Using Siberian Fir (*Abies sibirica*) Dead Wood in Wood Fiberboard Production

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This paper considers the possibility of using Siberian fir (*Abies sibirica*) wood damaged by *Polygraphus proximus* Blandford after various periods of its death (up to 19 years) as raw material to produce fiberboard. Damaged wood was mechanically processed into chips of various dimensions as per GOST 15815(1983). The produced chips were used to prepare wood fiber pulp using thermomechanical methods and two stages of grinding with approximately the same conditions as those used to produce wet fiberboard. Fiber refining was performed using fibrillating refiner discs with all other conditions being equal. The paper considered the changes in quality indicators and fractional composition of fibers during the preparation of wood fiber pulp after different periods of wood death, as well as physical and mechanical properties of produced boards. The obtained research results may indicate the possibility of effectively using damaged Siberian fir wood after different periods of its death as raw material to produce fiberboards, while providing physical and mechanical properties of products (density 960 to 1070 kg/m^3, static bending strength 36 to 44 MPa, internal bonding 0.51 to 0.7 MPa, modulus of elasticity 3880 to 4750 MPa, deflection 2.7 to 3.6 mm) that comply with GOST 4598-2018 (EN 622-2), while not requiring binding resins.

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INTRODUCTION

The woodlands of taiga, the boreal forest, are the most important link in the global ecosystem (Bonan 2008; Hansen *et al.* 2013; Safonova *et al.* 2019; Sul'tson *et al.* 2020). Despite the renewability of woodlands, in the context of climate change, it is important to consider the spread of various pests, in particular, the bark beetle (*Polygraphus proximus* Blandford). Beetle infestation causes rapid death of firs (*Abies sibirica*) in forest ecosystems (Baranchikov *et al.* 2010; Hansen *et al.* 2013; Kerchev 2014; Helbig *et al.* 2016; Pashenova *et al.* 2018; Safonova *et al.* 2019). The resulting forest deterioration and degradation are very significant (Hansen *et al.* 2013). In Siberia, over the past 15 years, massive outbreaks of *P. proximus* have occurred in large forest areas, particularly in the Krasnoyarsk Territory (Baranchikov *et al.* 2010; Pashenova *et al.* 2018; Debkov 2018; Vais *et al.* 2024), where the problem has reached catastrophic proportions. Healthy trees dry out in 3 to 4 years, with a high rate of firs dying off in the outbreak (Krivets *et al.* 2015; Sul'tson *et al.* 2020). Such changes can be attributed to the wood's low bioresistance to fungal diseases and formation of internal rot (Falaleev 1963).

The accumulation of significant volumes of Siberian fir with different periods of time having passed after its death, including in the Krasnoyarsk Territory, and lack of measures to remove dead wood entails the risk of catastrophic fires and subsequent proliferation of secondary pests (Bonan 2008; Baranchikov *et al.* 2010; Hansen *et al.* 2013; Krivets *et al.* 2015; Helbig *et al.* 2016; Debkov 2018; Pashenova *et al.* 2018; Safonova *et al.* 2019; Sul'tson *et al.* 2020; Vais *et al.* 2024). The use of dead wood, low-quality, low-value, logging residues, and wood processing waste in wood processing is a task of primary importance (Ihnat *et al.* 2017, 2020; Ammar *et al*. 2018; Irle *et al.* 2018; Vititnev *et al.* 2021c; Bekhta *et al.* 2022). The solution to this problem will contribute to the increased efficiency and comprehensive use of wood biomass (Pirayesh *et al.* 2013; Lubke *et al.* 2014; Ihnat *et al.* 2017, 2018).

Previous research (Trent *et al.* 2006; Korotaev *et al.* 2013; Pen *et al.* 2023; Koptev *et al.* 2024; Park *et al.* 2024) has noted the possibility of using damaged dead wood of various coniferous species, particularly Siberian fir (Pen *et al.* 2023), as raw material to produce pulp and paper products.

The paper (Marra 1978) has also considered the issues of using dead pine wood to produce fiberboard using a dry method as per the standards with some reduction in physical and mechanical properties of the board materials.

Refining is the main unit operation in the production of wood fiber materials that determines the dimensional and qualitative characteristics of fibrous semi-finished products (Laskeev 1967; Bordin *et al.* 2008; Alashkevich *et al.* 2010; Chistova 2010; Kerekes 2011; Li *et al.* 2011; Hua *et al.* 2012; Zyryanov 2012; Lubke *et al.* 2014; Gharehkhani *et al.* 2015; Forouzanfar *et al.*2016; Berna *et al.* 2018; Vititnev 2019; Przybysz *et al.* 2020), and in turn, the physical and mechanical properties of finished products (Laskeev 1967; Alashkevich *et al.* 2010; Chistova 2010; Zyryanov 2012; Ihnat *et al.* 2015; Tikhonova *et al.* 2015; Vititnev 2019).

