buildings

MDPI

Article

Ensuring the Durability of Buildings through the Use of Insulation Systems Based on Polyethylene Foam

Aleksey Zhukov *, Irina Stepina and Sofia Bazhenova

Department of Building Materials Science, National Research Moscow State University of Civil Engineering, Yaroslavskoe sh. 26, 129337 Moscow, Russia

* Correspondence: lj211@yandex.ru

Abstract: In modern polymer composite technology, the use of waste products from other industries or processed waste is reasonable, but this requires more research. The purpose of the research presented in the article was to develop a methodology for selecting the composition of modified polyethylene foam and to assess the flammability of the materials obtained. In these studies, the content of recycled polyethylene, as a result of solving optimization problems, was taken to be equal to 23% of the mass of the polymer. CO_2 was used as the foaming gas. The structure of the polymer was modified with flame retardant. This made it possible to obtain materials belonging to the group of flammable, self-extinguishing materials, which significantly expanded the field of application of products based on polyethylene foam. Taking into account the possibilities of seamless insulation casings, the following systems of application of products based on polyethylene foam are considered: floors under mechanical load on the ground; permafrost soil insulation; insulation of external building elements in harsh climatic conditions; floating floors.

Keywords: polyethylene waste; foamed polymers; flame retardants; modified polyethylene

check for updates

Citation: Zhukov, A.; Stepina, I.; Bazhenova, S. Ensuring the Durability of Buildings through the Use of Insulation Systems Based on Polyethylene Foam. *Buildings* **2022**, *12*, 1937. https://doi.org/10.3390/buildings12111937

Academic Editors: Anatoly Alekseytsev and Alla Sokolova

Received: 27 September 2022
Accepted: 7 November 2022
Published: 10 November 2022

1. Introduction

The characteristic trends of technological development and the development of the construction industry, in particular, imply an orientation towards saving energy resources, the introduction of digital technologies, and information models, as well as the implementation of the requirements of environmentally sustainable development [1–3]. The performance of these directions for the technologies of insulating systems involves the use of materials with a reasonable minimum average density, the use of by-products of other industries or processed waste, the introduction of modern methods for calculating technologies and building systems, as well as increasing the operational stability of materials and the durability of isolation systems [4,5].

In modern general building insulation systems, plate and roll products are used, as well as seamless sprayed or rolled insulation with special technological processing [6–8]. The most popular insulating products include slabs and mats based on stone wool, slabs based on mineral and glass fibers, slabs made of foam glass, extruded polystyrene, polyurethane foam, polyisocyanurate foam, and products based on foamed polyolefins [9,10]. Products are fixed into structures with special glue, followed by mechanical fixation. Piece products are mounted, as a rule, with additional insulation at joints, but this does not entirely exclude "heat transfer bridges" and, consequently, a decrease in the uniformity and thermal efficiency of the insulating shell during operation under changing temperature and humidity conditions [11,12].

Seamless joints are made by spraying foaming compositions based on polyurethane. These technologies are accompanied by the obligatory fulfillment of several requirements. Firstly, these are restrictions on the nature of the work, and means of protection against harmful emissions accompanying the preparation and application of foaming polyurethane are mandatory. Secondly, work is recommended to be carried out at temperatures of at least 5 °C. Thirdly, considering the fact that the seamless coating is kept in the structure only by adhesion to the base, the possibility of delamination of such a coating and destruction of the entire insulation system always remains [13,14].

The most promising is the formation of seamless insulating shells using polyethylene foam (RF Patent No. 2645190). In this case, polyethylene rolls are locked together and mechanically fastened to the base. Next, the lock joint is welded with hot air using a construction heat gun, and, thus, a seamless insulating shell is formed [15,16].

Polyethylene foam is an elastic, highly porous material with a high thermal insulation capacity. The material has high tensile strength, resistance to water, and low vapor permeability. The material has the possibility of hot air welding and flammability. Reducing combustibility would greatly expand the range of applications for products based on polyethylene foam.

Various additives can be introduced into the original polyethylene or polyethylene foam during its technological processing. By adding olefins and polar monomers, transparency and elasticity are achieved, and cracking is reduced; introducing copolymers and other polymers enhances impact resistance; chlorination, bromination, and fluorination improve chemical and thermal resistance. Soot and benzophenone derivatives are added to reduce the rate of aging under the influence of sunlight and ultraviolet radiation.

Secondary polyethylene is a product of the recycling of technogenic products and polyethylene wastes. As a rule, secondary polyethylene is modified when making products. At the stage of modification, additives that increase plasticity, decrease combustibility, and mineral fillers that increase strength properties and perform flame retardant functions can be added to polymer compositions [17,18].

Modification of the properties of secondary polyethylene is carried out by introducing various additives: cross-linking and foaming reagents: dicumyl peroxide and azodicarbonamide, their analogs with less toxicity, azodicarbonamide, etc.

Most types of foamed polymers, including polyethylene foam, belong to the category of flammable building materials. Note that in the Russian regulatory framework in systems of buildings and structures up to three floors, such materials are allowed, but this is not a solution to the problem.

The reduction of the flammability of foamed polymers is carried out as follows. First, a chemical effect of chemicals on the polymer matrix that reduces the flammability of the polymer is carried out. Secondly, given that freons, propane-butane, or iso-butane are traditionally used as gas-forming substances, their replacement with inert gases (which do not support combustion) also makes it possible to reduce the combustibility of the material. Thirdly, this is the introduction of finely dispersed (or ultradispersed) mineral powders containing intracrystalline or interpacket water into the matrix. A good result can be obtained using non-combustible adhesive coatings connected with the primary polymer foam-specialized sandwich panels [19–21].

Research to study the possibilities of modifying the properties of cellulose fiber, which is used as the basis for a group of thermal insulation materials and as a reinforcing component for building products, has shown the feasibility of using borates and their derivatives.

