Tensile Strength of Wood Modified Polymer Composition with Carbon Nanotube Filler

Mikhail Lukin, Tatyana Glebova, and Anatoly Naichuk

Abstract For the rational use of wood in the manufacture of new types of wooden structures, strengthening of nodes and interfaces, it is currently advisable to use new materials and technical solutions using polymer compositions. Of the greatest interest are structural elements and manufacturing technologies of wooden structures using modern composite polymer materials with the inclusion of carbon nanotubes (CNTs) in their composition, which leads to increased strength and rigidity, reduced material consumption and mounting weight of structures, reduces the effect of anisotropy of properties and defects of wood on the bearing capacity.

Modification is carried out using a polymer composition based on dimethacrylic polyester with a nanostructured filler. In order to establish the mechanical properties of wood, experimental tests were carried out with a polymer composition without filler and with a nanostructured filler. The increase in strength properties during the modification of wood was 23.55%, and with the addition of carbon nanotubes—37.15%. Experimental studies have proved the promising possibility of using a polymer composition to modify wood in order to increase its strength properties.

Keywords Stretching · Testing · Polymer composition · Modification · Microstructure · Nanotubes

1 Introduction

Wood as a structural material is used in many industries and engineering. The combination of high physical and mechanical characteristics and low specific gravity of wood in comparison with metal and reinforced concrete determines its high demand in construction [1–3].

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Coniferous and deciduous wood consists of a different set of anatomical elements, for which their ordered fibrous structure is common. The mechanical function in coniferous wood is performed by tracheids, which are located mainly vertically in the growing tree and make up 90% of the volume of wood. The location of wood fibers along the axis of the tree causes a sharp difference in the mechanical properties of wood along and across the trunk. The elastic modulus of pine for the direction along the fibers is almost 40 times greater than across, and the compressive strength is 10 times, and the tensile strength is 20–30 times [4, 5].

One of the ways to increase the physical and mechanical properties of wood is its modification. Modification of wood should be considered as a process of directed change of physico-mechanical, thermophysical, tribotechnical, biochemical properties of wood in relation to the operating conditions of products made of it [6–8].

Thermochemical modification is based on the impregnation of wood with synthetic monomers and oligomers, followed by polymerization and curing by a thermocatalytic method [9–12]. The technological process of saturation of wood with a modifying composition is similar to impregnation with antiseptics and flame retardants, carried out according to the vacuum-pressure or vacuum-pressure-vacuum method at a temperature of 20–30 °C. The amount of the absorbed impregnation composition is assumed to be equal to 30–80% of the mass of the original wood. The compositions of monomers and oligomers (phenol alcohols, furan-, acetate, methyl methacrylate, styrene methylmethacrylate, styrene vinyl acetate, polyester resins, styrene polyester resins, etc.) and polycondensation resins (phenol–formaldehyde, epoxy, furan, urea–formaldehyde, etc.) are used as modifiers, the conditional viscosity of which according to the viscometer VZ-4 should be 11–14 c at a temperature of 20 °C [13–16]. The viability of the modifier should ensure a complete technological cycle of wood impregnation. The composition can be cured by radiation and thermocatalytic method [17–19].

The purpose of the study is to study the tensile strength properties of wood impregnated with a polymer composition.

2 Methods

The impregnation composition for wood modification is a polymer composition based on dimethacrylic polyester with a nanostructured filler. The main components that make up the polymer composition are: liquid resin, dry hardener (0.25 mass parts), surfactant (OP–10) in an amount (0.5 mass parts), carbon nanotubes (CNTs of the Taunit-M series) (0.5 mass parts). Mixing of the components was carried out using a PE-8300 top-drive agitator equipped with a built-in control unit.

The modification was carried out in the following order:

1. Drying of workpieces to a humidity of 5–7% for 2 h at (110 + 5) °C in a standard drying cabinet (SHS-100-01) at atmospheric pressure.