The raw materials, their type and species composition, structural features, and properties are vital and determine the efficiency of production at various technological stages of wood fiber production (Alashkevich *et al.* 2010; Chistova 2010; Zyryanov 2012; Vititnev *et al.* 2021a,b,c, 2022).

Once damaged by insects, the wood is destroyed by wood-decay fungus. Its structure and properties change, which to a certain extent can increase its susceptibility to subsequent processing in the production of fibrous semi-finished products used to produce wood-fiber materials (Mersov 1989; Park *et al.* 2024).

Based on numerous studies (Marra 1978; Mersov 1989; Strand and Mokvist 1989; Nabieva 2004; Bordin *et al.* 2008; Alashkevich *et al.* 2010; Vititnev *et al.* 2021a, 2021b, 2022; Park *et al.* 2024; Wu *et al.* 2024), it can be assumed that dead fir wood can be used as a raw material for the production of environmentally friendly fibreboards with the required physical and mechanical properties with the exclusion of binder resins. The use of an effective mechanism of influence during refining, taking into account the peculiarities of fibre destruction after the death of wood can ensure the production of wood-fibre semi-finished products with the required dimensional and qualitative characteristics while reducing energy consumption for the refining process.

Until now, insufficient attention has been given to issues related to the possibility of using dead wood of Siberian fir as raw material for the preparation of fibrous semi-finished products without chemical treatment in the production of fiberboards, the features of wood fiber destruction, their dimensional and quality characteristics, *etc.*, taking into account the period after its death (Marra 1978; Mersov 1989; Alashkevich *et al.* 2010; Chistova 2010; Zyryanov 2012; Vititnev 2019; Vititnev *et al.* 2021a, 2021b, 2021c, 2022;

Park *et al.* 2024; Wu *et al.* 2024).

Research in this area will reveal the potential and improve the rationality of the integrated use of secondary resources for existing enterprises and help address a number of environmental and economic issues.

The aim of this research was to define whether it is possible to use dead Siberian fir wood as raw material to produce environmentally friendly fiberboards while excluding binding resins, to analyze the features of fiber destruction during refining using a fibrillating action mechanism and physical and mechanical properties of resulting fiberboards with account of the period after the wood death.

EXPERIMENTAL

Methods for Conducting Experimental Studies

Forest stands were selected using the database of damaged and dead stands as a result of outbreaks of mass reproduction *P. proximus* provided by the Center of Forest Protection of the Krasnoyarsk Territory. Subsequent subjective selection of damaged areas was based on the time of death of stands, in accordance with generally accepted methods of taxation. The cores were sampled, followed by the selection of models from 100 trees with various death age. The period of wood death was determined using cross-sectional dendrochronology methods (Shiyatov 1986; Naurzbaev 2005; Baranchikov *et al.* 2011, 2014; Tychkov *et al.* 2012, 2015). For cross-dating, four cores were taken from fir trees dead as a result of bark beetle impact at a breast height of 1.3 m, with subsequent abrasion of the samples to perfect smoothness of the surfaces. The cores were further processed and analysed in CooRecorder (version 9.3.1, Cybis Elektronik & Data AB, Saltsjöbaden, Sweden), and cross-dated in CDendro (version 9.3.1, Cybis Elektronik & Data AB, Saltsjöbaden, Sweden). In the authors' case, control and model trees were located within the same quarter and exposed to the same external factors, which allows determining the date of death with high accuracy using such methods (Andreev *et al.* 1999).

The raw material was wood chips obtained mechanically from Siberian fir wood with different periods of death after being attacked by the bark beetle *P. proximus* on a tree stand in the Emelyanovsky district of the Krasnoyarsk Territory. A block was taken from each tree sample at a level of 1.3 m from the ground. The period after death ranged from 5 to 19 years, and a block of living fir wood of a similar diameter (20 to 25 cm) was also collected as a reference sample of undamaged wood (0 years). The samples were sawn into discs for subsequent manual mechanical production of chips to be used as raw materials in the production of fiberboards.

Dimensions of the produced chips corresponded to those of technological chips as per GOST 15815 (1983). The resulting chips were processed in two stages to produce thermomechanical wood pulp (TMP) under similar conditions as during fiberboard production. The resulting semi-finished products were used to manufacture fiberboard samples as per the traditional wet-process technology of fiberboard production (Vititnev 2019).

