Effective thermal insulation based on recycled polyethylene

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Abstract. Foam polyethylene is an effective insulating material in systems of frame and frameless buildings, floating floors, and technical thermal insulation. The products based on this material enable to obtain seamless insulating shells, which significantly reduce heat loss through joints. The use of recycled polyethylene for the production of foamed polyethylene is advisable both from the point of reducing the cost of the material itself, and from the point of preserving the environment. The aim of the work was to assess the possibility of using recycled polyethylene for the manufacture of foamed polyethylene, taking into account the possible application of modifiers and varying the foaming modes. The results of the experiment made it possible to evaluate the influence of prescription and technological factors on the properties of products. The implementation of optimization solutions made it possible to construct a nomogram that allows predicting the properties of products and establishing the optimal costs of the main components. The optimal interval of consumption of recycled polyethylene has been established, which is 20…25%. The properties of such a material practically do not differ from the properties of products made from foamed polyethylene that enables its application in all insulation systems where pure foamed polyethylene is used.

1. Introduction

The relevance of using effective heat-insulating materials in building systems is due to both the need to save energy and the requirements for the comfort of the internal environment and the durability of structures. Taking into account the peculiarities of heat-insulating materials, special building systems have been developed, including insulating layers, load-bearing and protective elements.

In construction and technology, the main thermal insulation materials used are mineral fiber materials (based on basalt and glass fibers, as well as rock wool), products based on foam glass, products based on foamed rubber, as well as products based on foamed plastics [1–3].

The group of foamed plastics includes foamed and extruded polystyrene, polyurethane foams, polyisocyanurate foam, foamed polyethylene and foamed polypropylene. Plate products are made on the basis of rigid foamed plastics; on the basis of elastic foamed polymers, rolls, cylinders and shaped products can be manufactured [4–6].

The prices and price of thermal insulation materials can be optimized by changing the type of the main chemical compound, by introducing modifiers, fillers or secondary polymers similar in composition to the main chemical. In this regard, it becomes relevant to study the possibility of using secondary raw materials for the production of such materials. Each launch of a new line for the recycling of plastics is not only another successful step in the development of the polymer market and protecting the environment, but also increasing the economic efficiency and competitiveness of production. Practice shows that investments in such lines quickly pay off [7-9].
Almost all foamed plastics have high water resistance, combined with low water absorption, water and vapor permeability. This makes it fundamentally important to use the entire complex of positive properties of these materials in structures [10–12]. At the same time, when using plate products, the problem of the joint arises, or rather the need to seal it, which has not been fully resolved and involves the use of additional roll vapor and waterproofing.

The formation of a seamless connection is possible either as a result of the use of sprayed polyurethane, or rolled foamed polyethylene using special installation technologies. A number of works describe the technology of forming a seamless shell of rolled foamed polyethylene, which consists in joining individual products into a lock followed by welding along the seam with hot air [13–15].

Foam polyethylene belongs to the group of polyolefin foams and is characterized by high elasticity and water resistance, low thermal conductivity, good sound insulation, low vapor and water permeability. In construction, foamed polyethylene with an average density in the range from 21 to 79 kg/m³ are used [16–18]. Creation of filled polymer materials based on recycled polyethylene raw materials is of great scientific and practical interest.

The aim of the work was to assess the possibility of using recycled polyethylene for the manufacture of foamed polyethylene, taking into account the possible use of modifiers and varying the foaming modes.

2. Materials and Methods
To achieve this goal, a number of specific tasks were implemented, including the establishment of the effect of the consumption of the additive and modifier on the properties of products, factoring in the regulation of the air pressure supplied for foaming; optimization of component costs and development of a methodology for selecting the optimal content of secondary polyethylene additive and assessment of the effect of additive consumption on the properties of products.

During the experiment, methods of mathematical planning and processing of results were used. The study of the obtained polynomials was carried out by the method of analytical optimization. The analytical optimization technique was developed by the NRU MGSU and was tested in the study of technologies of various building materials and in the implementation of system solutions based on these materials [19–21]. The analytical optimization concept is based on two statements. First, the resulting mathematical model (in the form of a polynomial) is adequate to the real process, that is, it describes it with a specified degree of accuracy. Secondly, the obtained mathematical model is an algebraic nonlinear function of several variables: with this function, all types of actions can be performed using the apparatus of mathematical analysis [22].

