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Protective coatings of building structures and pipelines for operation in the Arctic

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Abstract. The article is devoted to the study of the efficiency of using insulating (protective) coatings of building structures and pipeline transport for their reliable and trouble-free operation in extreme conditions of the Arctic zone. Innovative construction and composite materials – rubber concrete and rubber mastic, which have a combination of high physical, mechanical, and operational characteristics, are proposed to be used as protective coatings. A mandatory condition for the structure formation of rubber concrete and rubber mastic with the formation of a durable and corrosion-resistant protective layer is the dosed introduction of thermal energy into the composite material during an experimentally established period of time, which ensures the production of a protective coating with high specified properties. To establish rational technological modes of structure formation of the rubber-containing protective layer, experimental studies were carried out to optimize the temperature and time modes of introducing thermal energy into the composite material of the protective coating. Optimization of the technological modes of forming a protective coating from rubber concrete for reinforced concrete building structures was carried out on a developed and manufactured experimental heat-generating stand with a working element in the form of an uninsulated metal wire. Optimization of technological modes of formation of protective coating from rubber mastic for pipe metal was carried out on an experimental stand using induction heating. It was proposed to use a number of industrial wastes (fly ash, rubber crumb, etc.) as a filler in rubber concrete and in rubber mastic. A comparative analysis of the characteristics of the protective coating of pipe metal based on rubber mastic with the characteristics of the currently widely used multilayer polyethylene coating was carried out. The competitive advantages of rubber-containing protective coating of pipe metal are determined.

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1. Introduction

The harsh climate and engineering and geological conditions of the Arctic zone place increased demands on the protective characteristics of construction projects operated in this region.

Road surfaces, airfield runways, reinforced concrete emergency dumping areas for fuels and lubricants, sludge beds of treatment facilities, metal tanks and reservoirs, as well as on-site and main gas pipelines are subject to destructive impact.

At the same time, special attention should be paid to protecting steel pipeline transport, widely used for the preparation and transportation of hydrocarbon raw materials, from the negative impact of the environment. First of all, this is due to ensuring industrial safety for people and the unique ecosystem of the Arctic region. The damage from an accident on a main gas pipeline is estimated at hundreds of millions of rubles, associated with both the destruction of pipelines and the costs of their restoration, and with destructive negative man-made impacts on the biosphere of the Arctic zone. Thus, in the conditions of the Arctic region, it is necessary to use protective coatings with the following characteristics: resistance to low temperatures, high physical and mechanical characteristics, a coefficient of thermal linear expansion as close as possible to the coefficient of thermal linear expansion of the protected structure, high adhesion of the coating to the protected surface, high resistance to thermal cycling, low water and air permeability.

A necessary and mandatory factor in the creation of effective protective coatings is the use of Russian-made components, including raw materials, equipment, and technologies required both for the mass production of initial composite materials [1–4] and for technologies for the direct industrial installation of protective coatings for building structures and pipelines in field and factory conditions [5–7].

It should be noted that in the modern scientific community, the greatest relevance is the development of effective polymer composite building materials with high strength and performance characteristics [8–11], as well as improving the applied building materials by optimizing their compositions and introducing nano-components [12–14]. Particular attention is paid to the development of protective coatings for building structures and pipeline transport using polymer composite materials that are resistant to the effects of chemically aggressive environments [15–18], as well as climatic and engineering-geological impacts of the operating environment [19].

In addition, at present, the approach to solving the issue of recycling waste from industrial production and the construction industry, by using it as a filler for concrete, including polymer concrete, is of significant scientific importance, which ensures the sanitation of the surrounding urban and natural environment [20–23].

Thus, the relevance of the study lies in the need to develop effective insulating coatings to protect building structures and pipeline transport from the negative climatic and engineering-geological impacts of the Arctic region with the possibility of using domestic raw materials and recycling a variety of man-made waste. The object of the research work is effective protective coatings of building structures and steel pipeline transport, intended for use in the harsh climatic and engineering-geological conditions of the Arctic region.

