Wood-Filled Polyurethane Foam and Modeling Properties of the Heat-Insulating Material Obtained From It

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Abstract. The results of mathematical modeling of physical and mechanical, thermophysical properties of wood polymer thermal insulation material are presented in this article. Modeling is carried out with the aim of predicting the quality parameters of wood polymer thermal insulation material (density, water absorption, flexural and tensile strength, thermal conductivity coefficient) and determining the boundaries of the mode parameters (component consumption, foaming time, conveyor speed, draft intensity in the plate forming units) of plant operation for the continuous production of wood-filled thermal insulation boards.

1. Introduction
A promising filler for the production of cheaper thermal insulation materials based on polyurethane foam are wood particles obtained from woodworking waste products [16, 17, 34]. The addition of such a filler to the material improves its structural and operational properties with a significant cost reduction [1, 41].

Manufacture of thermal insulation materials solely on the basis of polyurethane foam is carried out in batch plants, in which automation of work is severely limited [12, 40]. The peculiarity of obtaining heat insulation boards with the use of wood filler and polyurethane foam is that this process is organized continuously. This makes it possible to regulate component consumption, foaming time, conveyor speed, etc. The control effect on the mode parameters of continuous installations is determined by the final properties of the resulting material [3, 8, 14]. Accordingly, modeling the properties of the resulting thermal insulation material is an integral part of the automation of similar productions [39, 30].

2. Methodology of study
The pilot installation for the continuous production of thermal insulation boards is shown in Fig.1. The principle of the installation is as follows: a special form 11 for board samples of wood-filled polyurethane foam is placed on the belt 10 of the conveyor 1, mounted on the frame 2 with side guides to organize the movement of the mold.
The conveyor runs from drive 12. Form 11 moves along the conveyor from left to right. The filling heads for feeding a mixture of polyurethane foam components operate from the drive 9 and are mounted on the support 4. The gateway feeders are installed under the chip bunkers located on the support block 8. The filling unit is assembled on the frame 3. When the mold passes under the first filling head due to the triggering of the sensors, a compressor 13 supplying compressed air through the hose 14 to the filling head is on. Simultaneously with the compressor, the pump of the foam generator 15, that supplies component "A" through the hose 16, the component "B" through the hose 17 is on too. The foaming in the molds is under the draft of vacuum pump 18. After the components are placed in the mold, the mold is closed and the composition is raised to a predetermined volume limited by the shape [5].

Figure 1. Pilot installation for obtaining wood-filled thermal insulation material: 1 - conveyor, 2 - conveyor frame, 3 - filling unit frame, 4 - engine support, 5 - electric motor, 6 - filling head, 7 - chip bin, 8 - bin engine support 9 - sluice valve drive, 10 - conveyor belt, 11 - mold, 12 - conveyor drive, 13 - compressor, 14 - compressed air supply hose, 15 - PPU machine, 16 - supply hose of component A, 17 - supply hose of component B, 18 - vacuum pump.

In order to optimize the operating parameters of the installation, a mathematical modeling of the properties of the thermal insulation materials was carried out [2, 6, 18, 37].

A mathematical description of the properties of wood-polymer thermal insulation material was carried out by the method of complete factorial experiment [9, 20]. As initial data, the numerical results of experiments processed in the software environment of Table Curve 3D (they are presented in the graphs below) were used [13, 25, 31]. Variable factors were: concentration of wood filler (from 0 to 80%) \( W_{\text{mw}} \), concentration of isocyanate component of polyurethane foam (from 52.4 to 60%) \( W_{\text{mb}} \), humidity of wood particles (from 10 to 110%) \( U \), and amount of vacuum (from 10 to 30kPa) \( P_{\text{vac}} \) created during the formation of a board thermal insulation material.

