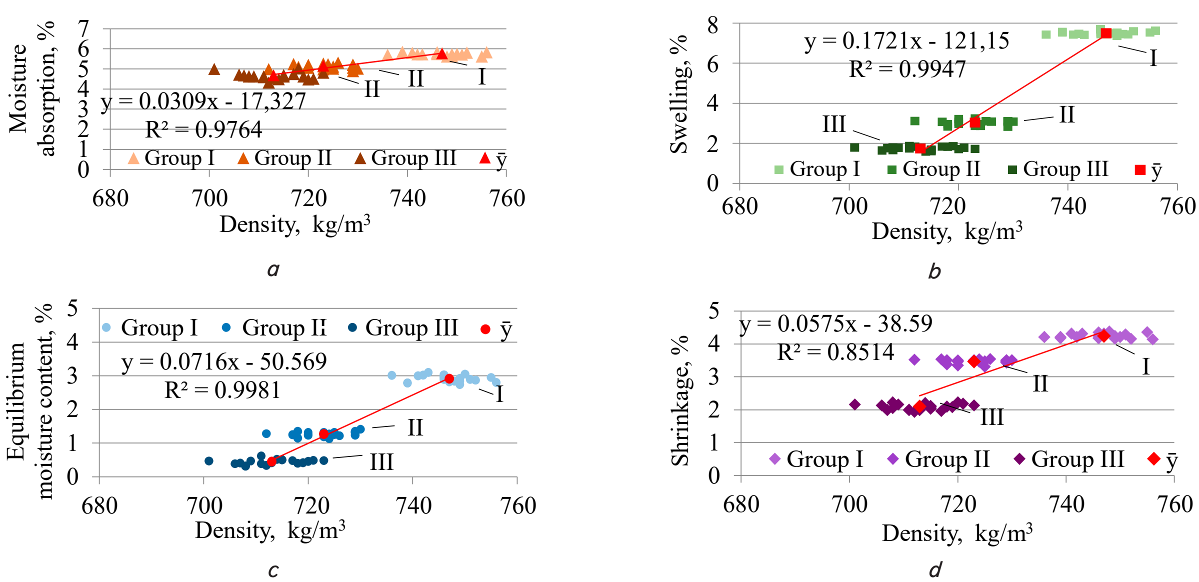


Fig. 4. Correlation between the calculated physical parameters relative to the average density of samples: Group I — untreated ash wood, Group II — thermally modified at a temperature of 180 °C; Group III — thermally modified at a temperature of 200 °C; *a* — moisture absorption; *b* — swelling; *c* — equilibrium moisture content; *d* — shrinkage; ȳ — average value of the parameter in each group

5. 3. Assessment of the effectiveness of thermal modification of ash wood on compressive strength indicators in the natural environment

Regarding the effect of weathering on the strength of ash wood along and across the fibers, the results are ambiguous (Fig. 5).

One can see that the resistance to compressive loading along the fibers of the samples of groups I and II increased slightly – by 7 and 9 %, respectively. For ash thermally modified at 200 °C after weathering, the indicator decreased by 2 times. Under the conditions of loading across the fibers, the result is different. Thus, in the control samples, as well as modified at a temperature of 180 °C, after exposure to environmental conditions, the tensile strength decreased to a greater extent – by 12 and 29 %, respectively. For the samples of group III, an increase in the value by 2 times was recorded.

Worth considering is the crushing of the samples and the nature of the fracture (Fig. 6–8).

During the study, while loading along the fibers, creasing in the diagonal direction was observed in all samples with some differences. Thus, in samples of group I (Fig. 7, *a, b*) a longitudinal crack in the center is clearly visible. In wood thermally modified at a temperature of 180 °C (Fig. 7, *d*), delamination occurred from the side of the surface, which was actively exposed to the environment. And the samples with the greatest degree of modification (Fig. 7, *f*) scattered into prismatic particles with a fracture line perpendicular to the annual layer.

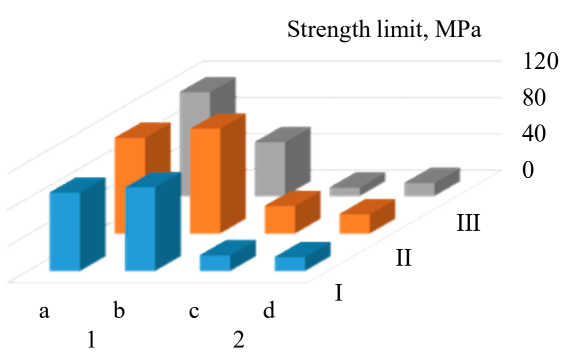


Fig. 5. Strength of ash wood under compression conditions: *1* – along the fibers; *2* – perpendicular to the fibers; *a, c* – at the beginning of the experiment; *b, d* – after weathering

During the compression test across the fibers, the same result of destruction was obtained – delamination of wood in annual layers (Fig. 8). Small fractions of destroyed particles were observed in samples of group II before weathering and group III after weathering (Fig. 8, *e, f*). Also worth noting is the brittle structure of wood thermally modified at 200 °C.