Fundamental research work on the creation of rubber concretes and rubber mastics (the "rubber concrete" category) was carried out at the Voronezh State Technical University (VSTU) [18, 24–26]. Rubber concrete is a composite building material obtained by vulcanizing a rubber-concrete mixture.

The filler of the rubber-concrete mixture can make up more than 85 % of its total mass. The filler of the rubber-concrete mixture can make up more than 85 % of its total mass. In this case, it is advisable to use production waste generated during the operation of industrial enterprises [22, 27–29], rubber crumb obtained during the processing of car tires [30], waste from the disposal of electronic products (printed circuit boards, microcircuits, etc.) [31], recycled plastic, etc. as filler. Such a circumstance allows us to solve the global problem of recycling various industrial waste.

The combination of high physical, mechanical, and operational characteristics of rubber concrete creates the necessary prerequisites for its effective use as a protective coating material for construction projects operating in the extremely low temperatures of the Arctic region.

Studies have been conducted to determine the chemical resistance of rubber concrete in relation to various aggressive environments that are widespread in industrial production. Based on the results of the studies, a conclusion has been made that allows us to classify rubber concrete as a chemically resistant material in relation to the aggressive environments studied. Table 1 contains data on the chemical resistance coefficients of rubber concrete.

Table 1. Chemical resistance coefficients of rubber concrete [17].

№	**Names of the studied aggressive environments**	**Values of the chemical resistance coefficient of rubber concrete**
1.	Solutions of organic acids	0.81 – 0.95
2.	Solutions of inorganic acids	0.81 – 0.97
3.	Solutions of alkalis and bases	0.81 – 0.87
4.	Solutions of salts, solvents, petroleum products	0.83 – 0.95
5.	Water	0.995

Rubber concrete has a wide operating temperature range from +80 °C to –80 °C, without deterioration of physical, mechanical, and operational characteristics. At the same time, experimentally established data indicate an increase of up to 25 % in the physical and mechanical characteristics of rubber concrete in the range of negative temperatures from 0 °C to – 80 °C.

Rubber concrete is a frost-resistant, water- and air-impermeable material capable of withstanding up to 500 freeze-thaw cycles without a significant reduction in strength characteristics.

The specified values of the given characteristics of rubber concrete show the feasibility of its use in low-temperature conditions inherent in the Arctic zone. Rubber concrete has been shown to be resistant to thermal-oxidative degradation and ultraviolet radiation, which makes it possible to use the corresponding protective coatings based on it without additional shelter from the influence of sunlight.

The value of the coefficient of linear thermal expansion of rubber concrete is at the level of the coefficient of linear thermal expansion of steel, which allows rubber concrete to be used for external insulation of steel pipes without the risk of its destruction during thermal expansion of steel.

Rubber concrete is a classic dielectric, since its main binding component is synthetic rubber. This circumstance significantly reduces the likelihood of stray currents appearing at the boundary of the rubber concrete-coated pipe metal and the soil, eliminating the possibility of electrochemical corrosion. Table 2 shows the main physical and mechanical characteristics of rubber concrete.

Table 2. Values of physical and mechanical characteristics of rubber concrete [26].

№	**Names of physical and mechanical characteristics of rubber concrete**	**Values of physical and mechanical characteristics of rubber concrete**
1.	Compressive strength, MPa	50…100
2.	Tensile strength, MPa	10…20
3.	Modulus of elasticity, ´10^4 MPa	1.5…3.0
4.	Compressive duration coefficient	0.72…0.76
5.	Poisson’s ratio	0.2…0.3
6.	Heat resistance	100…110
7.	Frost resistance, freeze-thaw cycles	notless than 500
8.	Abrasion, g/cm^2	0.07…0.79
9.	Water absorption by weight, wt. %	0.05

Among the operational characteristics, it is worth noting the high resistance of rubber concrete to abrasion. The minimum value of rubber concrete abrasion – 0.07 g/cm^2 is possible when using corundum as a filler of the composite material.

The structure formation of an effective composite material – rubber concrete, occurs as a result of vulcanization of the rubber component of the material. During heat treatment of the rubber component, the vulcanizing agent – a sulfur-containing substance – forms cross-links between the rubber macromolecules, with the formation of a three-dimensional mesh structure.

