Foam Polyethylene Made of Recycled Polyethylene

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\textbf{Abstract}. The paper deals with the main principles of foam polyethylene production by the addition of recycled polyethylene and a modifier in the initial mixture. Obtaining of the modified foam polyethylene will accomplish two important tasks: solve the environmental problem of recycling polyethylene waste and reduce the cost of the material. The optimal consumptions of recycled polyethylene and a modifier were determined by using the methods of mathematical experiment planning. To predict the main characteristics of the modified foam polyethylene a special nomogram was worked out. The properties of the developed material were studied. Based on the obtained results, it was found that the modified foam polyethylene had quite proper physical and mechanical characteristics and could be recommended for use in insulation systems of frameless and frame buildings, as well as in floating floor systems.

1. Introduction
Polyethylene is a high-molecular compound consisting of long chains with branches of various lengths; material properties depend on the polymerization conditions. The main characteristics of polyethylene are the following: low vapor and gas permeability; high resistance to organic and inorganic acids (with the exception of a 50\% solution of the nitric acid); high resistance to salts and alkalis solutions of salts; low solubility in organic solvents (slightly swells); the melting temperature of various types of polyethylene is from 103 to 137\(^{\circ}\)C [1–3].

Foam polyethylene is a gas-filled thermoplastic polymer with a closed-porous structure. It is a soft and elastic material with good cushioning properties. Foam polyethylene is obtained by injection molding, or by extrusion of a foamed mass from various ethylene polymers (LDPE, HDPE), mainly from low-density polyethylene with the addition of special agents to improve its properties. Depending on the production technology and additives used, the resulting material can differ in both structure and properties, leaving the main qualities of the initial substance such as: plasticity, water resistance, chemical inertness, resistance to temperature jumps, softening at temperatures above 100\(^{\circ}\)C, toxicity [4–6]. The thermal conductivity of foam polyethylene is about 0.040 W/(m\(\cdot\)K).

Mats and rolls made of foam polyethylene are used in systems of frameless and frame buildings for insulation of walls, roofs, attic floors, as well as in floating floor systems, including industrial floors [7–13].
The basic problem associated with the use of products made of polyethylene (or foam polyethylene) is waste disposal, since the polymer does not decompose and does not rot, and this creates an environmental danger. This problem can be solved by recycling polyethylene waste, for example, in the production of modified foam polyethylene.

Therefore, the main goal of the research was to develop the heat insulating material from foam polyethylene with the addition of recycled polyethylene waste and to study the properties of the derived modified material.

2. Materials and methods
Modification methods of recycled polyethylene can be divided into chemical (cross-linking, introduction of various additives, mainly of organic origin, processing with organic-silicon liquids, etc.) and physical-mechanical (filling with mineral and organic fillers).

The technological processing of polyethylene waste includes the following operations: sorting, crushing and washing of polyethylene waste; processing of waste with an organic-silicon liquid at 90±10°C for 4–6 hours; drying of modified waste by centrifugation; re-granulation of modified waste [14–17].

To obtain a modified foam polyethylene with additives of recycled polyethylene waste and a modifier it was necessary to carry out the following tasks:
- to work out a methodology for determining the optimal consumption of recycled polyethylene and a modifier;
- to develop a technological scheme;
- to select the necessary equipment;
- to conduct experimental tests of the obtained material and study its properties;
- to give recommendations of possible applications of modified foam polyethylene.

The experiment methodology included the following stages: realization of the experiment, getting statistical data, obtaining the basic polynomials and performing analytical optimization; interpolating of the results and solving the optimization problems; and graphical interpretation of the optimized models. On the basis of optimal rotatable plans, experiment planning, construction of quadratic equations and their interpolation solutions. Analysis of the results, testing statistical hypotheses and estimation the significance of the obtained coefficients of the regression equations were carried out by standard methods for statistical modeling [18–21]. The calculated coefficients of the equations were compared with confidence intervals. These confidence intervals were determined for each response function using the Student's criterion and the calculated error of the experiment. If the coefficient for this factor ($X_i$) was less (in absolute value) than the confidence interval $\Delta b_i$, it was considered insignificant and equal to zero ($b_i = 0$).

3. Experiment and results
The aim of the experimental study was to assess the effect of the consumption of a recycled polyethylene additive and a modifier on the properties of the material, taking into account the regulation of air pressure supplied to the foaming, as well as to optimize of the mixture composition. The technological aspect of the implementation of this task was the optimization of the mixture composition based on the methods of mathematical statistics and the experiment data.

The experiment was conducted on the equipment of the technological line for the production of non-crosslinked polyethylene.

The following parameters were taken as independent variable factors: consumption of the recycled polyethylene ($X_1$, %), consumption of the modifier ($X_2$, %) and the air pressure in the extruder ($X_3$, kPa). Maleic anhydride was used as a modifier. The density of the modified foam polyethylene ($Y_1$, kg/m$^3$), the strength at 10% compression ($Y_2$, MPa) were taken as optimization parameters. The experimental conditions are shown in table 1.
Table 1. The experimental conditions.

| Variable factors                          | Symbol \(X_i\) | Average value \(\bar{X}_i\) | Range of variation \(\Delta X_i\) | Variable factors values at levels |
|------------------------------------------|----------------|-----------------------------|---------------------------------|---------------------------------|
| Consumption of the recycled polyethylene, % | \(X_1\)        | 20                          | 10                              | -1                             |
| Consumption of the modifier, %           | \(X_2\)        | 6                           | 1                               | +1                             |
| Air pressure in the extruder, kPa         | \(X_3\)        | 90                          | 10                              |                                |

Processing the results of the experiment made it possible to obtain regression equations (basic polynomials) that established a functional relationship between the variable factors and the optimization parameters:

\[ Y_1 = 34 + 3X_1 - 6X_2 - 3X_3 + 2X_1X_3 \]

at a confidence interval \(\Delta b = 1.8\)

\[ Y_2 = 160 + 33X_1 + 25X_2 + 28X_3 + 14X_1X_3 - 16X_2^2 \]

at a confidence interval \(\Delta b = 12\).