2. Checking the moisture content of each workpiece with a wood moisture meter (Testo-616). If the tests are not breaded immediately after drying, then they should be stored for no more than 3 days in a tightly closed container, for example, in a desiccator) at a temperature of (18–25) °C and humidity control.
3. The blanks are placed in a container for impregnation, fixed with a plate from floating the blanks and filled with an impregnating compound 5 cm above the plate. The container is transferred to a mobile unit for vacuum infusion MVS-20 (−01). Slowly, preventing rapid foaming of the impregnating composition from the air available in the blanks, the air is pumped out to a residual pressure of minus (0.8–0.9) atm. The blanks are kept under vacuum until there is no visible release of even the smallest air bubbles in the layer of the impregnation composition above the blanks, then the vacuum is discharged (Fig. 1a).
4. To achieve the effect of modification for full volume impregnation, it is recommended to carry out additional exposure (soaking) already impregnated billets in the impregnation composition for up to 15 days.
5. Visually control the degree of filling with the composition of the workpiece. At the end of impregnation, the workpiece should sink in the impregnation composition, and not float. The completeness of the impregnation of the workpiece is controlled visually by a cross-section.
6. The samples are wrapped in aluminum foil and placed at atmospheric pressure in a drying cabinet with forced internal ventilation. The curing temperature is (95–105) °C. The holding time is determined by the type of wood, it is selected for the dimensions of the workpiece and is usually at least 1 h (Fig. 1b).

a) b)

Fig. 1 Technology of wood modification: **a** vacuuming of samples; **b** polymerization of samples

The research was carried out on a RM-50 M bursting machine. The bursting machine with a pulsator is equipped with an electrohydraulic automated control system for the loading process based on a computer, which provides static and dynamic tensile tests of metal and alloy samples, concrete samples, wood and polymer materials in manual and semi-automatic modes. Loading of standard samples was carried out uniformly with a constant speed of movement of the loading head of the machine—4 mm/min [20–23].

Tensile tests were performed on standard samples (Fig. 2).

15 samples were tested—3 series of samples of 5 pieces each. 1 series—samples without modification, 2 series—images with modification by polymer composite and 3 series with modification by polymer composition with nanostructured filler. According to the test results, statistical processing of experimental data was carried out.

In order to clarify and confirm the mechanical properties of wood modified with polymer composites, optical and scanning microscopy of samples was performed [24–26].

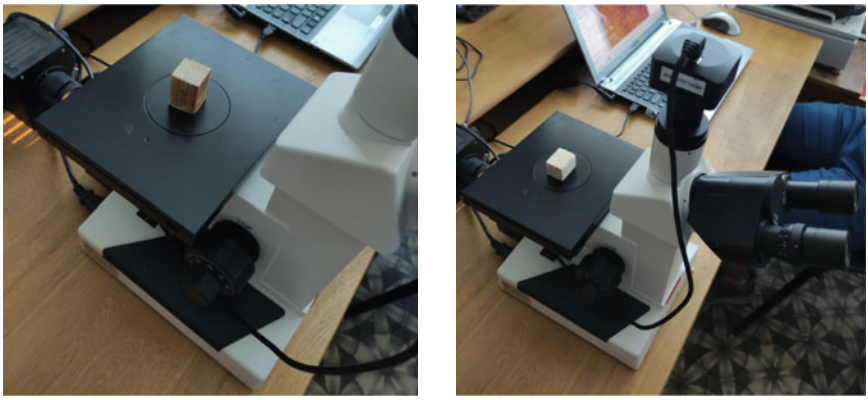
a) b)

Fig. 2 Tensile testing of modified wood samples: **a** a sample during testing in a bursting machine; **b** samples after destruction

3 Results and Discussions

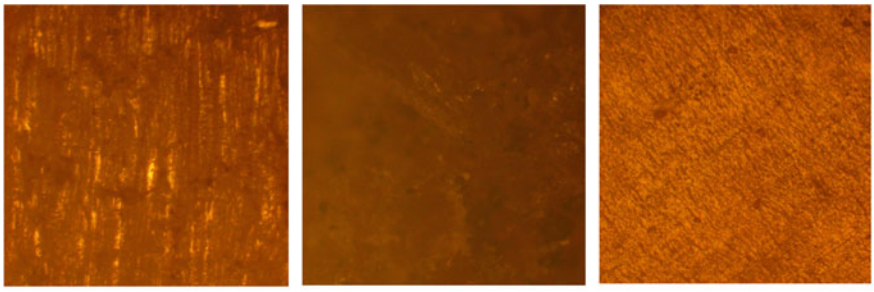
Optical microscopy was performed on a Raztek MRX9-D digital optical microscope (Russia), which allows visual observation of the microstructure of opaque objects (see Fig. 3). The results of optical microscopy, presented in Fig. 4, illustrate the distribution of the polymer composition in the micropores of wood.

