Insulation systems based on foamed plastic

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Abstract. In the design and construction of residential and industrial buildings outbuildings, it is necessary to use effective thermal insulation materials that provide a comfortable microclimate in the room, as well as the required conditions for implementing technological processes. An essential factor is the reduction of the negative impact on the environment, which is expressed both in the reduction of energy consumption and in the possibility of rational use of industrial waste for partial replacement of the main raw material components. To increase the efficiency of heat-insulating materials based on foamed polyethylene, it was necessary to develop a technique for selecting the composition of synthetic polyethylene foam matrix, considering the possibility of using secondary modified polyethylene foam at different foaming modes. The compositions of modified polyethylene foam were selected using statistics methods and analytical optimization. The developed bases of optimization and composition selection methodology allowed to establish optimal consumption values of main components and process parameters corresponding to the specified requirements. Using alignment charts, the solution of the predictive problem of estimation of values of strength and average density of foamed polyethylene depending on the value of consumption of main components was realized.

Keywords: thermal insulation, polyethylene foam, cellular structure, mathematical planning, analytical optimization, secondary polyethylene foam

1 Introduction

The development of production and technology entails an increase in overall energy consumption. The U.S. Energy Information Administration (EIA) predicts that total U.S. energy consumption will increase by 31% between 2017 and 2050. The largest share of energy consumption belongs to the transportation segment and construction projects (up to 60-65% of final energy consumption) [1-3].

At present, Russia’s current energy needs are met through the use of traditional sources – coal, gas, and nuclear energy. The introduction of alternative energy sources into...
operation maintains a steady growth rate but does not yet exceed 0.5% of total generation. By 2030, they will account for only 2% of the electricity generation sector. Thus, energy conservation is an effective method to achieve global energy sustainability. Secondly, the need to reduce the negative environmental load is also associated with strict requirements to improve the thermal insulation performance of buildings. Thirdly, the realization of building systems with effective thermal insulation provides the basics of comfort in living spaces and compliance with processing parameters in production or storage facilities [4-6].

Considering the peculiarities of the operation of thermal insulation materials in building structures, certain standard requirements are imposed on these materials. Firstly, it is the stability of properties, including thermal performance, over time (operational stability) and in different operating conditions (primarily in terms of humidity and temperature of outdoor and interior environments). Both during installation and operation, thermal insulation materials are exposed to weathering and stresses, and therefore, the durability of structures using such materials should be high [7-9].

Important for thermal insulation materials is resistance to bio-damage and fire safety. These requirements primarily apply to thermal insulation materials containing organic components. At the same time, considering the high porosity of these materials and the possible presence of open and communicating pores, we cannot exclude the penetration of moist media into the internal volumes of the materials, which reduces the fire protection properties (and primarily the integrity of the material under fire) and the resistance of these materials to biological effects. Special formulations containing antiseptics and/or flame retardants are introduced, and insulation systems are developed with these features in mind to improve these performances [10, 11].

The main functional property of thermal insulation is its low thermal conductivity due to the structure of the matrix and porosity characteristics – the size and shape of pores, distribution of their size, etc. Ultralight thermal insulation materials, particularly aerogels, achieve the best performance in this respect. Special formulations, matrix processing, and foaming technologies allow to obtain materials with porosity of more than 99% and thermal conductivity at the level of immobilized air and lower in the case of lighter gases [12-14]. The technologies of their manufacture are very complex and involve highly specialized equipment, so in general construction practice, such materials are used in exceptional cases. In construction practice, preference is still given to traditional materials due to the proven technology of their production, stability of properties, and relatively low cost.

Thermal insulation inorganic materials, both fibrous (glass wool, rock wool, slag wool, basalt, and chrysotile fiber) and cellular (expanded perlite, expanded vermiculite, and ceramic products, especially lightweight concrete and silicates), are quite effective, but do not allow to significantly increase the values of their properties without a radical technology change. Metal or metalized reflective membranes must have a space filled with air, gas, or vacuumed space, which is also relatively difficult to implement and does not spare the materials from conductive heat transfer across the matrix walls.

The best performance indicators among traditional thermal insulation materials are characterized by thermal insulation organic materials and composites based on them. These materials, both fibrous (cellulose, nanocellulose, cotton, wood, cellulose pulp, and synthetic fibers) and cellular (cellular cork, expanded rubber, polystyrene foam, polyurethane foam, polysisocyanurate foam, polyolefin foams, and other polymers), are much more easily subjected to modification of their structure and the technology of their production.