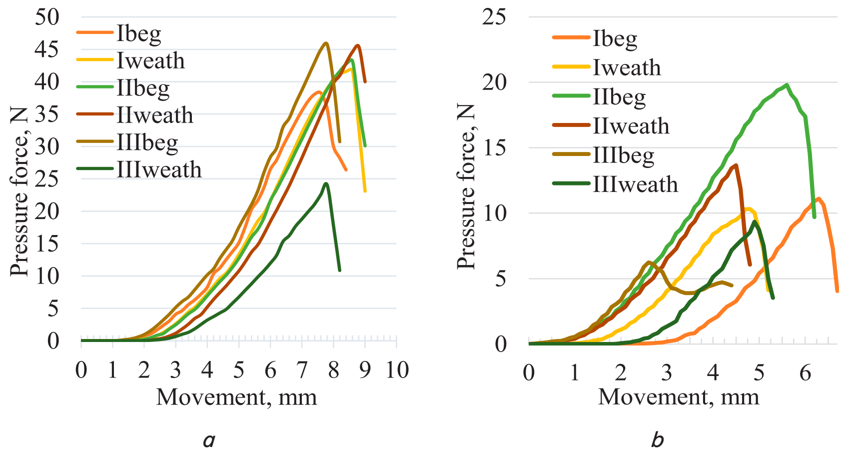


Fig. 6. Dynamics of fracture of samples in the load-displacement system: *a* – compression along the fibers; *b* – compression across the fibers; I – untreated; II – thermally modified at a temperature of 180 °C; III – thermally modified at a temperature of 200 °C; index beg – value for samples at the beginning of the study; index weath – value after weathering under natural conditions

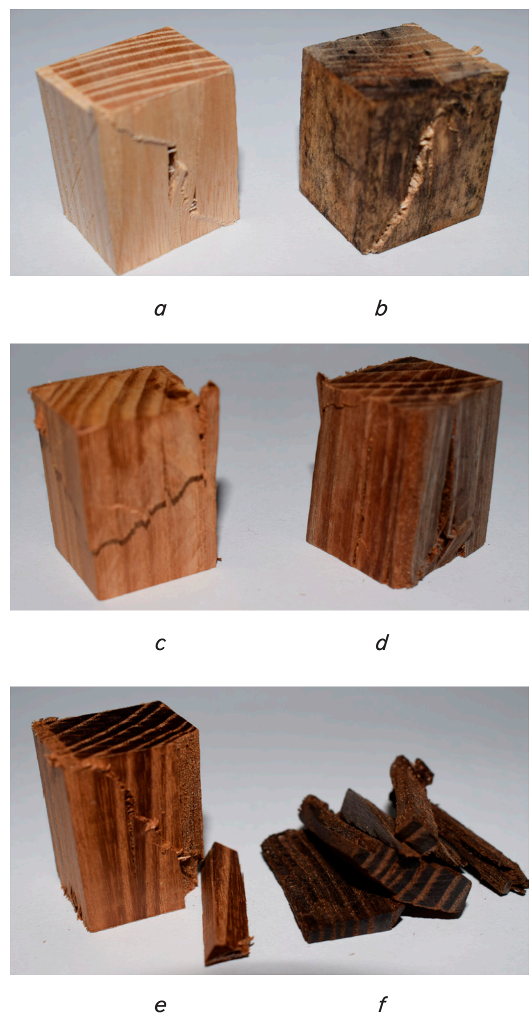
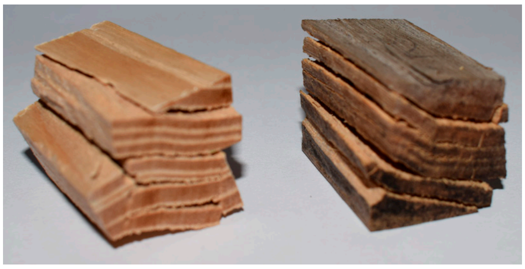