Figure 4b shows that the tracheids of wood, when modified with a polymer composition, are systematically filled with it. The introduction of carbon nanotubes into the composition contributes to an even deeper filling of the tracheids (Fig. 4c). Eventually, wood turns into a composite with a more ordered structure at the cellular level, the anisotropy of properties decreases [27–30].



a) b)

Fig. 3 Microscopy of wood samples: **a** along the fibers; **b** across the fibers

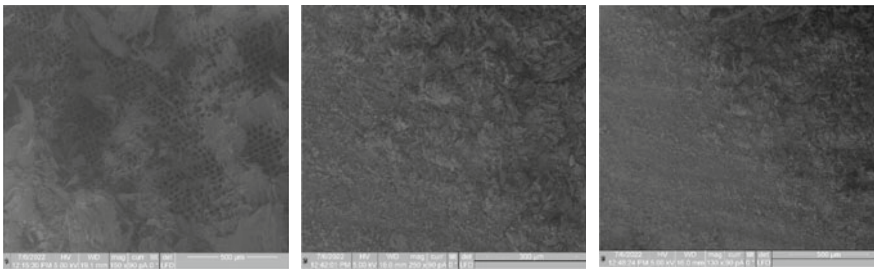


a) b) c)

Fig. 4 Results of microscopy of wood samples across fibers: **a** sample without modification; **b** sample with modification of polymer composition; **c** a sample with a modified polymer composition with a carbon nanotube filler

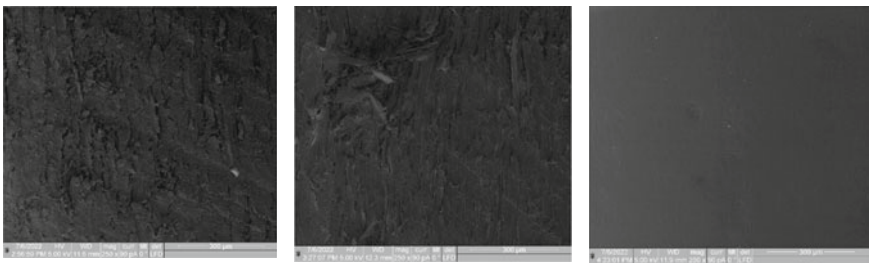
The microstructure of wood was determined using scanning electron microscopy on a Quanta 200 3D microscope. At the molecular level, this method is the most suitable for determining the structure of wood [31–33]. The results of this study contribute to a better understanding of changes in the microstructure of wood when modifying the mechanism of changes in the strength properties of wood (Fig. 5 and 6).

The micrographs shown in Figs. 5 and 6 can be interpreted as follows: with the introduction of a polymer composition into the wood, the pores between the strands of the tracheids are filled. The introduction of nanotubes into the composition contributes to a more complete filling of all the pores present in the cells of wood. As a result of polymerization, the density of wood increases [34–38]. Before the start of the tests, the samples were weighed and their density was determined. The average density value for wood samples without modification was 482 kg/m^3, and the polymer composition with nanostructured filler was 646 kg/m^3. Thus, the density of wood during its polymerization increases by an average of 34%. The introduction



a) b) c)

Fig. 5 Examination of samples along fibers by scanning microscopy: **a** sample without modification; **b** sample with modification by polymer composition; **c** a sample with a modified polymer composition with a carbon nanotube filler



a) b) c)

Fig. 6 Examination of samples across fibers by scanning microscopy: **a** sample without modification; **b** sample with modification by polymer composition; **c** a sample with a modified polymer composition with a carbon nanotube filler