The chip preparation process at the first stage was studied in a laboratory hammer mill at a concentration of ≈40% to pre-break the chips into bundles and coarse fibers comparable in size and quality characteristics and fractional composition (Marra 1978; Mersov 1989; Chistova 2010; Zyryanov 2012; Vititnev 2019; Vititnev *et al.* 2021a, 2021b, 2021c, 2022). The separated fibers were obtained at the first stage in a defibrator in the course of fiberboard production. The prepared wood chips were soaked for 12 h in tap water at a temperature of

22±2 °C, after which they were subject to short-term thermohydrolytic treatment in a heater at 160 °C for 2 min. Steamed chips were fed by gravity and crushed in one pass through the crushing chamber, all other conditions were equal.

The wood fiber pulp refining process was studied on a single-disc MD experimental refiner, a unit maximally similar to an industrial one. All other production conditions were equal. At the second stage, wood fiber pulp was refined using a scientifically sound design of fibrillating refiner discs having an interknife distance of 6 mm and an interknife depth of 6 mm (Vititnev 2019; Vititnev *et al.* 2021a, 2021b, 2022) at the optimal process parameters for fiberboard production established earlier by the research (Vititnev 2019; Vititnev *et al.* 2021b, 2022): the working gap of the discs was g = 0.1 mm, and the concentration of wood fiber pulp was = 3%. The preferential efficiency and feasibility of using innovative discs in refining wood fibers in fiberboard production has been confirmed by numerous research (Vititnev *et al.* 2018, 2021a, 2021b, 2022).

In the experiment process, after each stage of processing the dimensional and qualitative characteristics (degree of refining (DS), water retention values (WRV, %), fraction composition (F_1, F_m, F_f, %), average length (L_a, mm), average diameter (d_a, mm), slenderness ratio (L_a/d_a)) of the obtained wood fiber samples were evaluated according to literature studies (Laskeev 1967; Mersov 1989; Chistova 2010; Zyryanov 2012; Lubke *et al.* 2014; Vititnev 2019; Vititnev *et al.* 2021b, 2022).

Subsequent forming of the wood-fiber carpet, its cold squeezing (up to relative humidity of 78 to 80%), and hot pressing of boards were carried out under laboratory conditions at the Department of Industrial Technology and Machine Engineering of the Siberian State University named after M. F. Reshetnev, Krasnoyarsk. All other conditions for the wood fiberboard production were equal. When producing wood fiber boards, no additives were added, and hydrophobic and strengthening additives were excluded (binding resins) (Mersov1989; Chistova 2010; Zyryanov 2012; Vititnev 2019). The wood boards were hot pressed in the LabPro 1000 laboratory press. The hardboard samples were produced with high density (960 to 1070 kg/m^3). The samples were 200 mm in diameter and 2.5±0.3 mm thick. The hot-pressing mode is described in Table 1.

Table 1. Hot Pressing Mode

Process Parameters	Value
Temperature (t press, °C)	180
Specific pressing pressure (extraction) (Rspec, MPa/time, s)	5/20
Relief to pressure (1 MPa, s)	200
Specific pressing pressure (drying), (Rspec, MPa)	1/110
Pressing cycle time (tperiod, s)	330

The experimental results were processed with Microsoft Office 2007 (version 12, Microsoft, Redmond, WA, USA) using the Quasi-Newton method. Statistical tests analysis of variance (ANOVA) were used in the STATISTICA-6 software package to confirm significant differences between groups and confidence in the results for all analysed parameters. While processing the results of experimental studies, dependencies were obtained that reliably describe the investigated process of wood fiber pulp preparation and physical and mechanical properties of finished boards from fir wood with different period after its death when using fibrillating refiner discs. The obtained dependences were found to be adequate at a confidence level of 95 to 99%. The values of the coefficient of determination (R^2) were close to unity (Borovikov and Borovikov 1998; Pizhurin 2005).

Dimensional and Qualitative Characteristics of Wood Fibers

Degree of refining wood fiber

The degree of refining wood fiber pulp was determined using the Defibrator-Second device (Sunds-Defibrator, Stockholm, Sweden) used in fiberboard production. The methodology has been presented in previous work (Chistova 2010; Zyryanov 2012; Vititnev *et al.* 2021a, 2021b, 2021c, 2022).

Water retention values

Water retention values (WRV, %) were determined according to literature studies (Watte 1968). Water retention values of the wood fiber pulp were determined by the moisture remaining in it after centrifugation under certain conditions. The method includes centrifuging the fibrous mass, where in 20 mL contains 0.1 to 0.2 g of completely dry fiber (concentrations from 2 to 5g/L), at 3000 rpm for 10 minutes. This indicator can characterize the degree of fiber fibrillation, due to its connection with its swelling and available hydroxyl groups (Hanhikoski *et al.* 2020).