Normal structure formation of rubber concrete is possible when creating a given uniform temperature field over the volume of the vulcanizate. The structure formation of rubber concrete occurs as a result of the metered introduction of thermal energy into the rubber mastic over an experimentally established period of time, which significantly complicates the technological process of obtaining reliable protective coatings in the conditions of work directly in the open areas of the Arctic region. Therefore, there is a need to develop a technology for the installation of protective coatings based on rubber concrete using energy-efficient heat-generating devices.

The aim of the study is to develop a technology for the installation of high-strength corrosion-resistant protective coatings for building structures and pipe metal used in the climatic and engineering-geological conditions of the Arctic region using a composite material based on domestic synthetic rubber (low-molecular oligodiene) and using effective methods for introducing thermal energy to ensure the necessary temperature conditions for the structure formation of the coating material.

To achieve the stated goal of the study, the following tasks were solved:

1. New design and technological solutions for devices based on domestic materials, structures, and equipment were developed, implementing various methods for introducing thermal energy into an insulating composite material (low-molecular oligodiene), which ensures high physical, mechanical, and operational properties of the protective coatings of building structures and pipe metal formed in this way.
2. A rational composition of the composite material of the protective coating with a filler made of man-made waste (fly ash, rubber crumb, etc.) was established.
3. A technology for forming protective coatings for building structures and pipe metal has been developed, including the selection of a rational composition of a composite material based on low-molecular oligodiene and the optimization of the modes of introducing thermal energy into the vulcanized coating material.
4. The physical, mechanical, and operational characteristics of protective coatings for building structures and pipe metal using a composite material based on low-molecular oligodiene have been determined.

2. Methods

2.1. Development of Technology for the Installation of Coatings Based on Rubber Concrete for Protection of Building Structures

In order to form protective coatings based on rubber concrete on the surface of reinforced concrete structures, an experimental electric heat-generating device using a heating wire was developed and constructed, and a corresponding technology for the formation of protective coatings of building structures and buildings was developed using this experimental device [5].

The formation of rubber concrete coatings by vulcanizing the rubber component when introducing thermal energy from a heating wire into rubber concrete by passing an electric current through is a complex technological process that begins with the preparation of the surface of the reinforced concrete structure to be protected.

The surface of the reinforced concrete structure is cleaned of any debris, de-dusted, and degreased. The next step is to install the heating wire fastening pins to a height corresponding to the coating thickness on the surface of the protected structure.

Next, steel washers with a thickness of 2.0–2.5 mm are put on the pins of the heating wire fastening, and the heating wire is directly mounted. This heating wire is essentially the working element of the experimental electric heat-generating device, the basic electrical circuit of which is shown in Fig. 1.

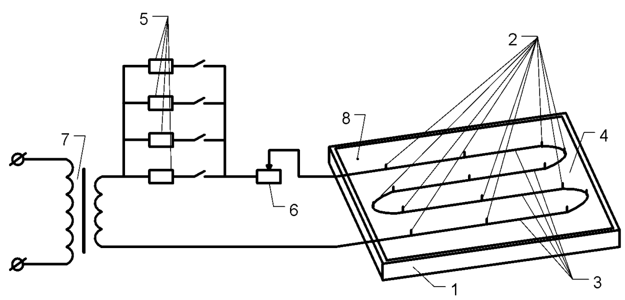

Figure 1. Basic circuit diagram of the experimental electric heat-generating device using a heating wire: 1 – formwork; 2 – heating wire fastening pins; 3 – non-removable heating wire; 4 – surface of the protected reinforced concrete structure; 5 – load resistors; 6 – rheostat; 7 – step-down transformer, 8 – thermocouple.

Steel washers are used to establish the required gap between the heating wire and the surface of the reinforced concrete structure in order to obtain the lowest value of the temperature field dispersion during vulcanization of the coating material by the heating wire. Then, the formwork is mounted and rubber concrete is laid on the surface of the reinforced concrete structure limited by the formwork.

The insulated surface of the reinforced concrete structure is filled with rubber mastic to the height of the mounted pins for fastening the heating wire and covered with polyethylene film in order to reduce heat loss during vulcanization of rubber concrete. The temperature regime is controlled using a thermocouple placed in the vulcanizate and connected to a thermoelectric device.

