Analysis of Creep of Wood-Polymer Composites

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Abstract. The paper describes the results of studying the creep of wood-polymer composites under load. The results of long-term testing wood composites based on thermoplastic and thermoset polymers are given. It has been established that empirical dependencies in the form of elementary functions are suitable to describe the composite deformation. The parameters of these functions are experimentally determined.

1. Introduction
Wood-polymer composites are materials with tailor-made properties determined by the composition and parameters of modifying polymers, the wood impregnation technology, and the polymer curing. Therefore, theoretical ideas of the basic concepts of their structuring and the kinetics of aging in operating environments, as well as the technological capabilities of increasing the composite resistance in building products with more accurate forecasting their durability may serve as fundamental principles in controlling the composite structure and properties.

As a result of the wood impregnation with polymers followed by curing (modification), the material properties and structure change (the cell membrane thickens and hardens, and the cell cavities are partially filled with polymers). Herewith, the change in strength and creep are integral properties of polymer composite materials, including wood-polymer ones, which are exhibited under force [1-3].

In general, the wood-polymer composite strain is the result of deformations of its components, changes in their interaction, and distortion of the structure under stresses. Studies of the highly elastic wood strain have shown [4] that the ratio of the activation energies of the forced highly elastic strain development (Eₜ), kJ/mol, and the wood tissue carrier - cellulose bond opening (U₀), kJ/mol, is less than 1:

\[
\frac{Eₜ}{U₀} = \frac{117}{170} = 0.7.
\] (1)

This means that the development of a forced highly elastic strain of the composite wood base is not caused by the cellulose bond opening and occurs when intermolecular forces are surpassed.

2. Experimental and discussion
A wood-polymer composite modified with a thermoset polymer has a lot of additional bonds in the supramolecular structure of cellulose. Phenolic alcohols penetrate the wood cell wall, expand the cellulose fibrils, and fix them in a swollen state after the polymer curing [5, 13]. In this case, between the phenolic alcohol molecules and the lignin-carbohydrate matrix, physical (hydrogen) bonds of the polymer with cellulose hydroxyls and mechanical bonds due to the mutual linking of segments are formed, and ether bonding is possible. Being fixed in a swollen state during modification, fibrils
become inactive and contribute to the emergence of local overstresses when loading. Therefore, when loaded in water, the wood-polymer composite modified with thermoset phenolic alcohols and the natural wood have the highest and the lowest strain rate, respectively, and the wood-polymer composite modified with thermoplastic polystyrene occupies an intermediate position (Fig.).

![Figure 1. Strain-Stress Curves of Wood-Polymer Composites when Heated (40 °C) in Water and in a Weak Acid Medium under a Load of 0.2R_{ex}, 0.4R_{ex}.](image)

Modifying a wood-polymer composite with a thermoplastic polymer has a different nature. Styrene is virtually non-polar and fills the cell cavities only. It is generally accepted [6] that styrene does not interact with the wood substance. Since the most active (hydroxyl) groups in the composite wood base are not blocked by sufficiently strong polymer bonds, water penetrating the cell wall reduces the strength of intermolecular bonds and thereby facilitates the ‘slip’ of cellulose fibril molecular chains relative to each other. This is also manifested in the wood-polymer composite strain (Fig. 1).

Studying the wood-polymer composite stress-strain properties in aggressive solutions has shown that an increase in the solution temperature increases the composite strain rate. At stresses (0.3...0.4 R_{ex}), the strain f_n continuously increases, which leads to material destruction. The ultimate strain (f_{max}) depends slightly on the strain rate and achieving this value under static bending can be taken as a destruction condition in the first approximation. Long-term elastic moduli and elastic modulus
coefficients can be determined by the wood-polymer composite decaying creep curves for various media:

\[ n_0 = \frac{E_{ae}}{E_0} = \frac{f_0}{f_{max}}, \]  

(2)

where \( f_0 \) is the initial (elastic) deflection, \( mm \); \( f_{max} \) is the full deflection, \( mm \).

Under the action of forces applied to the composite, elastic strains caused by irreversible changes in the average interparticle distances, viscoelastic strains associated with reversible rearrangement of particles, and viscoplastic strains caused by the irreversible displacement of cellulose fibrils may occur [3, 4].

When describing the time dependence of the wood-polymer composites strain, pure mathematical and artificial mechanical (rheological) models are distinguished. The first group models are built empirically based on experimental data. In mechanical models, a material is considered as a combination of two bodies: ideal elastic one obeying Hooke’s law and viscous one obeying Newton’s law. These bodies are illustrated by an elastic spring and a viscous damper.

Potential functions are most often used to describe the wood-polymer composite creep by empirical dependence [4]. When considering the development of strain in time in semi-logarithmic coordinates, prof. N.L. Leontiev (1957) proposed the below strain development equation:

\[ \varepsilon(t) = a + b \cdot t^n \]  

(3)

where \( a \) and \( b \) are the material constants.