The porous structure of the stems of Sosnovsky's bramble has aroused interest in this material as a source of raw material for the production of thermal insulation boards. Monoethanolamine-(N→B)trihydroxyborate was used to protect the plant material against the action of microorganisms. With the antisepticidation of plant materials with a composition based on monoethanolamine-(N→B)trihydroxyborate, the component composition of the lignocarbohydrate complex of cell walls undergoes significant changes. According to the data from electron microscopy and infrared spectroscopy, the presence of modifier molecules in the composition of cell walls of modified plant material after prolonged extraction to constant weight has been established [22,23]. In addition, it was found that interaction between the modifier and the substrate occurs over the most reactive hydroxyls of lignin. This is evidenced by the disappearance of characteristic frequency peaks in

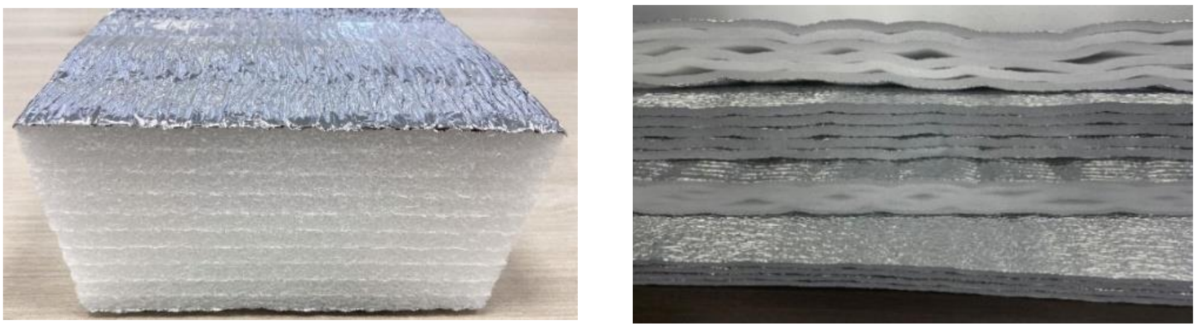
IR spectra after modification [23]. As a result of chemisorption, the modifier molecules are reliably fixed in the substrate during the process of lignin-carbohydrate raw material antisepsis with monoethanolamine-(N→B)-trihydroxyborate and can provide long-term protection against biocorrosion.

Technology on the basis of modified borscht and other biopositive materials of natural origin is still under development [24,25], while the technology of using polyethylene foam in the structures of residential and public buildings has been widely developed. Firstly, it is the insulation systems of low-rise buildings and cottages. Polyethylene foam is used in the structures of facades and roofs as a heat-soundproofing and waterproofing material. Secondly, it is the insulation systems of hangars of frame and non-frame types and the technologies of polyethylene foam application that are being developed by different companies, first of all by TepoFol Ltd (Moscow, Russia). The fields of application of polyethylene foam in construction can be expanded if the issue of the flammability reduction of this material is solved.

The purpose of the research presented in the article was to develop a methodology for selecting the composition of modified polyethylene foam and to conduct research to assess the combustibility of the materials obtained.

2. Materials and Methods

Foam polyethylene has traditionally been used in building structures as a lining or vibration-proof material in rolls or sheets, the thickness of which did not exceed 5 mm. The implementation of methods for obtaining products with a thickness of up to 100 mm (and, in some cases, up to 200 mm) made it possible to use them in wide-profile insulation systems. Products were made monolithic with welded layers with or without a heat-reflecting coating (Figure 1a).



a b

Figure 1. Products made of polyethylene foam: (**a**)—layered products; (**b**)—multilayer products with an air gap of the AirLayer line.

The model is a laminated structure consisting of load-bearing elements, insulation layers, and outer and inner liners. The technology of welding products based on polyethylene foam enables the formation of seamless insulating shells, which can be placed on smooth walls, roofs, and any structures in contact with the ground. Thermal conductivity of polyethylene foam. The value is 0.030–0.034 W/(mK). Moreover, practically zero water absorption makes this index stable in different humidity environments. The absence of thermal conductive joints on the smooth surface of the wall makes it possible to obtain the thermal resistance of the insulated structure at a level of 2.86–3.20 ($m^2 \cdot {}^\circ C$)/W. The heat and mass transfer equations formed the basis of the numerical method for visualizing the processes. Experimental testing was carried out by measuring the temperature and humidity conditions of the structure at 9 sites, using up to 20 measurement points in each case.

The AirLayer line (RF patent for utility model No. 199048) [26] is a multilayer product containing flat layers of foamed polyethylene (polypropylene or rubber) connected with each other by seams with air gaps between the layers (Figure 1b). These products have lower thermal conductivity than monolithic laminates. Studies of the properties of materials and structures were carried out on the basis of the following standards in Russia. Determination on the basis of full-scale tests of the resistance to heat transfer (GOST 26254-84 and GOST R 56623-2015). Measurement of the density of heat flows passing through the enclosing structures (GOST 25380-2014). Thermal imaging (GOST R 54852-2011). Taking into account the fact that vapor-air mixture flows are minimized due to the properties of the insulation shell, the temperature gradient is the determining parameter of heat transfer, and the boundary conditions are determined by the temperature on the external surface of the insulated structure and the temperature inside the room.

The experiment to determine the optimal composition of modified polyethylene foam was carried out using mathematical planning methods based on full four-factor D-optimal plans, followed by testing statistical hypotheses.

Variable factors are the consumption of recycled polyethylene (X_1), the consumption of the modifier (X_2), the consumption of flame retardant (X_3), and the pressure in the extruder (X_4). Maleic anhydride was used as a modifier. The flame retardant is introduced into the mixture of recycled polyethylene during its heat treatment, followed by granulation. As response functions, the following are taken: the average density of polyethylene foam products (Y_1, kg/m^3) and the compressive strength of the plates at 10% deformation (Y_2, kPa). The compressive strength of the plates was taken as the optimization parameter. The conditions of the experiment are presented in Table 1.

Table 1. Experimental conditions.

Factor Name	SymbolX_i	Average Value of the Factor, X_i	Variation Interval, ΔX_i	Factor Values at Levels	
				−1	**+1**
Content of recycled polyethylene, %	X_1	20	10	10	30
Modifier content, %	X_2	6	1	5	7
Flame retardant consumption, kg/M^3	X_3	9	3	6	19
Extruder pressure, kPa	X_4	90	10	80	100

Regression equations obtained as a result of processing statistical data on the fact of realization of the active experiment are mathematical models of studied processes within the realization conditions of the cybernetic model "black box". Corresponding tests of hypotheses either reject or confirm the adequacy of these mathematical models for real processes. If the model is adequate, it can be used for solving direct and inverse technological problems, as well as for graphical interpretation.

On the other hand, each response function (regression equation) is a second-order mathematical polynomial: a complete or incomplete quadratic algebraic equation–function of several variables. This allows us to use the apparatus of mathematical analysis to study such functions of several variables or their systems. The adequacy of models is a prerequisite. These provisions have provided the basis for the method of analytical optimization developed at the Moscow Engineering and Construction University. This method has been tested in the study of formulations and technologies of various construction materials [27–29].

According to this method, the obtained regression equations are considered as a single system of algebraic functions of several variables. Extrema are determined (if it is possible) for functions containing significant quadratic factors. The results are substituted into each equation of the system, and the optimized functions are obtained. Note that, from the point of view of mathematical analysis, it is necessary to check on the boundaries of the area of factor changes. According to mathematical statistics, the statistical accuracy of predictions of results decreases on the outskirts of areas of change in factors.