Vulcanization of the protective coating material based on rubber mastic is carried out in two stages. At the first stage, lasting 55–65 minutes, heat treatment is performed with maintaining the temperature of the coating material in the range from +85 °C to +95 °C. This stage is required to form the initial structural bonds in the protective coating material. The second stage – the main stage of vulcanization of the protective coating material is carried out by maintaining the temperature in the range from +115 °C to +125 °C for 180–200 minutes.

The temperature mode is adjusted using load resistors and a rheostat included in the electrical network. After completion of the main stage of vulcanization of the protective coating material, the power supply to the heating wire is disconnected and the resulting protective coating cools smoothly to the outside air temperature. When observing the above-mentioned experimentally obtained temperature-time technological regimes, the protective coating based on rubber concrete acquires the physical, mechanical, and operational characteristics necessary for the material of the protective coating of building structures.

Fig. 2 shows a full-scale installation of a non-insulated heating wire on a reinforced concrete base, as well as vulcanization of the protective coating material of a reinforced concrete platform by a heating wire connected to the electrical network using the developed experimental device.

a b

Figure 2. Experimental device for structuring a protective coating based on rubber concrete on the surface of reinforced concrete structures: a – installation of a non-insulated heating wire on a reinforced concrete base; b – vulcanization of the protective coating material by a heating wire connected to the electrical network.

2.2. Development of a Technology for Installing a Protective Coating Based on Rubber Concrete for External Insulation of Pipe Metal

In order to develop the design of a heat-generating device for the effective introduction of thermal energy into the material of the protective composite rubber-containing coating of the pipe metal, a series of exploratory experiments were conducted.

Based on the results of the experiments, it was possible to create a temperature field in the volume of the vulcanizate in the required range from +134 °C to +135 °C with an exit to the temperature mode at a rate of no more than 10 °C/min as a result of induction heating of the steel pipeline [6–7]. The full cycle of structure formation of the rubber mastic on the surface of the steel pipe using induction heating of the pipe metal is about 60–65 minutes.

In order to implement an effective method of introducing thermal energy into rubber mastic, a structural diagram of a pilot experimental device using an induction method of heating pipe metal has been developed. This structural diagram is shown in Fig. 3.

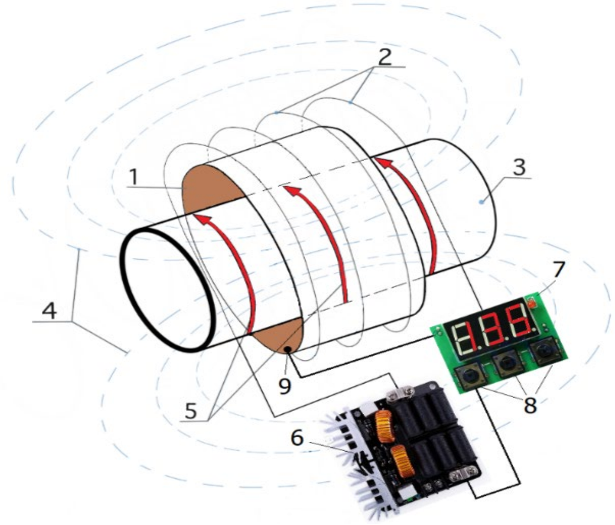

Figure 3. Structural diagram of the electric heat-generating device for vulcanization of rubber mastic on the surface of pipe metal using the induction method: 1 – vulcanizable protective coating of pipe metal; 2 – induction coil; 3 – insulated steel pipe; 4 – magnetic field; 5 – eddy currents in pipe metal; 6 – high-frequency current generator; 7 – thermostat; 8 – temperature setting keys; 9 – thermocouple.

Thus, when using induction heating for heat treatment of a protective layer of rubber mastic on the surface of pipe metal, the heating element itself is the insulated steel pipe as a result of contact with which the heating and vulcanization of the protective coating material occurs. This allows minimizing heat loss and noting the high efficiency of the electric heat-generating device due to the direct contact of the heated material – the protective coating and the heating element – the working body, i.e. the insulated steel pipe heated by the eddy electric currents induced in it.