Fractional composition of semi-finished product

The fractional composition of the semi-finished product was categorized as follows: large F_l (>4 mm), medium F_m (4 to 1.5 mm), small F_s (1.5 to 0.04 mm). Each size category is reported as a%. The fiber fractioning device filters a certain amount of wood fibers through sieves with mesh sizes corresponding to qualitative assessment categories (Laskeev1967; Chistova 2010; Zyryanov 2012; Vititnev 2019, Vititnev *et al.* 2021a,b,c, 2022).

In the fraction separation of fibrous semi-finished products on the FVG-2 fractionator, the wood fiber lengths and diameters were measured by microscope using a Hitachi TM-3000 digital microscope with up to 1,000x magnification. The geometric characteristics were determined according to literature studies (Laskeev1967; Chistova 2010; Zyryanov 2012; Ferritsius *et al.* 2018; Vititnev 2019; Vititnev *et al.* 2021a,b,c, 2022) with the assessment of at least 100 fibers for each sample by calculating the arithmetic mean of length (L_a, mm) and diameter (d_a, mm), followed by the calculation of slenderness ratio (L_a/d_a).

Specific power consumption for refining

During the wood fiber refining process, the specific electricity consumption of the refiner (E, kWh/$\Delta DS \cdot t$) was determined according to literature studies (Chistova 2010; Zyryanov 2012; Vititnev *et al.* 2021a,b, 2022).

Physical and mechanical properties

The physical and mechanical properties of finished fiberboards were assessed in accordance with GOST 10633 (2018) and GOST 10636 (2018) standards. In determining the strength properties of the specimens, the modulus of elasticity (E, MPa) and deflection (z, mm) of the board were additionally recorded.

RESULTS AND DISCUSSION

Prepared Semi-finished Fibrous Products and Obtained Fiberboards

Figure 1 illustrates the cuts of studied Siberian fir wood with different periods of its death after damage by the bark beetle (*P. proximus*).

Fig. 1. Siberian fir wood with different period after death

According to Fig. 1, it is evident that as the duration after death increases, wood destruction occurs. With a period of 19 years, progressive destruction of wood and pronounced rot formation were observed. When preparing chips from Siberian fir wood, including living ones (0 years) and with different periods after death, with all other conditions being equal, differences were found in the dimensional and qualitative characteristics and composition of semi-finished products, both at the first stage of processing (Fig. 2a through 2d, Fig. 5a), and during fiber refining at the second stage (Fig. 2e through 2h, Fig. 5b).

Fig. 2. Wood fiber obtained from live wood (0 years old) of Siberian fir and at different periods after its death (5 to 19 years old) after the first stage of chip preparation (a to d), and after refining (e to h)

Figures 3 and 4 illustrate the graphical dependencies reflecting the features of process of preparing wood fibers (TMP) from Siberian fir wood with the influence of the period after its death on some dimensional and qualitative characteristics of fibers. These include degree of refining (DS, "defibrator-second"), water retention values (WRV), average length (L_a) and diameter (d_a), slenderness ratio (L_a/d_a)) and the ratio of their fractions (large (F_l), medium (F_m), small (F_s)) in the total mass at different stages of obtaining fibrous semi-finished products for the production of fiberboards.

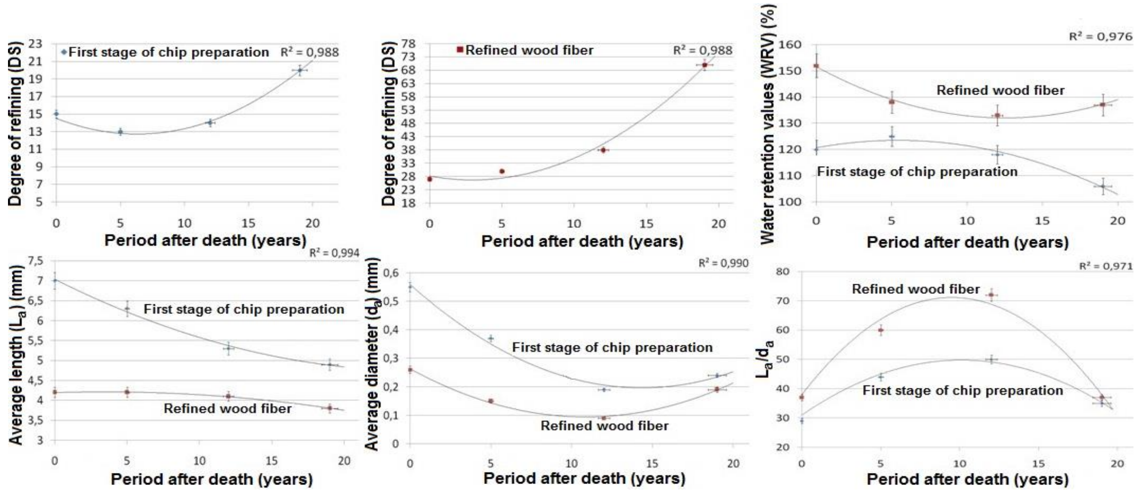

Fig. 3. Influence of the period after Siberian fir death on the change of dimensional and qualitative characteristics of wood fiber pulp in the process of its preparation