Flammability tests of polyethylene foam with an optimized composition were carried out in accordance with the standards adopted in the Russian Federation, "Method of testing flammable building materials to determine their combustibility groups". The test facility consisted of a combustion chamber, an air supply system for the combustion chamber, a gas outlet pipe, and a ventilation system for removing combustion products. For each test, the following indicators are determined: flue gas temperature; the duration of self-burning and (or) smoldering; sample damage length; the mass of the sample before and after the test; the formation of a burning melt; and the appearance of samples after testing.

Taking into account the fact that vapor-air mixture flows are minimized due to the properties of the insulation shell, the temperature gradient is the determining parameter of heat transfer, and the boundary conditions are determined by the temperature on the external surface of the insulated structure and the temperature inside the room. Thermal conductivity of polyethylene foam. The value is 0.030–0.034 W/(mK). Moreover, practically zero water absorption makes this index stable in different humidity environments. The absence of thermal conductive joints on the smooth surface of the wall makes it possible to obtain the thermal resistance of the insulated structure at a level of 2.86–3.20 ($m^2 \cdot °C$)/W.

The visualization of temperature fields in the investigated structures and insulation systems was carried out with the help of the THERM computer program. The basis of the numerical method for visualizing the processes was the heat and mass transfer equations. This program allows the creation of models of two-dimensional heat exchange in building elements. With the help of the program, analysis of heat transfer makes it possible to evaluate the energy efficiency of the structure and local temperatures in different layers of the system under study. Experimental testing was carried out by measuring the temperature and humidity conditions of the structure at 9 sites, using up to 20 measurement points in each case.

3. Results and Discussions

Regression equations were obtained as a result of the statistical processing of the experimental results. Testing of statistical hypotheses (including the significance of equation coefficients) and model adequacy allowed for the generation of mathematical polynomials (functions that establish the relationship between the varying factors and the resulting response functions):

—for average density (with a confidence interval $\Delta b = 1$):

$$Y_1 = 23 + 3X_1 - 6X_2 + 2X_3 - 3X_4 + 2X_1X_4 \tag{1}$$

—for compressive strength (with a confidence interval $\Delta b = 8$):

$$Y_2 = 134 + 33X_1 + 24X_2 + 18X_3 + 28X_4 + 14X_1X_4 - 15X_2^2 - 10X_3^2 \tag{2}$$

By analyzing the magnitudes and signs of the coefficients of the regression equations, it is possible to establish the degree and direction of the influence of each factor on the result.

The absolute value of the coefficient value at the varying factor indicates the significance of the influence of this factor on the result, and the sign before the coefficient shows the direction of influence of the factor (in the direction of an increase or decrease of the result).

The analysis of mathematical models shows that the average density of foamed polyethylene (Y_1, kg/m^3) is mostly influenced by the consumption of modifying additives. When the flow rate increases within the range accepted under the experimental conditions, the density decreases. This is understandable from the viewpoint of the mechanism of action of maleic anhydride (a modifying additive), which has a plasticizing effect on melt in conditions of polymer melting in an extruder.

A change in the consumption of secondary polyethylene and flame retardants has less effect on the result. The increase in the consumption of secondary polyethylene and flame retardants contributes to a slight increase in melt density. This is attributed to a slight increase in the melt viscosity in the extruder (the consumption of secondary polyethylene) and some reduction of the foaming effect of the melt in the presence of a finely dispersed mineral component. An increase in air pressure in the compressor due to better polarization of the polyethylene matrix causes a slight density reduction.

The pairwise interaction ("X_1X_4") shows the significant effect on the result of the joint effect of the secondary polyethylene flow rate and the compressure on the change in the average density. The magnitude of this effect is insignificant and is presumably synergistic in nature.

The effect of modifier and flame retardant consumption on strength is extreme, which makes it possible to solve analytical optimization problems by studying the algebraic functions of four variables (1) and (2) by factors X_3 and X_2.

Optimization by the X_3 factor (fire retardant consumption) is carried out in the following sequence: the method of analytical differentiation determines the optimal flame retardant consumption in coded (reduced to the interval $[-1, 1]$) values and in natural values. Next, Equations (1) and (2) are solved with the optimal value of the X_3 factor set (in coded form) (3), (4), (5), and functions (6) and (7) optimized for X_3 are obtained.

$$\frac{\partial Y_2}{\partial Y_3} = 18 - 20X_3 = 0 \rightarrow X_3 = \frac{18}{20} = 0.9 \tag{3}$$

We determine the optimal consumption of flame retardant in its natural form (using the data in Table 1):

$$\mathrm{Ca} = 9 + 0.9 \times 3 = 11.7\ \mathrm{kg/m^3}$$

We calculate the X_3-optimized response functions: for average density (with a confidence interval Δb = 1):

$$Y_1 = 23 + 3X_1 - 6X_2 + 2 \times (0.9) - 3X_4 + 2X_1X_4 \tag{4}$$

for compressive strength (at a confidence interval Δb = 8):

$$Y_2 = 134 + 33X_1 + 24X_2 + 18 \times (0.9) + 28X_4 + 14X_1X_4 - 15{X_2}^2 - 10 \times (0.9)^2 \tag{5}$$

We get the X_3-optimized response functions: for average density (with a confidence interval Δb = 1):

$$Y_1 = 25 + 3X_1 - 6X_2 - 3X_4 + 2X_1X_4 \tag{6}$$

for compressive strength (with a confidence interval Δb = 8):

$$143 + 33X_1 + 24X_2 + 28X_4 + 14X_1X_4 - 15{X_2}^2 \tag{7}$$

Graphical interpretation of dependences (3) and (4) is shown in Figures 2 and 3.

A feature of the polynomial $Y_2(X_1, X_2, X_4)$ is that the dependence of the compressive strength of the plates at 10% deformation (Y_2, kPa) on the consumption of the modifier (X_2) is non-linear (the coefficient at "${X_2}^2$" is equal to "-16"). With an increase in the consumption of the modifier (ceteris paribus), the strength first increases and then begins to decrease. It is possible to determine the range of modifier consumption values (X_2) at which the strength is at its maximum using the method of analytical optimization.

Thus, the function $Y_2(X_1, X_2, X_4)$ has a local optimum in the factor X_2, which is determined by the differential analytical method (8):

$$\frac{\partial Y_2}{\partial X_2} = 24 - 30X_2 = 0 \rightarrow X_2 = \frac{24}{30} = 0.8 \tag{8}$$

Analytical optimization is carried out according to the function $Y_2(X_1, X_2, X_3)$.

We determine the actual value of the modifier flow rate, defined in coded values (X_2). To do this, we use the information contained in Table 1. The natural value of the content of the modifier by weight of the polymer (primary and secondary polyethylene) is: Cm = 6 + 1 × 0.78 = 6.8%.