Maintaining the temperature regime in the required temperature field range of 134–135 °C is carried out using a thermostat built into the electrical circuit of the induction heater. Signals with information about the actual parameters of the vulcanizate temperature field are sent to the thermostat through the connection of the electric wire with a thermocouple placed in the vulcanized material. That is, when the vulcanizate temperature reaches + 135 °C, the induction heating of the pipe metal is temporarily stopped, until the vulcanizate temperature drops to + 134 °C; in this case, the induction heating is automatically turned on again, and thus, a cyclic process of maintaining the temperature regime occurs. The process of structure formation of a protective coating of pipe metal using rubber concrete consists of sequentially performed technological operations:

1. Cleaning the pipe metal from rust and dirt;
2. Application of a protective layer of rubber concrete 2–3 mm thick to the pipe metal;
3. Heat treatment of the protective coating material – rubber concrete – by induction heating, with mandatory provision and control of the temperature regime of vulcanization of rubber mastic.

To ensure the formation of a protective coating based on rubber concrete on the surface of the pipe metal, an experimental setup using induction heating was designed, the appearance of which is shown in Fig. 4.

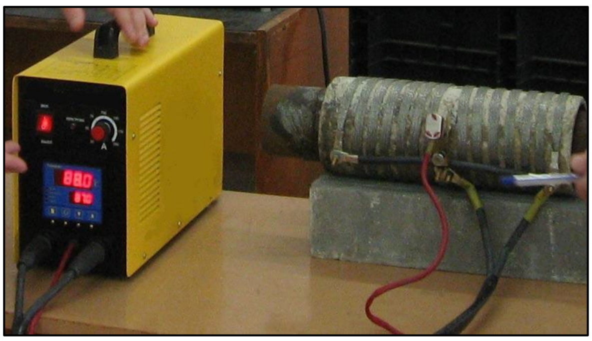

Figure 4. External appearance of the experimental setup for ensuring the formation of a protective coating based on rubber concrete on the surface of the pipe metal using induction heating.

3. Results and Discussion

The combination of high physical, mechanical, and operational characteristics of rubber concrete make it possible to effectively use it as a material for protective coating of construction objects operating in conditions of extremely low temperatures of the Arctic region.

As a result of a series of exploratory experiments, temperature and time modes of rubber concrete vulcanization were determined when installing protective coatings on reinforced concrete building structures using a heating wire as a working element of a heat-generating device. With a protective coating layer thickness of 8–12 mm, heat treatment of rubber concrete should be carried out in two stages to avoid vulcanizate swelling due to increased gas evolution.

The first stage lasting 55–65 minutes is carried out with maintaining the temperature in the range from +85 °C to +95 °C to form initial structural bonds in the vulcanized rubber mastic.

The second main stage of caoutchouc vulcanization lasting 180–200 minutes is carried out maintaining the temperature from +115 °C to +125 °C for the final formation of a protective coating based on vulcanized rubber mastic. Exceeding the temperature of +125 °C leads to increased gas formation, and as a consequence, swelling and destruction of the protective coating material. Also, in order to avoid swelling of the material, the rate of temperature increase during transient processes should not exceed 1 °C/min.

Fig. 5 shows a graph of experimentally established temperature-time modes of rubber concrete vulcanization when using it to create effective protective coatings for building structures.