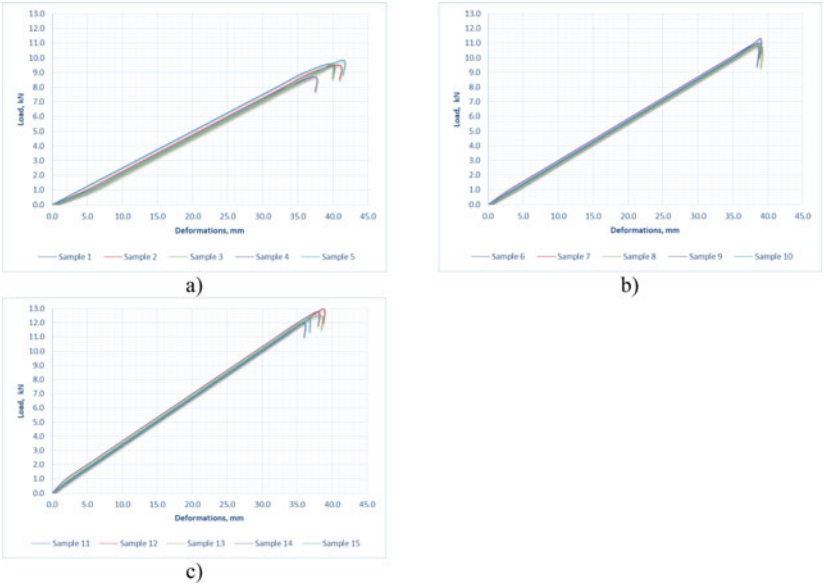


Fig.7 Diagram of "Load-strain" for tensile wood samples: **a** samples without modification; **b** samples with modified polymer composition; **c** samples modified with a polymer composition with a nanostructured filler

of nanotubes into the polymer composition practically does not increase the density of wood.

Figure 7a shows the results of mechanical tensile tests of standard wood samples without polymerization, Fig. 7b—wood samples with a modified polymer composition, Fig. 7c—wood samples with a modified polymer composition with a nanostructured filler.

The compressive and tensile strength of the samples was determined by the formula:

$$\sigma_w = \frac{P_{max}}{a \cdot b} \tag{1}$$

where P_{max}—is the maximum load, kN; $a \cdot b$—re the cross-sectional dimensions of the working part of the sample, mm.

According to the test results, statistical processing of experimental data was carried out.

The lowest strength value was determined by the formula:

$$R_s = \overline{x} - \sigma \tag{2}$$

where $\overline{x}$—is the average strength value; σ—is the standard deviation.

The accuracy index of the obtained average value is determined by the formula:

Table 1 Comparative data on the mechanical properties of a polymer composition and a composition with a nanostructured filler

Type of test samples	Indicators		
	Without modification	With modification by polymer composition	With modification by polymer composition with nanostructured filler
Destructive load P_{max}, kN / Accuracy index P, %	8.64 / +3.84	10.68 / +1.39	11.85 / +2.36
Voltage σ, MPa / Strength gain, %	43.23 / –	53.41 / 23.55	59.29 / 37.15

$$\xi = \sigma_x / \overline{x} \tag{3}$$

where σ_x—is the average error of the average value.

To summarize the test results obtained, Table 1 has been compiled.

4 Conclusions

Thus, based on the results of studies of the tensile strength of wood with a modified polymer composition with a carbon nanotube filler, the following conclusions can be drawn:

1. Modification of wood with polymer composites has great prospects and can significantly increase the efficiency of the use of structural solutions of wooden structures.
2. At the stage of destruction of samples, the stress level in wood is equal to 23–24% of the temporary tensile strength along the fibers for wood modified with composite, and 37–38%—with the addition of carbon nanotube filler to the composite. The limiting state occurs at the moment of rupture of stretched fibers or by weakening in the form of various defects of the stretched zone.
3. As a composite, it is recommended to use the so-called impregnating composition, which is a polymer composition based on dimethacrylic polyester with a nanostructured filler. The main components that make up the polymer composition are: liquid resin, dry hardener (0.25 mass parts), surfactant (OP–10) in an amount (0.5 mass parts), carbon nanotubes (CNTs of the Taunit-M series) (0.5 mass parts).
4. At the cellular level, the tracheids of wood, when modified with a polymer composition, are systematically filled with it. The introduction of carbon nanotubes into the composition contributes to an even deeper filling of the tracheids. A composite with an ordered structure is formed at the cellular level, which ultimately leads to a decrease in the anisotropy of mechanical properties.

5. This study substantiates the theoretical possibility of using polymer composites with CNTs for thermochemical modification of wood, which gives a strong impetus to the development of composite building structures and their further promising implementation.

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