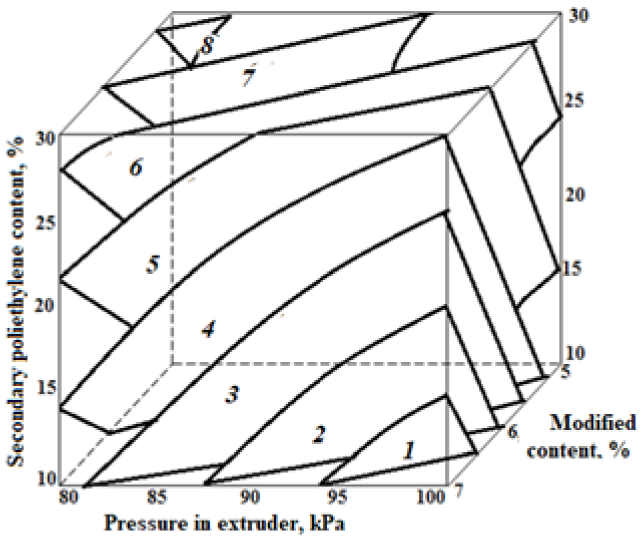


Figure 2. Dependence of the average density of polyethylene foam (Y1, kg/m^3) on the consumption of recycled polyethylene, modifier, and air pressure in the extruder at the optimum flame retardant consumption of 11.7 kg/m^3. Average density values, kg/m^3: 1–20; 2–22; 3–24; 4–26; 5–28; 6–30; 7–32; 8–34.

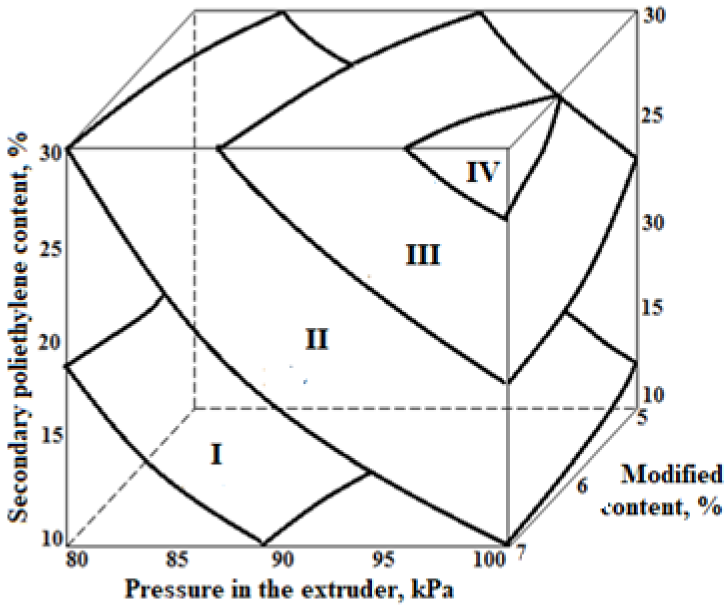


Figure 3. Dependence of the compressive strength of polyethylene foam boards at 10% deformation (Y2, kPa) on the consumption of recycled polyethylene and the modifier, as well as on the air pressure in the extruder at the optimum flame retardant consumption of 11.7 kg/m^3. The value of compressive strength, kPa: I-100; II-120; III-140; IV-160.

Solving polynomials (6) and (7) at $X_2 = 0.78$, we obtain the following optimization Equations (9) and (10):

$$Y_1 = 26 + 3X_1 - 6 \times (0.78) - 3X_3 + 2X_1X_3 \tag{9}$$

$$Y_2 = 150 + 30X_1 + 25 \times (0.78) + 30X_3 + 14X_1X_3 - 16 \times (0.78)^2 \tag{10}$$

or

$$Y_1 = 21 + 3X_1 - 3X_3 + 2X_1X_3 \tag{11}$$

$$Y_2 = 160 + 33X_1 + 28X_3 + 14X_1X_3 \tag{12}$$

Differentiation of the equation $Y_2(X_1, X_2, X_3)$ concerning the partial derivative made it possible to establish the optimization Equations (Functions) (11) and (12). The results of graphical interpretations of these functions are shown in Figures 4 and 5.

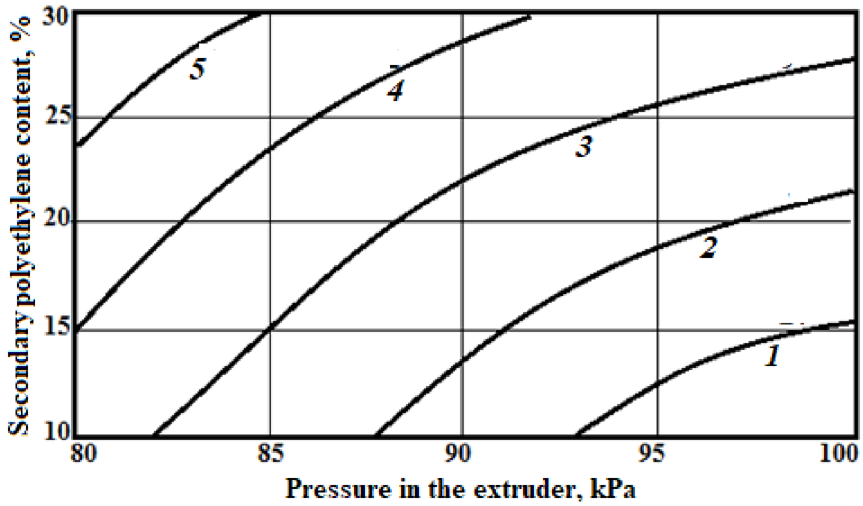


Figure 4. Dependence of the average density of polyethylene foam (Y1, kg/m^3) on the consumption of recycled polyethylene and the air pressure in the extruder at the optimum flame retardant consumption of 11.7 kg/m^3 and the modifier content of 6.8%. Average density values, kg/m^3: 1–20; 2–22; 3–24; 4–26; 5–28.