Since the values of factors vary from the minimum to the maximum, therefore, two levels of factor variation are used. The required number of experiments is determined by the formula:

\[
N = 2^k, \tag{1}
\]

where \( k \) is the number of factors.
Then the center of the plan is determined for each of the factors, for this the formula is used:

$$X^0_i = \frac{X_{i\text{min}} + X_{i\text{max}}}{2}$$  \hspace{1cm} (2)

In order to determine the dependence: \(x = f(\cdot)\), a linear regression equation is defined as:

$$\hat{y} = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2,$$  \hspace{1cm} (3)

where \(x_1\) and \(x_2\) are dimensionless (normalized) designations of factors, and \(b_0, b_1, b_2, b_{12}\) are coefficients of the regression equation.

We pass from the natural designation of factors to dimensionless:

$$x_1 = \frac{X_1 - X_{i0}}{\Delta_1}, \quad x_2 = \frac{X_2 - X_{i0}}{\Delta_2},$$  \hspace{1cm} (4)

where \(\Delta_1, \Delta_2\) – intervals of variation.

Interval of variation is calculated by the formula:

$$\Delta_i = X_{i0}^0 - X_{i\text{min}} = X_{i\text{max}} - X_{i0}^0$$  \hspace{1cm} (5)

Hence we get, that:

$$x_{\text{min}} = \frac{X_{i\text{min}} - X_{i0}^0}{\Delta_i}, \quad x_{\text{max}} = \frac{X_{i\text{max}} - X_{i0}^0}{\Delta_i}$$  \hspace{1cm} (6)

Based on the results of the previously obtained variation interval in the dimensionless coordinate system, the upper and lower levels for all factors are determined. Then the planning matrix is compiled.

Each regression coefficient \(b_j\) of equation (3) is defined as follows:

$$b_j = \frac{1}{N} \sum_{i=1}^{N} x_{ij} y_j$$  \hspace{1cm} (7)

Further, the significance of each of the coefficients is determined, i.e. whether they should all be substituted into the equation of regression (3). The standard deviation is calculated for this:

$$S_{b_j} = \sqrt{\frac{S_{\text{play}}^2}{N}},$$  \hspace{1cm} (8)

where \(S_{\text{play}}^2\) is the reproducibility estimation.

To find the reproducibility estimation, additional three parallel experiments were put in the center of the plan, an average value \(\bar{y}\) and dispersion \(S^2\) were determined for them. Since the dispersion is for one series of parallel experiments, it is a dispersion of reproducibility (error mean square) \(S_{\text{play}}^2\).
\[
S^2 = S^2_{play} = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{n - 1}}
\]  

(9)

The significance of the regression coefficients is determined on the basis of the condition:

\[
|b_j| \geq S_{b_j} \cdot t,
\]

(10)

where \( t \) is the Student's test (the tabulated value found for the number of degrees of freedom, \( f = N - 1 \) and the significance level \( q = 0.05 \)).

After determining the significance of the coefficients, a final form of the regression equation is compiled and the adequacy of the obtained mathematical model is checked.

3. Results and discussion

As a result, mathematical models that describe the induction time of the polymer (\( \tau_{ind} \)), the average rate of foaming of the mixture (\( \nu_{sp} \)), density (\( \rho \)), water absorption (\( U \)), tensile strength (\( \sigma \)) and thermal conductivity (\( \lambda \)) mass concentrations of system components and operating parameters of the installation were obtained.

Thus, the dispersion of reproducibility (error mean square) decreases the induction time of the components of polyurethane foam (polyol "A" and polyisocyanate "B") between themselves in the presence of wood particles (Fig. 2).