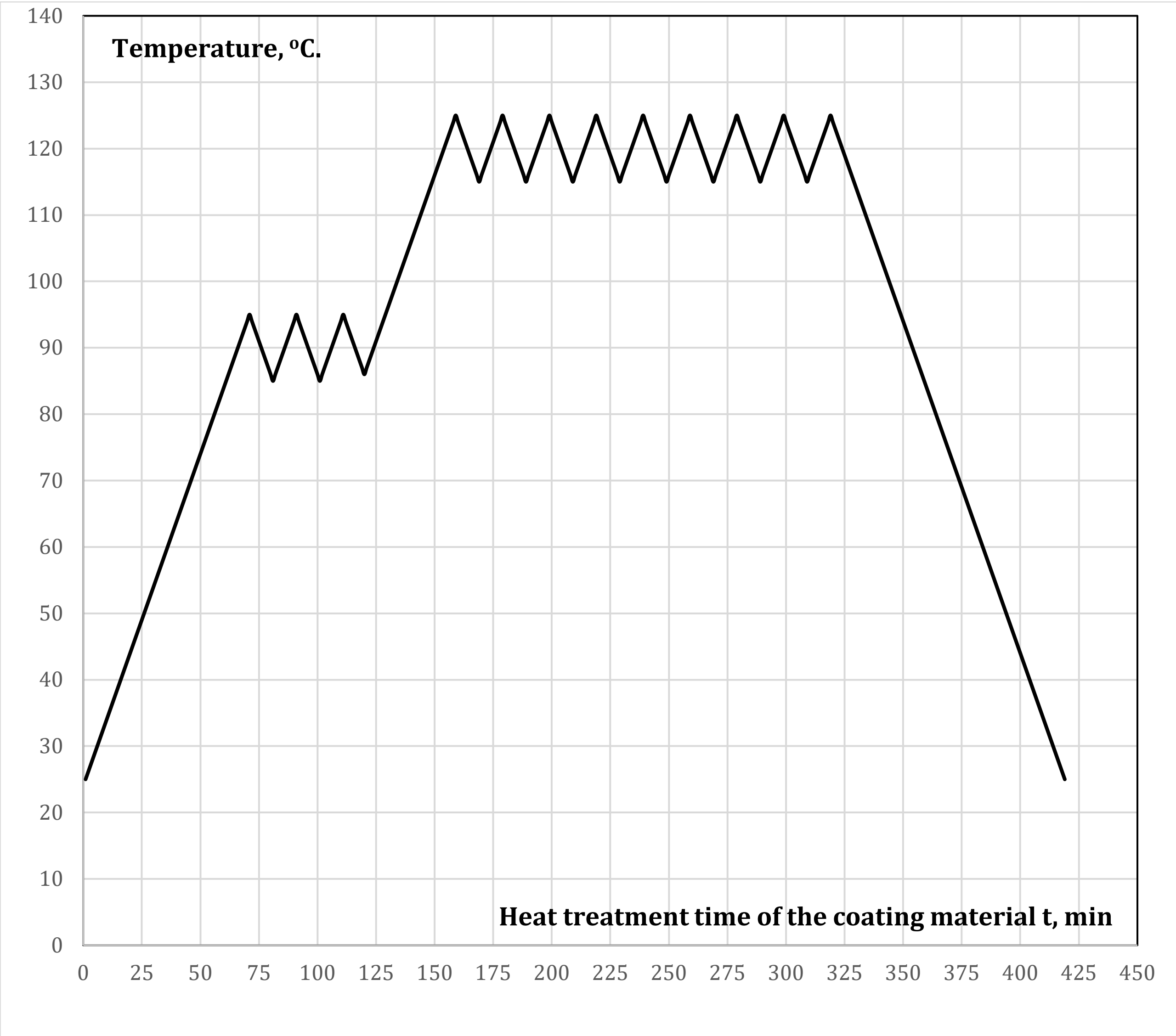

Figure 5. Graph of experimentally established temperature-time modes of rubber concrete vulcanization when using it to create protective coatings for building structures and constructions.

As a result of a series of exploratory experiments, the temperature and time modes of rubber concrete vulcanization were determined when a protective coating of pipe metal was installed on its basis using induction heating. With a protective coating layer thickness of pipe metal up to 1 mm, the heat treatment of rubber concrete can be carried out in one stage lasting 20–25 minutes with the temperature maintained at up to 135 °C. Exceeding the temperature of 135 °C leads to combustion and destruction of the material. At the same time, in order to avoid swelling and destruction of the material, the rate of temperature increase during transient processes should not exceed 10 °C/min.

Fig. 6 shows a graph of the experimentally established temperature and time modes of rubber concrete vulcanization when a protective coating of pipe metal is installed on its basis.