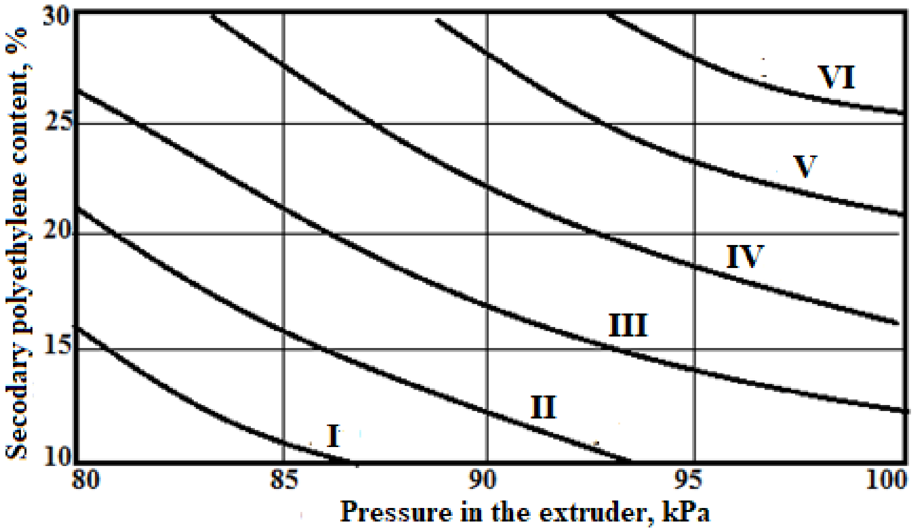


Figure 5. Dependence of the compressive strength of polyethylene foam boards at 10% deformation (Y_2, kPa) on the consumption of recycled polyethylene and the air pressure in the extruder at the optimum flame retardant consumption of 11.7 kg/m^3 and modifier content of 6.8%. Values of compressive strength, kPa: I-100; II-110; III-120; IV-130; V-140; VI-150.

The combination of the obtained specific graphic interpretations (Figures 4 and 5) and the use of optimized functions $Y_1(X_1, X_3)$ and $Y_2(X_1, X_3)$ enabled the construction of a nomogram (Figure 6). Using this nomogram, one can solve prognosticating tasks for the definition of material strength and density depending on various factors (depending on recycled PE consumption and extruder pressure), as well as the task of defining secondary PE consumption on the condition that it meets the set properties. If we need to determine the secondary polyethylene consumption, we set the extruder pressure and some characteristics of the foamed polyethylene (usually density) and solve the inverse problem. After obtaining the calculated data, it is mandatory to check the results using the behavior of control tests on natural samples.

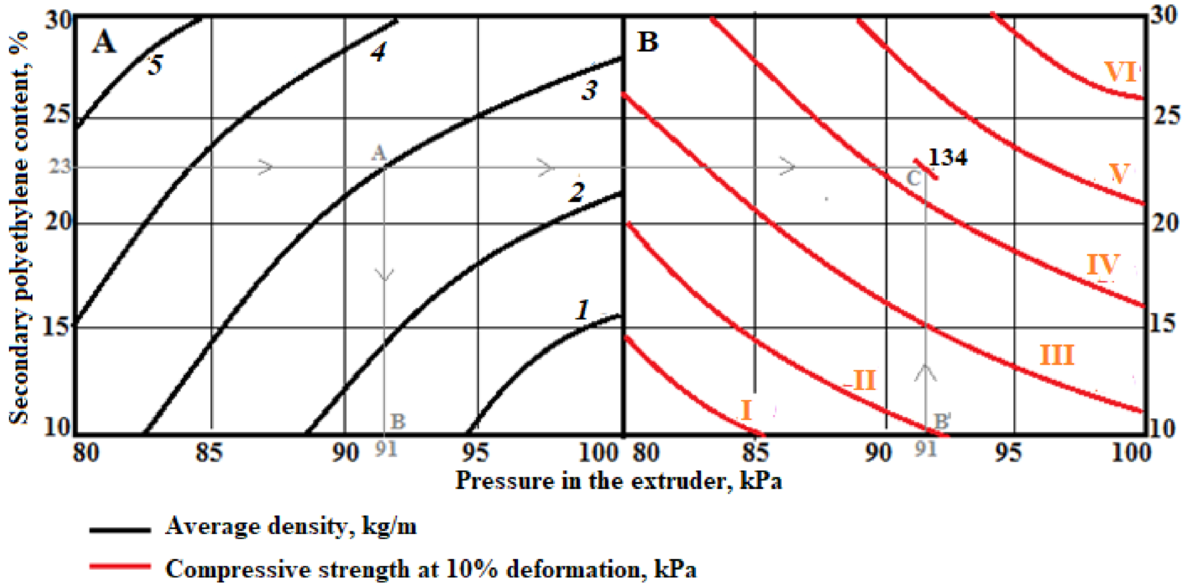


Figure 6. Nomogram for determining the consumption of recycled polyethylene. Average density values, kg/m^3: 1–20; 2–22; 3–24; 4–26; 5–28. Values of compressive strength, kPa: I-100; II-110; III-120; IV-130; V-140; VI-150.

The properties of the modified polyethylene foam were evaluated on samples measuring 100 × 100 × 100 mm and 500 × 500 × 50 mm, whose composition was selected taking into account the analytically determined optimal flame retardant consumption (11.7 kg/m^3) and the content of the plasticizer (6.8% by weight of the polymer). The content of recycled polyethylene was taken according to the nomogram (Figure 6) to be equal to 23% by weight of the polymer, and the gas pressure in the second extruder was maintained at a level of 90–91 kPa. CO_2 was used as the foaming gas.

It has been established that the strength of products in compression at 10% deformation is 140–160 kPa at an average density of 22–24 kg/m^3, is a function of the area of application of the load, and can be 260 kPa at loading areas exceeding 100 m^2. The tensile strength in the longitudinal direction is 80–92 kPa, and the strength of the weld is 29–32 kPa. Polyethylene foam has a thermal conductivity of 0.032–0.034 W/(mK), diffusion moisture absorption of 0.44 kg/m^2 without a metalized coating and 0.37 kg/m^2 with a coating; water absorption at partial immersion in water for 24 h is 0.013 kg/m^2; and water absorption by volume when completely immersed in water for 28 days is 0.96%. Long-term alternating temperature changes from −60 to +70 °C have little effect on the material's properties.

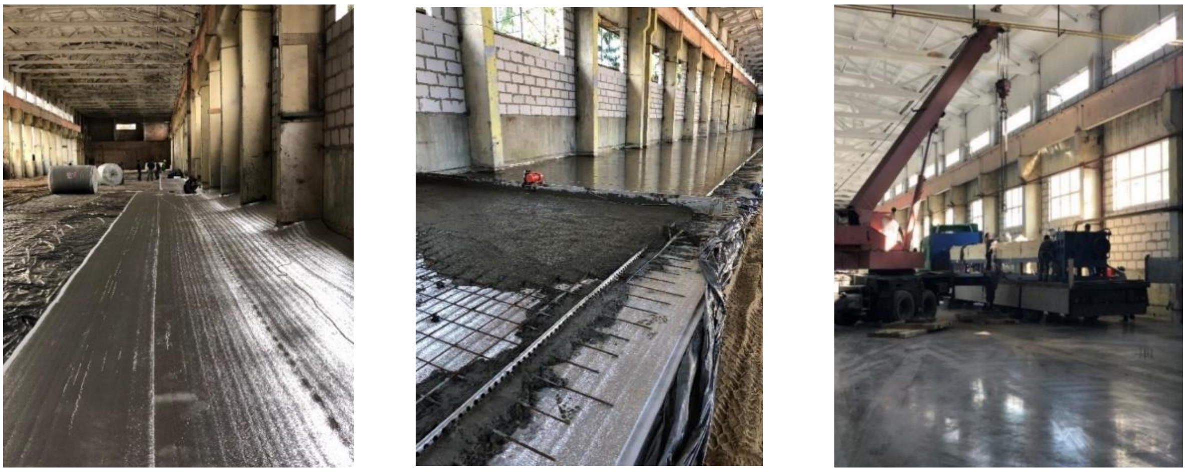
Following an estimation of the flammability of samples of foamed polyethylene with the optimized composition, the following results were obtained: the duration of soaking was 15–20 min; the damage length of the sample was 10–14%; weight loss was 10–15%; and the formation of burning melt was not observed.