This is due to the fact that the bulk density of the wood filler is greater than that of the polyurethane foam and the reaction for the formation of the gas phase slows down in the initial stage because the polymer is pressurized by the wood filler due to its gravity [4, 7, 10, 18, 22]. The regression equation describing this dependence looks like this:

\[
\tau_{ind} = 0.185 \cdot W_{wmc} + 2.834 \cdot W_{pol} - 128.486
\]  

(11)

Figure 2. Response surfaces the induction time from the mass concentration of components of the wood polymer composition

Figure 3. Response surfaces the average rate of foaming of the polymer from the mass concentration of the components of the wood polymer composition

The results of determining the average foaming rate of the polymer as a function of the mass concentration of the components are shown in Fig. 3. The decrease in the average foaming rate in the presence of wood filler is also explained by the pressure of the wood filler on the polymer [36, 40]. The regression equation is as follows:
Measurements of the density of the samples showed an obvious increase in it with the maximum possible concentration of wood filler. It is proved that the effect of vacuum in the range of 10 to 30 kPa makes it possible to increase the size and the number of bubbles, to prevent shrinkage of the polymer, which together makes it possible to reduce the density of DPTM (Fig. 4). The regression equation looks like this:

$$\rho = 58.775 + 0.464 \cdot W_{mb} - 0.207 \cdot P_{vac} - 0.008 \cdot W_{mb} \cdot P_{vac}$$

(13)

It is noted that as the degree of vacuum (Pvac) increases, the water absorption of the samples gradually decreases and becomes equal to slightly more than 1% at a vacuum of 30 kPa (Fig. 5). This dependence is explained by the fact that when a vacuum is removed after foaming, a dense film is formed along the entire outer surface of the sample, because the gas bubbles on the outer layer of the sample "collapse" due to the pressure difference, forming a continuous waterproof layer of small thickness. The regression equation looks like this:

$$U = 2.013 - 0.044 \cdot P_{vac} + 0.008 \cdot W_{mw}$$

(14)

The tensile strength of the samples is determined depending on the absolute moisture content of the wood filler (Fig. 6) at different concentrations of the components. It was found that the tensile strength of the obtained samples is reduced by almost two times. This confirms the assumption of the destruction of the boundary layer during the evaporation of free moisture in the outer layers of wood particles as a result of the exothermic reaction of the components of the polyurethane foam [15, 24, 26, 27, 33].

The regression equation:

$$\sigma = 0.356 - 0.0009 \cdot W_{abs} - 0.0022 \cdot W_{mb}$$

(15)
Figure 6. Response surfaces of the ultimate tensile strength from the moisture content of the wood filler and the mass concentration of the components

Figure 7. Response surfaces of the thermal conductivity of the mass concentration of the components of the wood-polymer composition

Investigation of the coefficient of thermal conductivity of wood polymer insulation material showed its obvious increase (Fig. 7). The regression equation:

$$\lambda = 0.02 + 0.009 \cdot W_{mw} - 0.0001 \cdot W_{mb} - 0.001 \cdot W_{mw} \cdot W_{mb}$$  \hspace{1cm} (16)

4. Conclusions
The analysis of experimental studies’ results of the main properties of thermal insulation material based on wood particles and a polymer binder reflects the reasonableness of the use of the material as thermal insulation one according to thermophysical and physical and mechanical parameters. The obtained results of experimental studies make it possible to determine the optimum range of mode parameters for the process of obtaining wood-polymer thermal insulation material in the installation [38]. The developed mathematical description allows to predict the main qualitative indices of a material depending on the mass concentration of components and the mode parameters of the process of its creation [19, 21, 23, 32, 35]. Forecasting of quality indicators depending on the composition makes it possible to obtain a material with initially specified properties [11, 28, 29].

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5. Notation
$P_{vac}$ – the underpressure, kPa; $\tau_{ind}$ – the induction time of the polymer, s; $v_{sp}$ – the average rate of foaming of the mixture, mm/s; $W_{mw}$ – the concentration of wood filler, %; $W_{mb}$ – the absolute humidity of wood filler, %; $\sigma$ – tensile strength, MPa; $\rho$ – density, kg/m$^3$; $\lambda$ – thermal conductivity, W/(m·K); $W_{mb}$ – the concentration of polyisocyanate "B", %.

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