The desire to improve thermophysical performance leads to the synthesis of new polymer compounds and the creation of composites, for example, based on hollow glass microspheres, cyclic polyolefins, the use of special fibers and nanofibers, the development of materials with cell anisotropy, etc. [15-17].
Research is being conducted to study the possibility of using various recycled wastes and secondary products in the binder component to reduce the cost of expensive and energy-intensive components that form the material matrix. Metallurgical slags, volcanic rocks, and fly ash can be used in the composition of mineral binders. There is a positive experience in using secondary polymers obtained by recycling municipal solid waste, etc., in the composition of polymers.

Methods of modification of secondary polyethylene raw materials can be divided into chemical (cross-linking, introduction of various additives, mainly of organic origin, treatment with organosilicon liquids, etc.) and physical and mechanical (mineral and organic fillers). The modification mechanism adopted in the research is the formation of chemical bonds between the siloxane groups of the organosilicon liquid and unsaturated bonds and oxygen-containing groups of secondary polyethylene. Technological process stages for obtaining the modified material include sorting, crushing, washing of the waste, its treatment with an organosilicon liquid at 90±10 °C for 4-6 h; drying of the modified waste by centrifugation; re-granulation of the modified waste.

The purpose of the research described in the article was to develop a methodology for selecting the composition of synthetic polyethylene foam matrix, taking into account the possibility of using secondary modified polyethylene foam at different modes of foaming, as well as to optimize the composition of modified polyethylene foam using statistics methods and analytical optimization.

2 Materials and methods

The study of sample properties of non-cross-linked polyethylene foam with the addition of secondary polyethylene was carried out following the provisions of GOST R 56729-2015 (EN 14313:2009) “Factory-made polyethylene foam insulation products used for engineering equipment of buildings and industrial plants. General technical conditions”.

The experiment was conducted based on the planning methods of a three-factor experiment using a complete rotatable design. The secondary polyethylene flow rate \(X_1\), porophore flow rate \(X_2\), and extruder pressure \(X_3\) were taken as varying factors. The average density of polyethylene foam products \(\rho_m (Y_1, \text{kg/m}^3)\) and the compressive strength of the boards at 10% strain \(R_{10\%} (Y_2, \text{kPa})\) were taken as response functions. The compressive strength of the slabs is taken as the optimization parameter. The experimental conditions are presented in Table 1.

<table>
<thead>
<tr>
<th>Factor name</th>
<th>Symbol</th>
<th>Factor mean, (X_i)</th>
<th>Variation interval, (\Delta X_i)</th>
<th>Factor values at levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled polyethylene consumption, %</td>
<td>(X_1)</td>
<td>20</td>
<td>10</td>
<td>10 30</td>
</tr>
<tr>
<td>Porophore consumption, %</td>
<td>(X_2)</td>
<td>6</td>
<td>1</td>
<td>5 7</td>
</tr>
<tr>
<td>Extruder pressure, kPa</td>
<td>(X_3)</td>
<td>90</td>
<td>10</td>
<td>80 100</td>
</tr>
</tbody>
</table>

Processing of the results of the active experiment results, testing of statistical hypotheses, and assessing the significance of factors, as well as evaluating the adequacy of the obtained models was carried out in the Statistika program.

3 Results and discussion
Regression equations (basic polynomials), which establish a functional relationship between the varying factors and the resulting parameters, have the following form:

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

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

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

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

Analysis of the coefficients of the regression equations shows that the average density of polyethylene foam products (\( Y_1, \text{kg/m}^3 \)) is most influenced by the modifying additive; moreover, as the additive consumption increases, the density of polyethylene foam decreases (coefficient at “\( X_2 \)” equal to “-6”). This is explainable in terms of the mechanism of action of maleic anhydride, which has a plasticizing effect on the melt under conditions of polymer melting in the extruder.

Increasing the consumption of secondary polyethylene additive (coefficient at “\( X_1 \)” equal to “+3”) leads to a slight increase in the average density of polyethylene foam, which is due to an increase in the viscosity of the melt in the extruder. The increase of air pressure in the compressor causes some decrease in density (coefficient at “\( X_3 \)” equal to “-3”) due to better porosity of the polyethylene matrix. The combined effect of secondary polyethylene flow rate and compressor pressure on the change in average density has a negligible effect (coefficient at “\( X_1X_3 \)” equal to “+2”, close to the “threshold” confidence interval).