The following factors are accepted as variable factors: consumption of recycled polyethylene (X₁), consumption of modifier (X₂) and pressure in the extruder (X₃). The response functions are: the average density of foamed polyethylene products (Y₁, kg/m³) and the compressive strength of products at 10% deformation (Y₂, kPa). The compressive strength of foamed polyethylene at 10% deformation was taken as an optimization parameter. The experimental conditions are presented in table 1. Maleic anhydride was used as a modifier.

| Table 1. Experimental conditions |
|---------------------------------|
| Factor                           | Coded symbol, Xᵢ | Factor average, \( \bar{X}_i \) | Variation interval, ΔXᵢ | Factor values at levels |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Consumption of recycled polyethylene, % | X₁               | 20              | 10              | 10              | 30              |
| Consumption of modifier, %       | X₂               | 6               | 1               | 5               | 7               |
| Pressure in the extruder, kPa    | X₃               | 90              | 10              | 80              | 100             |
3. Results
Having implemented a three-factor experiment, the matrix of which (in coded values of factors) was constructed according to the D-optimal rotatable design for a full quadratic polynomial, processing experimental data and testing statistical hypotheses, regression equations (basic polynomials) were obtained that establish a functional relationship between the variable factors and the resulting parameters:

For the average density of foamed polyethylene (kg/m$^3$):

$$Y_1 = 34 + 3X_1 - 6X_2 - 3X_3 + 2X_1X_3$$

with the confidence interval $\Delta b = 1.8$.

For the compressive strength of products at 10% deformation (kPa):

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

with a confidence interval of $\Delta b = 12$.

Graphical interpretation of the dependences $Y_1 = f_1(X_1, X_2, X_3)$ and $Y_2 = f_2(X_1, X_2, X_3)$ is shown in figures 1 and 2.

![Figure 1. Dependence of the average density of foamed polyethylene ($Y_1$, kg/m$^3$) on the consumption of recycled polyethylene and modifier, air pressure in the extruder](image_url)

The analysis of the coefficients of the regression equations shows that the modifying additive has the greatest influence on the average density of products made of foamed polyethylene ($Y_1$, kg/m$^3$); moreover, with an increase in the consumption of the additive, the average density of foamed polyethylene decreases (the coefficient at $X_2$ is equal to minus 6). This is understandable from the point of view of the mechanism of action of maleic anhydride, which, under the conditions of polymer melting in the extruder, has a plasticizing effect on the melt.

An increase in the consumption of secondary polyethylene additive (coefficient at $X_1$ equal to 3) leads to a slight increase in the average density of foamed polyethylene, which is due to an increase in the viscosity of the melt in the extruder. An increase in air pressure in the compressor causes a slight decrease in density (coefficient at $X_3$ equal to minus 3) due to better porosity of the polyethylene matrix. The combined effect of recycled polyethylene consumption and pressure in the compressor can be considered as a synergistic effect, but it is insignificant (the coefficient at $X_1X_3$ is equal to 2 and is close to the “threshold” confidence interval). This effect is explained by the fact that the introduction
of secondary foamed polyethylene (at stable temperatures in the extruder) increases the viscosity of the polymer melt and implies an increase in the pressure in the compressor to obtain a material of equivalent average density.

![Figure 2. Dependence of the compressive strength of foamed polyethylene at 10% deformation (Y2, kPa) on the consumption of recycled polyethylene and modifier, as well as on the air pressure in the extruder.](image)

The change in the compressive strength of products at 10% deformation (Y2, kPa) is most determined by the change in the consumption of recycled polyethylene (the coefficient at X1 is equal to 33). The flow rate of the modifier and the change in compressor pressure affect the result to a lesser extent. Moreover, an increase in the values of each of the factors causes an increase in strength to one degree or another (the coefficients at X2 and X3 are equal to 25 and 28, respectively).

The combined effect of the consumption of recycled polyethylene and the pressure in the compressor on the strength change is insignificant (the coefficient at X1X3 is equal to 14) and can be considered as a synergistic effect of the combined effect on the strength. The increased viscosity of the melt and high pressure on the polymer matrix explains this, causing the formation of denser durable intercellular foamed membranes polyethylene.

4. Discussion
A feature of the polynomial Y2 = f2 (X1, X2, X3) is that the dependence of the compressive strength of products at 10% deformation (Y2, kPa) on the consumption of the modifier (X3) is nonlinear (the coefficient at X32 is equal to minus 16). That is, with an increase in the consumption of the modifier (all other things being equal), the strength first increases, and then begins to decrease. The range of values of the modifier consumption (X3) at which the strength approaches the maximum and maximum can be determined by the method of analytical optimization.