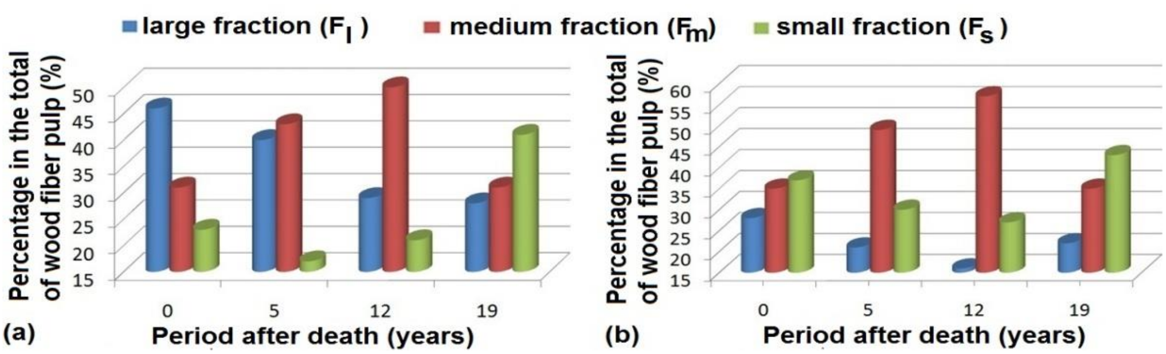

Fig. 4. Dependence of fractional composition of wood fiber pulp on the period after Siberian fir period after its death after first stage of chip preparation (a), and after refining (b)

Analyzing the obtained dependencies shown in Fig. 3 and 4, as well as the photographs presented in Figs. 2 and 5, it can be noted that the efficiency of chips processing at stage I increased (Fig. 2a through 2d, Fig. 5a) for the period up to 12 years after death. The degree of refining and water retention values of fibers did not undergo significant changes, but the intensity of chips destruction into fiber bundles and individual fibers in the longitudinal direction increased (L_a≈ 7 to 5.3 mm; d_a≈ 0.55 to 0.19 mm; L_a/d_a≈ 29 to 50). The fractional composition of wood fibers was significantly improved (Fig. 4a, Fig. 5a, Table 2), the content of large fibers decreased (F_l≈ 46 to 29%), medium fraction increased in the total mass (F_m≈ 31 to 50%), small fraction of fibers tends to decrease somewhat (up to F_s≈ 17%) at the period after death of 5 years (Fig. 4, Table 2). Such a change in the specificity of destruction may indicate a predominant weakening of intercellular connections (Scott 1996; Park *et al.* 2024). At the same time, it can be noted that with a longer period after wood death (after 12 years), the process of preparing wood fibers using chips after primary refining, with all other conditions being equal, was characterized by an increase in the degree of refining (up to 20 DS) and a decrease in water retention values up to 106% (Fig. 3). The intensity of fiber destruction in the transverse direction increased; in the total mass of the semi-finished product, the predominant formation of small fiber fraction (F_s≈ up to 41%) occurred, with a decrease in the medium (F_m≈ up to 31%) fraction of fibers (Fig. 3a, Fig. 4a, Table 2), indicating a significant weakening of their cell wall structure (Korotaev *et al.* 2013; Koptev *et al.* 2024).

Figure 5 illustrates wood fiber of the Siberian fir with different periods after death (5 to 19 years) and living wood (0 years) in the process of preparing wood fiber pulp (Table 2) using a refiner discs (new design) (Vititnev *et al.* 2018) to produce fiberboards, all other conditions being equal.