The change in the compressive strength of the slabs at 10% strain (\( Y_2, \text{kPa} \)) is determined to the greatest extent by changing the flow rate of recycled polyethylene (coefficient at “\( X_1 \)” equal to “+33”); the flow rate of the modifier additive 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 a greater or lesser extent (coefficients at “\( X_2 \)” and “\( X_3 \)” equal to “25” and “28”, respectively). The combined effect of secondary polyethylene flow rate and compressor pressure on the change in strength has a negligible effect (coefficient at “\( X_1X_3 \)” equal to “+14”).

A feature of the polynomial \( Y_2 (X_1, X_2, X_3) \) is that the dependence of the compressive strength of slabs at 10% strain (\( Y_2, \text{kPa} \)) on the modifier flow (\( X_2 \)) is nonlinear (the coefficient at “\( X_2^2 \)” is equal to “-16”). As the porophore flow rate increases (all other things being equal), the strength first increases and then begins to decrease. The interval of porophore flow rate (\( X_2 \)), at maximum strength, can be determined by analytical optimization method.

The analytical optimization method is a development of NRU MGSU and has been tested in the study of technologies of various building materials and in implementing system solutions based on these materials. The analytical optimization concept is based on two statements [18-20]. First, the obtained 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, it is possible to perform all types of actions using the apparatus of mathematical analysis.

Essentially, analytical optimization consists of determining the extrema of a function of several variables for each of the variables (for which the partial derivatives of each variable are found and equated to zero), solving polynomials given the found extreme functions, and obtaining regression equations optimized for one or more variables.
Thus, the function \( Y_2(X_1, X_2, X_3) \) has a local optimum for the factor \( X_2 \), which is determined by the differential analytical method. Analytical optimization is performed on the function \( Y_2(X_1, X_2, X_3) \):

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

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

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

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

or

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

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

Differentiating the \( Y_2(X_1, X_2, X_3) \) equation by a partial derivative allowed us to establish the optimization equations (functions) for \( Y_1 \) and \( Y_2 \).

We determine the natural value of the modifier consumption value defined in the coded values (\( X_2 \)). For this purpose, we use the information in Table 1. The natural value is:

\[
\bar{X}_2 = X_2 + \Delta X_2 \times X_2 = 6 + 1 \times 0.78 = 6.78\%
\]

Considering the statistical error of the experiment, we obtain the following optimal modifier consumption: 6.7±0.2 %.

Given the optimization data and using the optimized functions \( Y_1(X_1, X_3) \) and \( Y_2(X_1, X_3) \), an alignment chart was constructed (Figure 1). With the help of this chart, it is possible to solve the problems of prediction of properties (compressive strength at 10% strain and average density) depending on the secondary polyethylene flow rate and pressure in the extruder, as well as the direct problem of selection of secondary polyethylene flow rate from the condition of given properties.

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**Fig. 1.** Alignment chart for determining the consumption of secondary polyethylene: I – average density, kg/m³; II – compressive strength at 10% strain, kPa.
Work with the chart is done as follows (see Figure 1). The flow rate of recycled polyethylene (in the example, it is 23 %) and, say, the desired density of the polyethylene foam (in the example, 30 kg/m³) are predetermined. In sector A, draw a line parallel to the abscissa axis first to the intersection with the constant density curve (30 kg/m³). Lower the perpendicular to the abscissa axis and determine the required extruder pressure (91 kPa). Further, in sector B, mark the already set pressure value in the extruder (91 kPa) and, draw a perpendicular to the intersection with the extended line AC and get the value of compressive strength of polystyrene foam (kPa).

If we need to determine the flow rate of recycled polyethylene, we set the extruder pressure and one of the characteristics of polyethylene foam (more often density) and solve the inverse problem.

The fields of application of polyethylene foam products (rolls, mats, shaped products) cover almost all areas of construction and housing and communal services [21, 22]. The peculiarity of this material is the possibility of forming seamless insulation shells and, consequently, minimizing heat losses through cold bridges and increasing the thermal homogeneity of the structure [23, 24].

4 Conclusion

The use of thermal insulation materials in residential and commercial buildings can be attributed to the means of reducing energy losses and reducing the negative impact on the environment through direct fuel savings and by creating a favorable atmosphere around the facilities under construction and comfortable conditions inside the insulated premises.

Using insulation materials in construction will ultimately result in lower operating costs for electricity consumption for cooling and heating systems and lower initial installed fixed costs for cooling and heating equipment.

Application areas of products based on polyethylene foam (rolls, mats, shaped products) cover almost all construction areas, housing, and communal services. The peculiarity of this material is the possibility of forming seamless insulation shells and, consequently, minimizing heat losses through cold bridges and increasing the thermal homogeneity of the structure.

References