As a result, we can conclude that the resulting material remains flammable (but not as flammable as traditional polyethylene foam) and can be attributed to self-extinguishing. This allows us to recommend products based on polystyrene foam for structures with no ventilated interior space.

The properties of modified polyethylene foam using recycled polyethylene do not fundamentally differ from those of polyethylene foam. It is manufactured based on "pure" raw materials. Considering the compressibility and strength characteristics of the material, one of the possible areas of application is its use in seamless insulating shells of a flat roof under a concrete screed or in insulation systems for pilafs pilasters in contact with the ground.

Taking into account the fact that under industrial production conditions, the calculated specific load can reach 250 kg/m^2, and under the conditions of the installation of lines and the use of heavy equipment inside the workshop, up to 400 kg/m^2, additional studies were carried out with the ratio of the loading area to the thickness of the material S/h = 10/0.1 = 100, which showed that the deformation of polyethylene foam during compression does not exceed 1%. This material can be recommended as an insulating layer for an industrial floating floor.

An example of the application of roll-fed polyethylene foam in the structures of a loaded "floating" floor in contact with the ground is its use in the insulation of an industrial facility, the production building of TepoFol Ltd (Moscow, Russia) (Figure 7).



a **b** **c**

Figure 7. Installation of a floating floor in an industrial building: (**a**)—laying of rolled polyethylene foam on the prepared base and formation of a seamless shell; (**b**)—installation of reinforcement frames and pouring of concrete; (**c**)—installation of heavy equipment on the industrial floor.

As already noted, polyethylene foam and seamless insulation shells have low thermal conductivity and permeability. These properties make them promising for the development of insulation systems for buildings and construction operating in the polar region. Subzero temperatures and high wind loads are typical for the polar region. Taking into account the necessity of preserving permafrost, pile structures are the prevailing foundation system. The insulation is located both on the foundation (over the space ventilated between the piles) and on the walls of the building.

When using plate insulation (Figure 8a), there are always thermal transmission bridges through gaps in the joints of the thermal insulation plates and their adjacencies to the bearing structures. The heat loss from the premises is the same as the temperature outside.

Taking into account the experience of using polyethylene foam insulation jackets in the middle climatic zone, we proposed an insulation system that minimizes the possibility of heat transfer both over the insulated surfaces and various "cold bridges." The basis of this system is roll-fed polyethylene foam with a metalized surface, laid on the outer surface of the insulated building and inside as a "floating" floor (Figure 8b).

Metal-coated roll-fed polyethylene foam sheets are fastened to the outer surfaces of the structure, and a locking connection is formed between the individual sheets. The sheets are then hot-air-welded in the contact area to form a seamless insulating jacket. Holes for windows and doors are cut into the continuous sheathing and reinforced around the perimeter with protective frames. Then the finished facade cladding is fastened to the purlins.

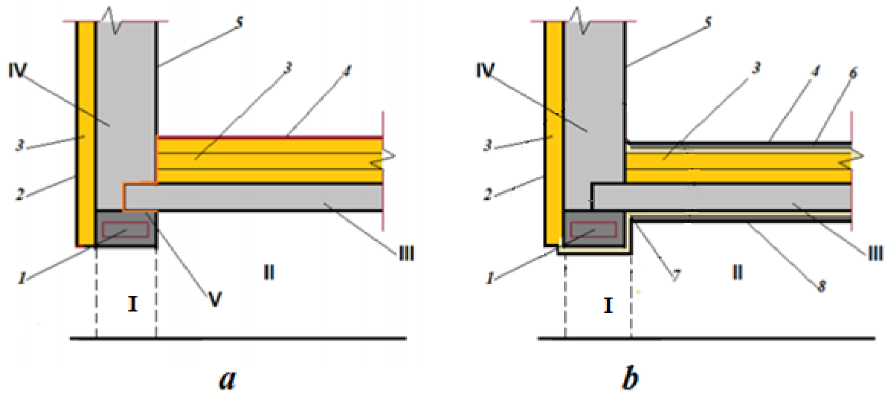


Figure 8. Floor plan of a residential building (Section 2—wall between columns and details of nodes): (**a**)—insulation with thermal insulation boards; (**b**)—seamless insulation with rolled polyethylene foam; I—column; II—ventilated space; III—overlap above ventilated space; IV—load-bearing wall; V is the area of increased heat transfer and cold air infiltration; 1—connection of columns; 2—facade insulation system; 3—thermal insulation of ceiling; 4—floor covering; 5—interior wall cladding; 6—floating floor system (dry assembly); 7—insulation above a ventilated space; 8—protective cladding.

Inside the premises, on reinforced concrete floor slabs, lay the plate heat insulation and, on top of it, also roll polyethylene foam, facing the metalized side inside the room. The rolls are laid so that the overlap with the vertical walls is not less than 100 mm. The rolls are welded into a single shell and then laid on a screed of dry assembly or tekstil-reinforced concrete. Then the finish coating is formed.

The effectiveness of the developed combined insulation system has been evaluated by means of simulating the conditions of two-dimensional heat transfer in the envelope structures (Figure 9). It was found that the proposed structural solutions based on the use of combined insulation systems allow the formation of an insulating envelope that meets the requirements of both heat savings and energy efficiency.