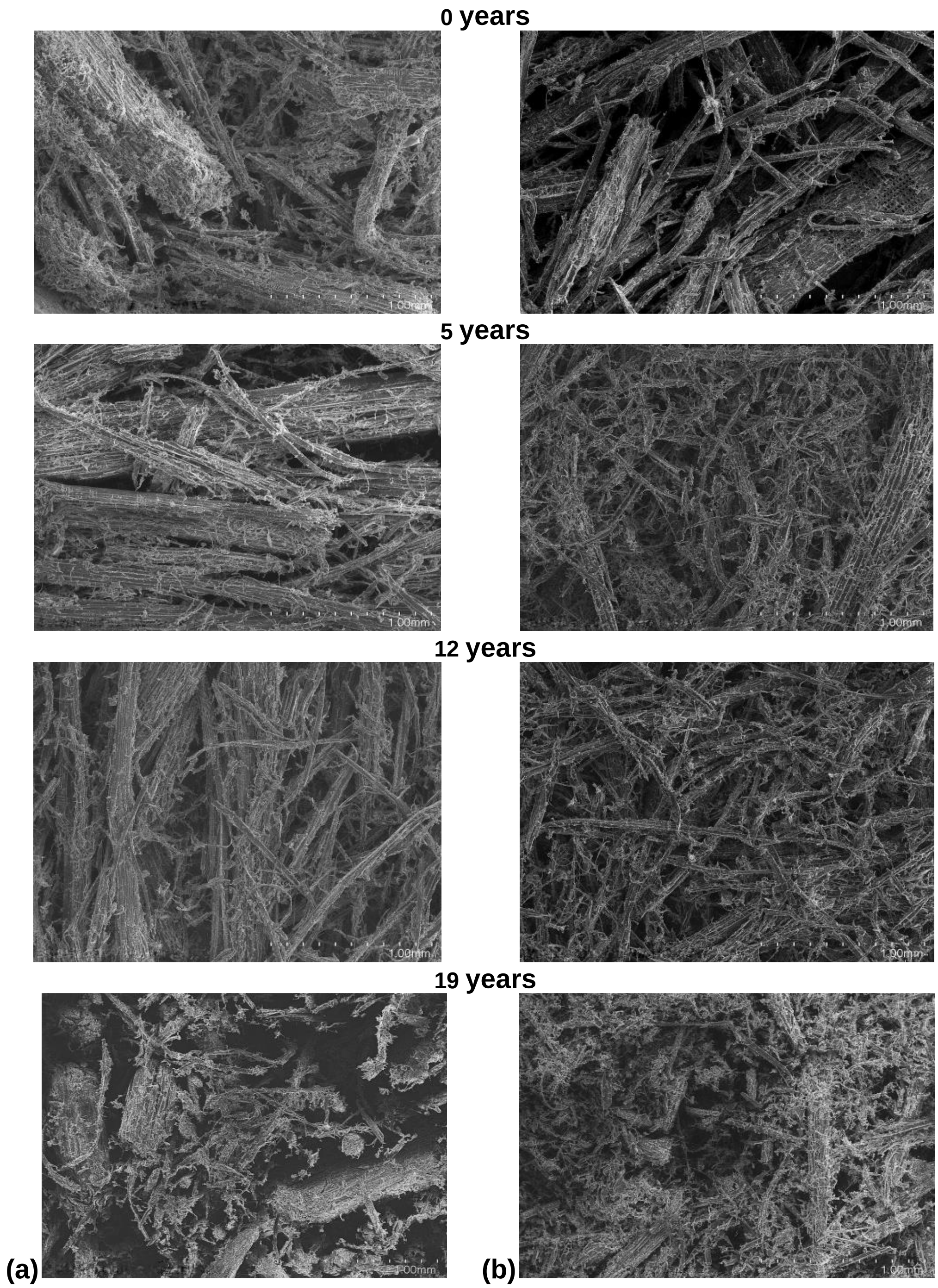

Fig. 5. Microscopic analysis of the wood fiber pulp (50x magnitude) after first stage of chip preparation (a), and after refining (b)

Table 2. Results of Refining Process of Wood Fiber Pulp from Siberian Fir with Different Period After its Death

Period After its Death, (years)	**Qualitative Characteristics**					**Fractional Composition**			Specific power consumption for refining, E(kW·h/ΔDS·t) (±0.5)
	Degree of refining, DS (±0.5)	Water retention values, WRV (%) (±0.5)	Average length of fibers, L_a, (mm) (±0.01)	Average diameter of fibers, d_a (mm) (±0.01)	Length-to-diameter ratio, L_a/d_a (±0.5)	Large fraction, F_l(%) (±0.5)	Medium fraction, F_m (%) (±0.5)	Small fraction, F_s (%) (±0.5)	
0	27	152	4.2	0.26	37	28	35	37	25
5	30	138	4.2	0.15	60	21	49	30	19
12	38	133	4.1	0.09	72	16	57	27	12
19	70	137	3.8	0.19	37	22	35	43	7
F-value	1698.75	154.75	135.22	260.11	1739.05	161.67	1054.82	485.49	830.00
Sign.level	$p < 0.05$								
R^2	0.98	0.99	0.99	0.99	0.97	0.98	0.98	0.97	0.98