Fig. 7. Condition of the sample after destruction under the action of compressive loading along the fibers: *a* – group I, before weathering; *b* – group I, after weathering; *c* – group II, before weathering; *d* – group II, after weathering; *e* – group III, before weathering; *f* – group III, after weathering



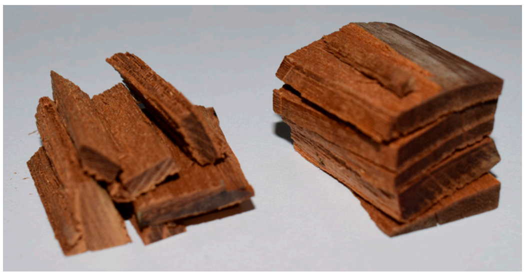


Fig. 8. Condition of the sample after destruction under the action of compressive loading across the fibers: *a* – group I, before weathering; *b* – group I, after weathering; *c* – group II, before weathering; *d* – group II, after weathering; *e* – group III, before weathering; *f* – group III, after weathering

6. Discussion of results based on investigating the influence of natural conditions on the properties of wood

When studying the surface changes of wood, the results (Table 2, Fig. 3) confirm that the change in color and graying of wood is a natural process that occurs under the influence of natural weathering. Wood, as a natural material, is exposed to various external influences, including ultraviolet radiation, humidity, temperature fluctuations, and precipitation. These factors significantly affect its physical and chemical properties. Weathering under natural conditions could lead to the oxidation of wood components, such as lignin and cellulose, which, in turn, causes changes in color [16, 18]. For example, over time, wood could acquire a gray tint, which is a consequence of the degradation of pigments and other organic elements. This process could vary depending on the type of wood, its initial color, as well as environmental conditions. Changes in the color of wood are not an isolated case and are confirmed by the results of many research groups that have studied similar phenomena on different types of wood [19]. These transformations are explained by chemical changes during irradiation and the appearance of new chromophore structures. In addition, it is noted that the greatest surface changes are experienced at the beginning of studying. However, the comparative studies did not take into account the positive effect of thermal modification on increasing the resistance of wood against impact factors.

UV radiation initiates photooxidation and leads to a decrease in the strength and aesthetic properties of the material (Fig. 3, 7, 8). Atmospheric factors also play an important role in the degradation of wood. In particular, regular wetting and drying of wood under the influence of precipitation, as well as daily and seasonal fluctuations in relative humidity, significantly affect its structure (Table 3). Our results are consistent with previous studies [9, 17] and indicate a proportional relationship between an increase in the modification temperature and a decrease in the hygroscopicity of the material and are consistent with the results of the equilibrium moisture content (Fig. 4). The reduced amount of bound water in both studied groups of thermally modified wood means that the cell wall of wood becomes more hydrophobic after thermal modification due to the partial elimination of hydrophilic hydroxyl groups of hemicelluloses. This means that taking this fact into account expands the possibility of reliable use of thermally modified wood directly under conditions of moisture difference.

The moisture removal efficiency (MEE) of modified wood is mainly due to irreversible chemical changes in cell wall components. In addition, they have an impact on the reversible effects of annealing at temperatures above 100 °C beyond the softening point of amorphous polymers. It could be assumed that the reversible change in hygroscopicity is associated with the presence of degradation products of thermal modification, which reduce the porosity of wood. Contrary to the generally accepted opinion that hydroxyl groups available for moisture absorption are significantly reduced during thermal treatment, there is a possibility that the equilibrium moisture content depends on the availability of hydroxyl groups. This issue has not been addressed in existing studies, therefore, the establishment of additional mechanisms for controlling equilibrium moisture content is a relevant and promising area for future research.

However, unlike [12, 20], our study has established a strong relationship between the average density of wood and its physical characteristics (Fig. 4) taking into account the influence of temperature differences and solar radiation, and not only wetting-drying. This will allow us to give a more comprehensive picture of the behavior of wood under operating conditions. That is, we can state that the mechanism of wood drying processes and its behavior under variable environmental factors have been determined, which are certain advantages of this study. This may be especially relevant under conditions of climate change, when the level of influence may vary more significantly.