In [3], the aftereffect composite strain in the air is described as a fractional power function of time:

\[ \varepsilon(t) = b \cdot t^c \]  

(4)

where \( b \) and \( c \) are parameters determined experimentally. This equation rather exactly coincides with the experimental data of strains caused by bending of both large structural elements (span 5,500 \( mm \), cross-section 260x260 \( mm \)), and small specimens with a span of 670 \( mm \) and a cross-section of 10x10 \( mm \). The composites of small specimens and large elements had an equilibrium moisture content \( \omega_0 \) of 13.5 and 30 %, respectively. Based on the experimental data analysis, it has been established that the moisture content of the wood composite is considered by the coefficient ‘\( b \)’, and the exponent ‘\( c \)’ does not depend on it.

In [7], the options for describing a large number (over 1,700) of experimental wood composite creep curves by the below functions have been analyzed:

\[ y = \beta_1 + \beta_2 (1 - e^{-\beta_3 X}) + \beta_4 X \]  

(5)

\[ y = \beta_1 + \beta_2 (1 - e^{-\beta_3}) \]  

(6)

\[ y = \beta_1 \cdot X^{\beta_2} + \beta_3 \]  

(7)

where \( y \) is the creep strain (deflection); \( X \) is the test duration; \( \beta_1 \) is the material parameter.

A comparative analysis of the possibility of using the above equations for extrapolatory forecasting the composite deflections during operational aging considering in-house experiments has allowed giving preference to the potential function (7) as the most suitable when extrapolating the wood-polymer composite deflections using accelerated aging tests. Accelerated test duration of up to 120 days is quite sufficient to forecast long-term strains.

In theoretical and practical studying a wood-polymer composite as a viscoelastic body, a standard rheological model consisting of a sequential connection of the Hooke's and Kelvin’s bodies is most commonly used. E.g., in [8], a rheological model of a linear viscoelastic body was used to describe the
wood creep in the air during transverse tensile testing. The stress-strain dependence of such a body is described by the below differential equation:

$$H \varepsilon + E \varepsilon = n \cdot \sigma + \sigma,$$

where $E$ and $H$ are instant and long-term elastic moduli; $n$ is the relaxation time.

For constant load ($\sigma = \text{const}$), the solution to the equation has the form:

$$\varepsilon(t) = \frac{\sigma}{E} \left[ 1 + \frac{H - E}{H} \exp\left(-\frac{Et}{Hn}\right) \right].$$

A similar model was adopted [3] to describe the birch ‘lignamon’ creep under longitudinal compression.

According to [9], the longitudinal compression creep of the birch wood composite modified with phenolic alcohols and polyester resin is described by the integral Boltzmann-Volterra equation:

$$\varepsilon(t) = \frac{1}{E} \left[ \varepsilon(t) + \int_0^t k(t - \tau) \cdot \sigma(\tau) \, d\tau \right].$$

A particular solution to this equation corresponds to the work of the standard rheological model of a viscoelastic body.

The generalization of the above rheological model studies has shown that the wood-polymer composite creep in them is limited mainly by dry air test conditions. The composite creep in aggressive media should be determined by other equations considering the factors of exposure to aggressive operating media. In this case, the studies of the plastic creep in the air and aggressive media can be used. E.g., in [10], it has been established that the fiberglass creep in chemically active media is well approximated by the below power function:

$$f_a = K \left( \frac{\sigma}{\sigma_0} \right)^m \cdot \left( \frac{\tau}{\tau_0} \right)^n,$$

where $K, m, n$ are constants; $\sigma_0, \tau_0$ are parameters depending on the initial load; $\sigma, \tau$ are the long-term load level and the test duration. In this case, creep was determined under a load of 0.3-0.8 of the short-term bending resistance.

To describe the plastic creep in aggressive solutions [11], the below dependence has been proposed:

$$\varepsilon = \frac{\sigma_0}{E} + A \cdot \sigma_0^k + B \cdot \sigma_0^m \cdot t,$$

where $\sigma_0$ is the constant voltage; $A, B, k, m$ are parameters depending on the medium temperature and concentration.

3. Conclusion

Thus, the analysis of studying the wood-polymer composite creep has shown that in most cases, empirical dependencies in the form of elementary functions are commonly used to describe the material strains. The parameters of these functions are experimentally determined [13, 14].

In general, to describe the wood-polymer composite strains in aggressive media, the dependence (12) can be used in the below form:

$$f = f_0 + f_{v.e.} + f_v,$$

where $f_0 = (P \cdot 1.3)/(56.3 \cdot E_0 \cdot J)$ is the elastic deflection in the middle of the beam specimen; $f_{v.e.} = A \cdot \sigma_0^k$ is the viscoelastic deflection strain; $f_v = B \cdot \sigma_0^m \cdot t$ is the visco-plastic deflection strain; $P$ is external (constant) load; $J, l$ are the cross-section inertia moment and beam specimen span; $E_0$ is the wood-polymer composite instant elastic modulus at the moment of loading; $t$ is the age of loading.

4. References

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