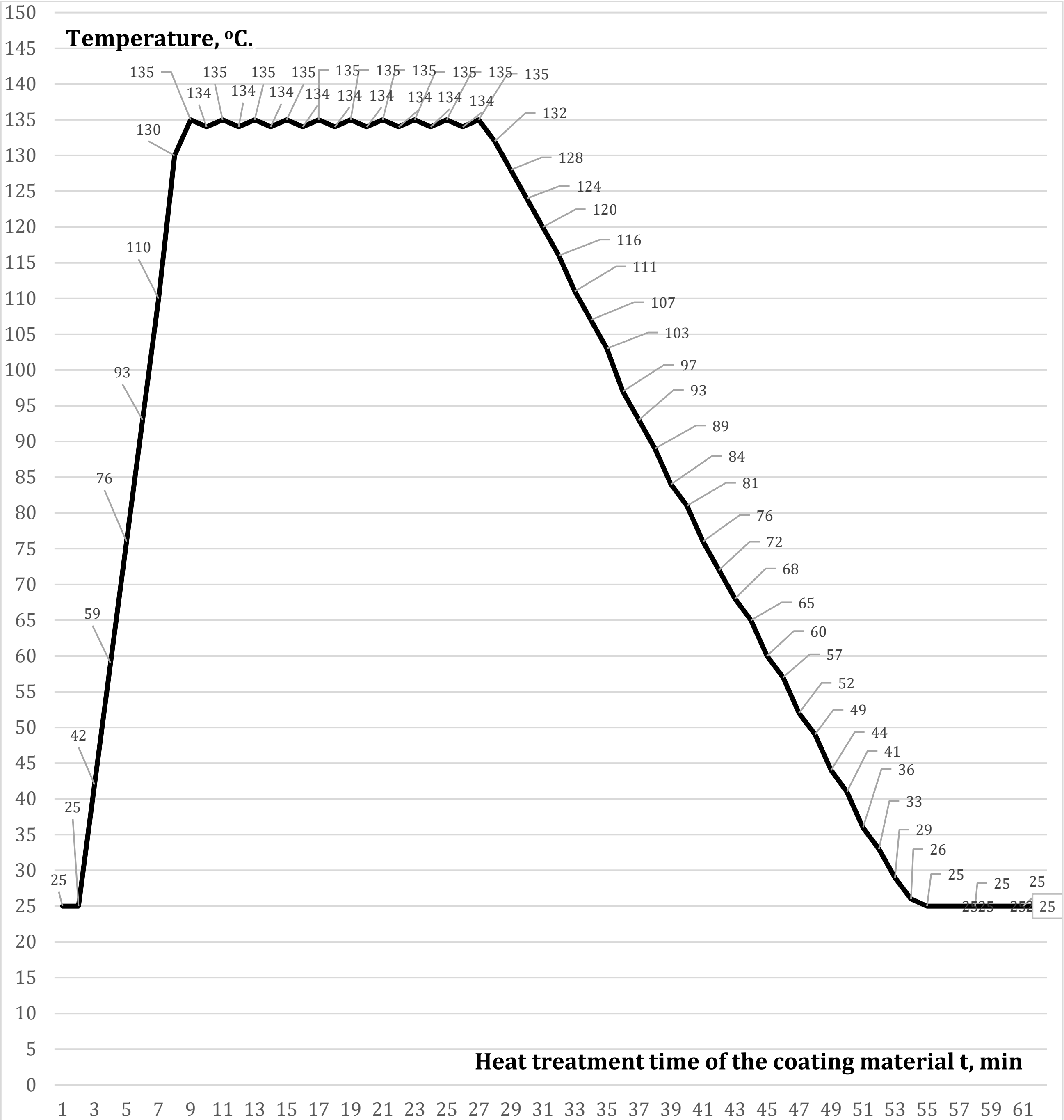

Figure 6. Graph of the experimentally established temperature and time modes of rubber concrete vulcanization when a protective coating of pipe metal is installed on its basis.

Experimental studies were conducted on the obtained samples to determine the characteristics of the protective coating of pipe metal based on rubber concrete. Table 3 presents a comparative analysis of the characteristics of the protective coating of pipe metal based on rubber concrete and the characteristics of the currently widely used multilayer polyethylene coating.