4. Discussion

Analysis of the coefficients of the regression equations shows that the density of samples made of the modified foam polyethylene \(Y_1, \text{ kg/m}^3\) is most influenced by the modifying additive. Moreover, when the consumption of the additive increases, the density of the modified foam polyethylene decreases (the coefficient at \(X_2\)). This is understandable from the point of view of the mechanism of maleic anhydride action, which under the conditions of polymer melting in the extruder has a plasticizing effect on the melt.

An increase in the consumption of the additive of the recycled polyethylene (the coefficient at \(X_1\)) leads to some raise of the density of the modified foam polyethylene, which is due to an increase in the viscosity of the melt in the extruder. The air pressure growth in the extruder causes a certain decrease in the density (the coefficient at \(X_3\)) owing to better foaming of the polyethylene matrix. The combined effect of the recycled polyethylene consumption and the air pressure in the extruder does not significantly affect the density change (the coefficient at \(X_1X_3\) is close to the “threshold” confidence interval).

The change in the strength at 10% compression of the samples \(Y_2, \text{ kPa}\) is mostly determined by the change in the consumption of the recycled polyethylene (the coefficient at \(X_1\)). The modifier consumption and the air pressure in the extruder change affect the result to a lesser extent. Moreover, an increase in the values of each of the factors leads to an increase in the strength to one degree or another (the coefficients at \(X_2\) and \(X_3\)).

The combined effect of the recycled polyethylene consumption and the air pressure in the extruder does not significantly affect the strength change (the coefficient at \(X_2X_3\) is “+14”). A graphical interpretation of the obtained dependencies is presented in figures 1 and 2.

The peculiarity of the polynomial \(Y_2 (X_1, X_2, X_3)\) is that the dependence of the strength at 10% compression \(Y_2, \text{ kPa}\) on the consumption of the modifier \(X_3\) is non-linear (the coefficient at “\(X_2^2\)” is “–16 ”). That is, with an increase in the consumption of the modifier (ceteris paribus), the strength first increases, and then begins to decrease. To determine the range of values of the consumption of the modifier \(X_2\) at which the strength has a maximum value, the method of analytical optimization can be used.
Figure 1. Dependence of the density of the modified foam polyethylene ($Y_1$, kg/m$^3$) on the consumption of the recycled polyethylene and the consumption of the modifier, as well as on the air pressure in the extruder.

Figure 2. Dependence of the strength at 10% compression of the modified foam polyethylene ($Y_2$, kPa) on the consumption of the recycled polyethylene and the consumption of the modifier, as well as on the air pressure in the extruder.

Based on the optimized data and using the obtained functions $Y_1(X_1, X_3)$ and $Y_2(X_1, X_3)$, a nomogram has been drawn (figure 3). Using this nomogram, it is possible to predict the main properties of the material (the strength at 10% compression and the density) depending on the consumption of the recycled polyethylene and the air pressure in the extruder, as well as to choose the consumption of the recycled polyethylene from the conditions of the specified characteristics.

Work with the nomogram is carried out as follows. The consumption of the recycled polyethylene (23% in the example) and, for instance, the desired density of modified foam polyethylene (30 kg/m$^3$ in the example) are pre-set. In sector A, a line is drawn parallel to the abscissa, first until it intersects with a constant density curve (30 kg/m$^3$). The perpendicular is dropped on the abscissa axis and the required pressure in the extruder (91 kPa) is determined. Further, in sector B, the already established pressure value in the extruder (91 kPa) is noted and a perpendicular is drawn until it intersects with the
extended A – C line and, thus, we obtain the value of the compressive strength of the modified foam polyethylene (186 kPa).

**Figure 3.** Nomogram for predicting the properties of the modified foam polyethylene or choosing the consumption of the recycled polyethylene: I – density, kg/m³; II – strength at 10% compression, kPa.

If we need to determine the consumption of the recycled polyethylene, we set the value of the air pressure in the extruder and any of the characteristics of the modified foam polyethylene (usually the density) and solve the inverse problem.

5. Conclusion
The following conclusions can be drawn from the analysis of the obtained results.

As a result of the research, it was found that when the consumption of the recycled polyethylene is in the range of 15–25%, and the air pressure in the extruder is 85–95 kPa, with the appropriate correcting of the modifier consumption, we can obtain a material that practically does not differ in its properties from the primary foam polyethylene. The optimal consumption of the recycled polyethylene is 20%. Introducing this amount of recycled polyethylene into the initial mixture could reduce the cost of insulation material by 12-15%.

Thus, the production of modified foam polyethylene will reduce the cost of the material and solve the environmental problem of recycling polyethylene waste.

Mats and rolls made of modified foam polyethylene can be used as vapor-, heat- and waterproofing materials in insulation systems for frameless and frame household objects as well as in floating floor systems.

6. References
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