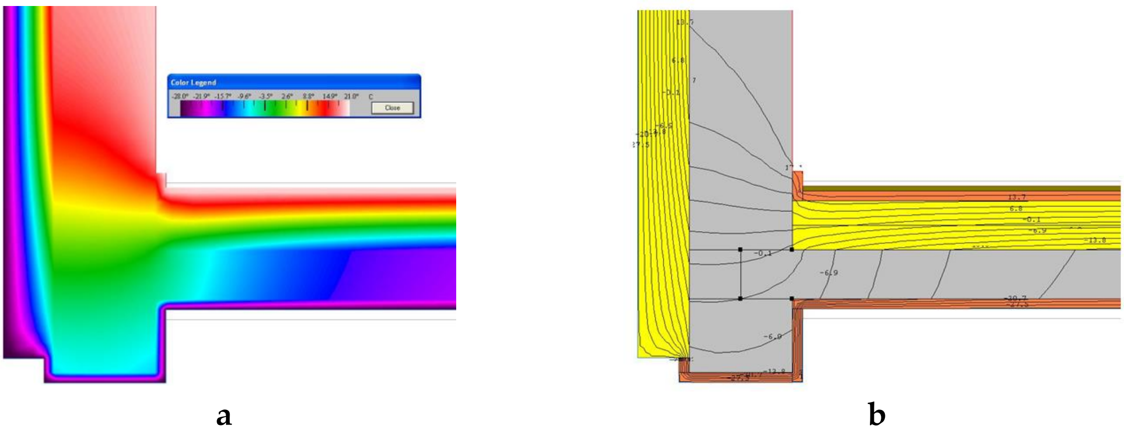


Figure 9. Structure of the temperature field formation in an isolated structure: (**a**)—visualization of the temperature field; (**b**)—graphical interpretation of the temperature distribution.

Seamless polyethylene foam shell systems are implemented in the construction of low-rise buildings for various purposes. Firstly, these are systems of cottage insulation on a wooden supporting frame (Figure 10). The PE foam rolls are rolled around the perimeter of the building and fixed to the wooden studs with self-tapping screws. The rolls are butt-jointed on the contact surfaces and hot-air-welded.

a **b** **c**

Figure 10. Thermal insulation of the cottage: (**a**) unrolling the roll of polyethylene foam; (**b**) fixing the insulation on the outer contour of the building and stitching the roll of polyethylene foam; (**c**) the insulating shell and window openings.

Secondly, these are framed and frameless technical structures: insulation systems for warehouses, parking lots, and livestock facilities (Figure 11). In this case, the insulation shell is formed along the internal contour of the structure. Structures of this type provide protection from atmospheric influences as well as operational safety of equipment, machinery, and so on. When insulating agricultural facilities, the priority is to maintain the internal microclimate. As already mentioned, effective solutions are also achieved in the systems of insulation of surfaces in contact with the ground.

a **b**

Figure 11. Insulation of technological objects: (**a**)—insulation of parking lot (frameless building); (**b**)—covered cattle yard (framed building).

4. Conclusions

The heat-insulating material based on polyethylene foam is environmentally friendly, easy to operate and use, and has high operational stability. The use of production waste and recycled polyethylene slightly changes the material's properties. The developed nomogram makes it possible to determine the optimal consumption of recycled polyethylene while taking into account technological factors. It can be used to develop a methodology for selecting the composition of modified polyethylene foam using recycled polyethylene.

Rolled polyethylene foam, including the use of waste and modifiers, is the only insulating material that allows the formation of seamless insulating shells. Taking into account the fact that the material is not only insulating but also has low vapor and water permeability and high water resistance, the shells being formed are universal in their properties.

Investigations showed that the operational characteristics of products based on foamed polyethylene as well as seamless insulation jackets allow the use of this material and structures based on it in contact with water-saturated or permafrost soils, including permanent mechanical loading, at subzero temperatures.

It is optimal to use two concepts for the application of polyethylene foam products. Firstly, it is the insulation of the surfaces that are in contact with the ground, including the ground of the permafrost, and working under the conditions of mechanical loads. Secondly, the development of low-combustibility polyethylene foam makes it possible to implement seamless shells for insulation of external surfaces of buildings and constructions as well as insulation in "floating" floor systems.

Author Contributions: A.Z.: Conceptualization of the direction and development of research methodology, preparation of the initial draft, and writing. I.S.: Checking the data received, reviewing and editing, and project support. S.B.: Process data and work with resources. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors are grateful to the Scientific Research Moscow State University of Civil Engineering for administrative and technical support of the published research. The evaluation of tensile strength in the longitudinal direction, compressive strength, water absorption, operational stability, and thermal conductivity was carried out according to standard methods. Studies of polyethylene foam and systems for its use were carried out at the Moscow University of Civil Engineering (NRU MGSU) and the Institute of Building Physics (NIISF RAASN). Part of the research presented in this paper was carried out using the equipment of the Central Collective Use Center named after Yu. M. Borisov VSTU, supported by the Ministry of Science and Higher Education of the Russian Federation, Agreement No. 075-15-2021-662. The authors thanked the general director of OOO. Tepofol Ltd. (Moscow, Russia), K.A. Ter Zakaryan, for help in organizing the experiments, the results of which are described in the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ibrahim, O.; Younes, R. Progress to global strategy for management of energy systems. *J. Build. Eng.* **2018**, *20*, 303–316. [CrossRef]
2. Shang, J. Construction of Green Community Index System under the Background of Community Construction. *J. Build. Constr. Plan. Res.* **2019**, *07*, 115–125. [CrossRef]
3. Gudkov, P.; Kagan, P.; Pilipenko, A.; Zhukova, E.Y.; Zinovieva, E.A.; Ushakov, N.A. Usage of thermal isolation systems for low-rise buildings as a component of information models. In *E3S Web Conference, Proceedings of the XXII International Scientific Conference "Construction the Formation of Living Environment" (FORM-2019), Tashkent, Uzbekistan, 18–21 April 2019*; EDP Sciences: Les Ulis, France, 2019; Volume 97, p. 01039. [CrossRef]
4. Dos Santos, G.H.; Mendes, N. Combined Heat, Air and Moisture (HAM) Transfer Model for Porous Building Materials. *J. Build. Phys.* **2009**, *32*, 203–220. [CrossRef]
5. Jelle, B.P.; Gustavsen, A.; Baetens, R. The path to the high performance thermal building insulation materials and solutions of tomorrow. *J. Build. Phys.* **2010**, *34*, 99–123. [CrossRef]
6. Umnyakova, N.; Chernysheva, O. Thermal features of three-layer brick walls. *Proc. Eng.* **2016**, *153*, 805–809. [CrossRef]
7. Gnip, I.J.; Kersulis, V.I.; Vaitkus, S.I. Predicting the Deformability of Expanded Polystyrene in Long-Term Compression. *Polym. Mech.* **2005**, *41*, 407–414. [CrossRef]
8. Zhukov, A.; Ter-Zakaryan, K.; Semenov, V. Insulation systems with the expanded polyethylene application. *IFAC-PapersOnLine* **2018**, *51*, 803–807. [CrossRef]
9. Umnyakova, N. Heat Exchange Peculiarities in Ventilated Facades Air Cavities Due to Different Wind Speed. In *Advances and Trends in Engineering Sciences and Technologies II*; CRC Press: London, UK, 2017.
10. Nardi, I.; Perilli, S.; de Rubeis, T.; Sfarra, S.; Ambrosini, D. Influence of insulation defects on the thermal performance of walls. An experimental and numerical investigation. *J. Build. Eng.* **2019**, *21*, 355–365. [CrossRef]
11. Shen, X.; Li, L.; Cui, W.; Feng, Y. Coupled heat and moisture transfer in building material with freezing and thawing process. *J. Build. Eng.* **2018**, *20*, 609–615. [CrossRef]
12. Chen, L.; Sun, X.; Ren, Y.; Liang, W.; Wang, K. Effects of thermo-oxidative aging on structure and low temperature impact performance of rotationally molded products. *Polym. Degrad. Stab.* **2019**, *161*, 150–156. [CrossRef]
13. Medvedev, A.; Bobrova, E.; Poserenin, A.; Zarmanyan, E. Evaluation of mineral fiber properties using x-ray fluorescence analysis and measurement of natural radioactivity. In *MATEC Web Conference, Proceeding of the International Science Conference (SPbWOSCE-2017) "Business Technologies for Sustainable Urban Development", Saint-Petersburg, Russia, 20–22 December 2018*; EDP Sciences: Les Ulis, France, 2018; Volume 170, p. 03018. [CrossRef]
14. Ter-Zakaryan, K.A.; Zhukov, A.D. Short Overview of Practical Application and Further Prospects of Materials Based on Crosslinked Polyethylene. In *Materials Horizons: From Nature to Nanomaterials*; Thomas, J., Thomas, S., Ahmad, Z., Eds.; Springer: Singapore, 2021. [CrossRef]