According to the results of fiber refining at the second stage (Fig. 3b, Table 2) and the images of resulting fibrous semi-finished product shown in photographs (Fig. 5b), it is evident that in the period after the wood death up to 12 years (Fig. 2e through 2g, Fig. 5b), the efficiency of fiber refining process increased and their dimensional and qualitative characteristics were better (Fig. 4b, Table 2). The degree of refining also increased from 27 to 38 DS, while the water retention values decreased from 152% to 133%. Fiber bundles were intensively destroyed mainly in the longitudinal direction, with the length preserved (L_a≈4.1 mm; d_a≈0.09 mm; L_a/d_a≈72). Fractional composition of the semi-finished product was improved (Fig. 2b, Fig. 5b, Table 2). In the total mass of the semi-finished product, there was a decrease in the proportion of large (F_l≈ up to 16%) and small (F_s≈ up to 27%) fiber fractions and an increase in the medium (F_m≈ up to 57%) fiber fractions. Analysing the obtained results (Fig. 3a, Fig. 4b, Table 2, Fig. 5b) it can be noted that with the period after wood death up to 12 years, the increase in the total mass of semi-finished products in the proportion of long and thin, respectively flexible fibrillated fibres with a decrease in specific energy consumption, indicated an increase in the efficiency of fibre formation and the refining process as a whole.

Improved quality characteristics and fractional composition of the semi-finished product ensures better strength properties of the board product (Table 3) during production, in accordance with the requirements of the Russian Federation standard GOST 4598 (2018) boards (Groups A), and EN 622 (2004) boards (types HB.H, HB.E) excluding binding resins (Vititnev 2019; Vititnev *et al.* 2021a, 2021b, 2021c, 2022). The positive effect of the predominance of total developed and flexible fibrillated fibers on the physical and mechanical properties of fiberboards is consistent with the research results (Laskeev 1967; Chistova 2010; Ihnat *et al.* 2015; Ayrilmis *et al.* 2017; Vititnev *et al.* 2021a, 2021b, 2021c, 2022).

In the process of fiber refining using woods with longer period after the wood death up to 19 years (Fig. 2h, Fig. 5b, Table 2), the degree of refining increased significantly up to 70 DS. The water retention value tended to increase; however, the efficiency of the fiberization process during refining was reduced, the semi-finished product was characterized by deteriorated dimensional and qualitative characteristics (L_a≈3.8 mm; d_a≈0.19 mm; L_a/d_a≈37) (Fig. 2h, Fig. 3, Table 2) and ratio of different fractions in the total semi-finished product (F_l≈22%; F_m≈35%; F_s≈43%) (Fig. 4b); the intensity of destruction in the longitudinal direction and fiber fibrillation decreased (Fig. 2h, Fig. 3, Fig. 5b, Table 2), there by affecting the strength properties of fibrous materials (Table 3), which is consistent with previous research (Bordin *et al.* 2008; Li *et al.* 2011; Ayrilmis *et al.* 2017; Ferritsius *et al*. 2018; Vititnev 2019; Vititnev *et al.* 2021a, 2022).

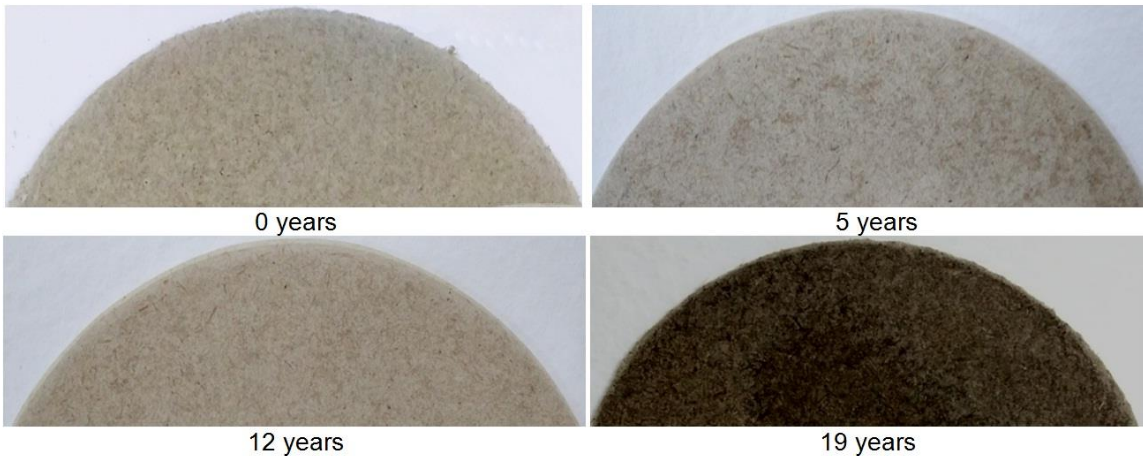

Fig. 6. Wood fiberboards from Siberian fir with different period after its death

Table 3. Physical and Mechanical Properties of Wood Fiberboards from Siberian Fir with Different Period After its Death