A comparison of experimental studies on the influence of natural conditions on the change in material strength under compressive loading along and across the fibers indicates an ambiguous nature. In particular, for thermally modified ash at a temperature of 200 °C after weathering, the compressive strength along the fibers decreased by half. Under conditions of loading across the fibers, the opposite result could be observed – a doubling of the indicator. This does not differ from practical data, well known from works [6, 21, 22]. In those studies, the authors emphasize that the decrease in wood strength could be caused by modification processes that occur at high temperatures. Such modification is not an isolated phenomenon; its consequences are significantly enhanced under the influence of long-term changes in temperature and humidity indicators of the environment. However, in contrast to the results of studies reported in [7, 20, 23], our data on the influence of thermal modification and natural weathering on the change in wood properties allow us to state the following:

– a significant impact on reducing the ability of wood to absorb moisture is exerted during thermal modification, which also reduces the risk of shrinkage and swelling;

– processing at temperatures below 200 °C contributes to an increase in the compressive strength of the material;

– the main regulator of the weathering process of wooden structural elements is the change in structural components under the influence of high temperature, which also prevents deformation and the appearance of cracks when air parameters change.

Such conclusions could be considered appropriate from a practical point of view because they allow for a reasonable approach to determining the optimal operating parameters of the technology of thermal modification of wood depending on the operating conditions of the finished product. That is, there is a possibility of minimizing production costs during the technological process of manufacturing modified wood with an increased service life. The cost of production of thermally modified wood could be adjusted downwards and the efficiency of selecting technological process modes could be increased for the purposeful production of material with specified properties. This, in turn, contributes to reducing the costs of repair and replacement of elements. It also increases economic feasibility, consumer interest, and expands the scope of use of such wood in construction and other industries, which are certain advantages of this study. However, it should be noted that certain surface changes still occur (Fig. 3). The presence of microcracks under favorable temperature and humidity parameters of the environment will eventually cause damage by biological factors [24, 25]. This uncertainty imposes some limitations on the use of our experimental results, which could be regarded as a drawback of this study. These limitations cannot be removed within the scope of this study; therefore, a potentially interesting field of future research arises. Thus, there are various synthetic and natural products on the market for protecting wooden surfaces from atmospheric influences. The development of protective measures in combination with thermal modification is of great importance for reducing the requirements for wood care in structures located outdoors and could have a serious positive impact on the environment.

7. Conclusions

1. Wood aging is a complex process that affects its physical-mechanical properties. This issue is of particular importance in construction, where wood is used not only for aesthetic but also for functional criteria. Understanding the wood aging process and its consequences makes it possible to find effective solutions to prevent negative effects, which, in turn, will ensure the durability and stability of wooden structures. Based on the analysis of the obtained visual assessment results, the following conclusions are drawn:

– the use of reflectance spectrometry in the visible range and the *CIELab* color coordinate system makes it possible to obtain more accurate and objective results regarding color changes;

– ultraviolet (UV) radiation causes changes in the color of the wood surface that are visible to the naked eye and has a destructive effect on the color pigments and wood structure, which leads to the loss of its original appearance;

– after exposure to natural conditions, the samples lost their color (the spectrum ranged from light yellow to dark chocolate), which indicates chemical changes that lead to the degradation of the color components of the wood. Systematic monitoring of the condition of wood in structures and timely treatment are key elements in ensuring its reliability and safety.

2. Weathering of wood is a complex process that includes not only the influence of UV radiation but also changes in air humidity and temperature. The influence of these factors on ash wood was established while determining its physical properties. There is a significant difference in swelling rates between untreated and thermally modified wood. The swelling of untreated wood is 7.49 %, which is 4 times higher compared to that modified at a temperature of 200 °C. The difference in shrinkage rates between treated and untreated wood is smaller, in particular, for wood with a higher degree of modification this indicator is 2.09 %, which is half as much as compared to untreated wood. The best moisture removal efficiency (84.4 %) is observed for wood modified at a temperature of 200 °C. This indicates that thermal modification under optimal conditions significantly reduces the ability of wood to change its dimensions and humidity. This is an important characteristic for using wood in an environment with variable temperature and humidity parameters.

3. Analysis of the compressive strength along and across the fibers demonstrates interesting results that may have practical significance in materials science and wooden housebuilding. An increase in load resistance was noted in samples of groups I and II by 7 and 9 %, respectively, i.e., low-temperature thermal modification has a positive effect on the structure of wood. However, a significant decrease in the indicator for ash thermally modified at a temperature of 200 °C indicates that excessive thermal treatment could lead to destruction of the wood structure and a decrease in mechanical resistance. The compressive strength across the fibers after the weathering process decreased by 12 and 29 % for the control and modified wood samples. As for the samples with the highest degree of modification, an increase in the tensile strength by 2 times was found. Thus, our results emphasize the importance of optimizing the processes of thermal modification of wood, as well as the need for a detailed study of the mechanisms underlying changes in its physical characteristics. This will contribute to the development of new wood processing technologies to achieve technically sound characteristics.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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