15. Ter-Zakarian, A. Locking Technology of Thermal Insulation Material for Seamless Welding of Joining Locks. Patent No 2645190; C1 Russian Federation, IPC E04B 1/78, E04B 1/76: No. 2016138156. 2016. Available online: https://patents.google.com/patent/RU2645190C1/en (accessed on 20 August 2022).
16. Ter-Zakaryan, K.A.; Zhukov, A.D.; Bobrova, E.Y.; Bessonov, I.V.; Mednikova, E.A. Foam Polymers in Multifunctional Insulating Coatings. *Polymers* **2021**, *13*, 3698. [CrossRef] [PubMed]
17. Lyapidevskaya, O.B.; Rubtsov, O.I.; Bessonov, I.V. Foam Polyethylene Made of Recycled Polyethylene. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1079*, 042073. [CrossRef]
18. Kozlov, S.; Efimov, B.; Bobrova, E.; Zinovieva, E.; Zhukova, E. Optimization of foamed plastic technology. In *E3S Web Conference, Proceeding of the XXII International Scientific Conference "Construction the Formation of Living Environment" (FORM-2019), Tashkent, Uzbekistan, 18–21 April 2019*; EDP Sciences: Les Ulis, France, 2019; Volume 97, p. 06010. [CrossRef]
19. Snegirev, A.Y.; Handawy, M.K.; Stepanov, V.V.; Talalov, V.A. Pyrolysis and combustion of polymer mixtures: Exploring additivity of the head release rate. *Polym. Degrad. Stab.* **2019**, *161*, 245–259. [CrossRef]
20. Stepina, I.V.; Kotlyarova, I.A. Modification of wood with monoethanolamino-borate by the data of x-ray photoelectron spectroscopy. In *MATEC Web Conference, Proceeding of the XXVII R-S-P Seminar, Theoretical Foundation of Civil Engineering (27RSP) (TFoCE 2018), Rostov-on-Don, Russia, 17–21 September 2018*; EDP Sciences: Les Ulis, France, 2018; Volume 196, p. 04005. [CrossRef]
21. Borovik, S.I.; Palatinskaya, I.P.; Soldatov, A.I. Criteria for evaluating the effectiveness of fire-resistant coatings for polystyrene thermal insulation materials. *Bull. South Ural. State Univ. Ser. Constr. Eng. Archit.* **2019**, *3*, 29–36. [CrossRef]
22. Stepina, I.V. Fire protection of timber building structural units by mono-and di-ethaholamine-(N→B)-phenylborates. In *MATEC Web Conference, Proceeding of the International Scientific Conference Environmental Science for Construction Industry—ESCI, Ho Chi Minh City, Vietnam, 2–5 March 2018*; EDP Sciences: Les Ulis, France, 2018; Volume 193, p. 03016. [CrossRef]
23. Stepina, I.V. Change in crystalline structure of cellulose caused by wood preservation. *Mater. Sci. Forum* **2018**, *923*, 51–55. [CrossRef]
24. Ter-Zakaryan, K.A. Heat-Insulating Multilayer Material. Useful Model Patent No. 199048 U1; Russian Federation, IPC E04B 1/76: № 2020115732, 2020.
25. Teuber, L.; Osburg, V.-S.; Toporowski, W.; Militz, H.; Krause, A. Wood polymer composites and their contribution to cascading utilisation. *J. Clean. Prod.* **2016**, *110*, 9–15. [CrossRef]
26. Bayer, J.; Granda, L.A.; Méndez, J.A.; P'elach, M.A.; Vilaseca, F.; Mutjé, P. Cellulose Polymer Composites (WPC). In *Advanced High Strength Natural Fibre Composites in Construction*; Woodhead Publishing: Sawston, UK, 2017; pp. 115–139. [CrossRef]
27. Efimov, B.; Rubtsov, O.; Bessonov, I.; Medvedev, A. Construction and insulation of agricultural buildings and structures. In *E3S Web Conference, Proceeding of the Topical Problems of Green Architecture, Civil and Environmental Engineering 2019 (TPACEE 2019), Moscow, Russia, 19–22 November 2019*; EDP Sciences: Les Ulis, France, 2020; Volume 164, p. 02030. [CrossRef]
28. Zhukov, A.; Bobrova, E.; Popov, I.; Arega, D.B. System Analysis of Technological Processes. *Int. J. Comput. Civ. Struct. Eng.* **2021**, *17*, 73–82. [CrossRef]
29. Zhukov, A.D.; Ter-Zakaryan, K.A.; Semenov, V.S.; Kozlov, S.D.; Zinovieva, E.A.; Fomina, E.D. Insulation systems for buildings and structures based on polyethylene foam. In *MATEC Web Conference, Proceeding of the VI International Scientific Conference "Integration, Partnership and Innovation in Construction Science and Education" (IPICSE-2018), Moscow, Russia, 14–16 November 2018*; EDP Sciences: Les Ulis, France, 2018; Volume 251, p. 01014. [CrossRef]