Table 3. Comparison of the characteristics of the protective coating based on rubber concrete with the characteristics of the multilayer polyethylene coating.

№	Characteristic of the protective coating of the pipe metal	Multilayer polyethylene coating	Rubbe rconcrete based coating
1.	Adhesion of the protective coating under shear, N/cm^2	70	100
2.	Water resistance, % reduction in adhesion strength to the steel surface	5-12	5
3.	Operating temperature range, ^{o}C	– 20…+60	– 80…+80
4.	Cost, USD/m^2 (according to the manufacturer's website https: www.tk-rapid.ru. as of 02/26/2025)	32.0	11.5

A comparative analysis of the data presented in Tables 2, 3 allows us to conclude that the coating of the pipe metal based on rubber concrete has advantages in higher physical and mechanical characteristics compared to the characteristics of the widely used multilayer polyethylene coating. In addition, the protective coating of metal pipes based on rubber concrete is more than 2.5 times cheaper than a multilayer polyethylene coating.

It has been experimentally established that rubber concrete used as a protective coating material has higher strength characteristics compared to polymer concretes based on polyester and epoxy resins [32]. It has also been experimentally determined that the physical, mechanical, and operational characteristics of rubber concrete are at the level of, or exceed similar characteristics of polymer concretes based on furan, furan-epoxy, urea, and acrylic resins [8–10]. Table 4 presents a comparison of the strength characteristics of rubber concrete with the strength characteristics of currently used polymer concretes obtained on the basis of various types of polymer resins.

Table 4. Comparison of the strength characteristics of rubber concrete with the strength characteristics of the used polymer concretes obtained on the basis of various types of polymer resins.

№	Type of polymer concrete by binder type	Compressive strength, MPa	Tensile strength, MPa	Bending strength, MPa
1.	Rubber concrete	60…110	8…20	19…30
2.	Polymer concrete based on polyester resin	41…68	10…12	12…19
3.	Polymer concrete based on epoxy resin	71…98	14…19	21…22
4.	Polymer concrete based on acrylic resin	70…90	10…13	30…33
5.	Polymer concrete based on furan resin	70…90	5…8	–
6.	Polymer concrete based on furan-epoxy resin	90…110	9…11	–
7.	Polymer concrete based on urea resin	40…70	3…7	–

At the same time, coatings based on rubber concrete can be filled with production waste by more than 85 % by weight, which is the highest indicator among the available results of scientific research in the field of developing "green concrete" [28–31].

Also, during experimental studies to determine the adhesion of a protective coating based on rubber concrete, it was noted that the destruction of samples occurs mainly along the coating material, without its peeling off from the metal surface. This circumstance indicates the high adhesive strength of coatings based on rubber concrete. The appearance of the destroyed sample when determining the adhesion of a protective coating based on rubber concrete is shown in Fig. 7.

Figure 7. The appearance of the destroyed sample when determining the adhesion of a protective coating based on rubber concrete.

4. Conclusions

1. A technology for the installation of protective coatings for reinforced concrete structures using a material based on rubber concrete has been developed for the effective protection of building structures in the climatic conditions of the Arctic region.
2. An experimental stand was constructed to study technological regimes for the formation of an effective protective layer of pipe metal using induction heating and the ability to automatically adjust and maintain the required temperature regime for the formation of the rubber-containing composite material of the protective layer.
3. A comparative analysis of the experimentally obtained characteristics of the protective coating of pipe metal based on rubber mastic with the characteristics of the currently widely used multilayer polyethylene coating has been carried out. The advantage of quantitative indicators of the characteristics of the protective coating of pipe metal based on Cautone compared to the characteristics of the multilayer polyethylene coating is given in Table 3.
4. The use of high-strength corrosion-resistant coatings based on rubber concrete is advisable for the protection of building structures and pipeline transport operating in the harsh climatic and engineering-geological conditions of the Arctic regions.
5. The use of protective coatings based on rubber concrete allows solving the problem of recycling various industrial wastes, as a result of their use as a filler for rubber-concrete mixtures, making up more than 85 % of its total mass.

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