Period After its Death, (years)	Static bending Strength (σ_i, MPa) (±0.1)	Internal Bond (σ_t, MPa) (±0.01)	Density (ρ, kg/m^3) (±10)	Thickness Swelling in 24 h (h_a, %) (±0.1)	Modulus of Elasticity (E, MPa) (±5)	Deflection (z, mm) (±0.1)
0	34.5	0.51	1070	56	3880	3.6
5	41.5	0.63	1069	56	4750	3.5
12	44	0.70	1046	49	4720	3.4
19	36	0.57	960	20	4000	2.7
F-value	238.74	71.62	156.58	267.50	679.60	99.06
Significance level	$p < 0.05$					
R^2	0.99	0.98	0.99	0.99	0.99	0.97

With the period after the death of Siberian fir up to 12 years, all physical and mechanical properties of wood fiberboards (Fig.6) increased (Table 3), especially strength properties. For instance, the internal fiber bonding increased due to the increase of fiberization, improvement of their qualitative characteristics (Table 2), fibrillation (Fig. 5b) and fractional composition (Fig. 4b). The indicators met the requirements of GOST 4598 (2018) boards (Groups A), and EN 622 (2004) boards (types HB.H, HB.E) with the exception of board swelling by thickness in 24 h, due to the absence of hydrophobic additives. With the period after death up to 12 years, elasticity modulus of the board material increased, showing a decrease in deflection, which indicates higher rigidity (Theng *et al.* 2017; Luo *et al.* 2022). However, it is worth noting that with a longer period after death, the strength properties of boards decreased (Table 3), while their moisture-resistant properties improved, which may be due to an increase in the lignin proportion due to significant rot formation over a period of 19 years (Theng *et al.* 2017; Luo *et al.* 2022).

Physical and mechanical properties of the wood fiberboards from Siberian fir wood with a period of 19 years after death, particularly their swelling index by thickness in 24 h, complied with the requirements of GOST 4598 (2018) boards (Groups B), and EN 622 (2004) boards (types HB), with no binding resins and hydrophobic additives used. A special feature is that such specimens may exhibit surface defects such as dark spots (Fig.6) on the surface of finished products.

Moreover, it should be noted that over time after the wood death, the specific energy consumption for fiber refining process was gradually reduced to 70% (Table 2), which can be attributed to higher susceptibility of fibers to destruction during preparation.

CONCLUSIONS

1. Siberian fir wood, including dead wood damaged by bark beetle with different periods after its death (up to 19 years), can be used as raw material to produce fiberboards.
2. When using fibrillating refiner discs in the process of refining wood fibres of Siberian fir after its death in the period of 5 to 12 years, the efficiency of the process of fiberization, the dimensional and qualitative characteristics of the fibre semi-finished products were found to improve with a tendency of their deterioration with a further period up to 19 years, in general providing an increase in the internal bonding between fibres. This contributed to strength properties of fibreboard, which would allow the production of environmentally friendly board as per GOST 4598 (2018), EN 622 (2004), while excluding binding resins.
3. After 5 years of fir wood death, the susceptibility of fibers to destruction increased due to the weakening of bonds between them; the efficiency of refining process increased while reducing energy costs to 50 to 70%. A significant increase in the grinding rate of fiber semi-finished products up to 38 to 70 DS, especially in the period after 12 years, can cause difficulties in casting and forming the fibermat, requiring more time for dewatering, and reducing the equipment performance during high-density fiberboards production.
4. It has been established that strength properties of finished boards were better for woods with a period of 5 to 12 years of decay; after 12 years, a decrease in strength indicators was characteristic with an improvement in moisture-resistant properties, which is probably associated with an increase in the lignin proportion due to significant rot formation during a period of 19 years. Wood fiberboards obtained from wood with a period of 19 years after death may exhibit surface defects such as dark spots, which may be due to hot-pressing conditions.
5. Changes in the wood properties over the period after death require timely use and various efforts to effectively refine the fibers and provide the required dimensional and quality characteristics during preparation of fibrous semi-finished products to ensure the required process parameters and equipment performance. Further research related to issues of modes adjusting and optimization of refining process and hot-pressing modes with account of the period after the wood death, as well as degree of its destruction, shall be required to increase the efficiency of using low-value damaged dead wood of Siberian fir. Overall, this will reduce the shortage of high-quality raw materials for board production and help address environmental and economic issues.

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