In essence (physical and mathematical sense), analytical optimization consists in determining the extrema of a function of several variables for each of the variables (for which partial derivatives are found for each of the variables and equated to zero); in solving polynomials taking into account the
found extreme values of functions and obtaining regression equations optimized for one or more variables.

Thus, the function \( Y_2 = f_2 (X_1, X_2, X_3) \) has a local optimum for the factor \( X_2 \), which is determined by the differential-analytical method. Analytical optimization is carried out according to the function \( Y_2 = f_2 (X_1, X_2, X_3) \):

\[
\frac{\partial Y_2}{\partial X_2} = 25 - 32X_2 = 0 \rightarrow X_2 = \frac{25}{32} = 0.78
\]  

(3)

Solving the basic polynomials at \( X_2 = 0.78 \), we obtain the following optimization equations:

\[
Y_1 = 34 + 3X_1 - 6(0.78) - 3X_3 + 2X_1X_3
\]

(4)

\[
Y_2 = 160 + 30X_1 + 25(0.78) + 30X_3 + 14X_1X_3 - 16(0.78)^2
\]

(5)

or

\[
Y_1 = 29 + 3X_1 - 3X_3 + 2X_1X_3
\]

(6)

\[
Y_2 = 170 + 33X_1 + 28X_3 + 14X_1X_3
\]

(7)

Differentiation of the equation \( Y_2 = f_2 (X_1, X_2, X_3) \) by the partial derivative made it possible to establish the optimization equations (functions) for \( Y_1 \) and \( Y_2 \). The results of graphical interpretations of these functions are combined into a nomogram.

Determine the actual value of the flow rate of the modifier, determined in coded values (\( X_2 \)). For this we use the information contained in table 1. The natural value is equal to:

\[
X_2 = \overline{X_2} + \Delta X_2 \times X_2 = 6 + 1\times0.78 = 6.78\%
\]

(8)

Taking into account the statistical error of the experiment, we obtain the following optimal consumption of the modifier: 6.7 \pm 0.2\%. Taking into account the optimization data and using the optimized functions \( Y_1 (X_1, X_3) \) and \( Y_2 (X_1, X_3) \), a nomogram was constructed (Fig. 3). Using this nomogram, one can solve the problem of predicting properties (compressive strength at 10% deformation and average density) depending on the consumption of recycled polyethylene and the pressure in the extruder, as well as the direct problem of choosing the consumption of recycled polyethylene from the condition of the given properties.

![Figure 3. Nomogram for determining the consumption of recycled polyethylene](image-url)

The work with the nomogram is carried out as follows (see Fig. 3). The consumption of recycled polyethylene (in the example, it is 23%) and, for example, the desired average density of foamed polyethylene (in the example, 30 kg/m³) are preset. In sector A, draw a line parallel to the abscissa axis until it intersects with the constant average density curve (30 kg/m³). We lower the perpendicular to the abscissa axis and determine the required pressure in the extruder (91 kPa). Further, in sector B, we
note the already set value of the pressure in the extruder (91 kPa) and draw a perpendicular to the intersection with the extended line AC and obtain the value of the strength of foamed polyethylene in compression (kPa).

If we need to determine the consumption of recycled polyethylene, then we set the pressure in the extruder and some of the characteristics of foamed polyethylene (usually of average density) and solve the inverse problem.

The optimal range of recycled polyethylene consumption is 20 ... 25%, which reduces the cost of the product by 8 ... 12%. The properties of such a material practically do not differ from the properties of products made of foamed polyethylene. This makes it possible to use a less expensive material in systems developed for conventional foamed polyethylene and, in particular, for facade insulation systems on a wooden frame, for insulation of attics, floating floors, as well as for insulating frameless utility facilities.

5. Conclusions
Foamed polyethylene is one of the materials that are widely used today in various industries and construction. Products based on foamed polyethylene are used for heat, steam and waterproofing of various building structures. One of the advantages of this material is the possibility of forming seamless insulating shells, which significantly reduce heat loss at the joints and exclude the migration of vapor-air mixtures or droplet moisture through the insulated surfaces.

The research has substantiated the technical, economic, and environmental feasibility of using recycled polyethylene as a raw material additional to the main one. The optimal range of recycled polyethylene consumption is 20...25%, which reduces the cost of the product by 8 ... 12%, as well as the environmental load, proportional to the area occupied by waste during storage. The properties of the material remain practically unchanged that enables its application in all insulation systems where pure foamed polyethylene is applicable.

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