Vol. 01, Iss. 3 (2024) 119-131, DOI: 10.61552/JSI.2024.03.004

JSDI

Journal of Sustainable Development Innovations

www.jsi.aspur.rs

Study of Using Electrical Heavy Concrete in the Improvement of Urban Areas

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Keywords:

Electrical conductivity, heated pavement systems, pavement deicing, carbon additive, concrete construction

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Received: 1 May 2024
Revised: 11 June 2024
Accepted: 18 July 2024

A B S T R A C T

In regions with negative average daily temperatures, the development of the construction sector, including transport infrastructure facilities, requires increasing the efficiency of heating systems and deicing systems, while reducing the material consumption of their production. In the study, samples with dimensions of 70x70x70 mm and products with dimensions of 500 × 500 × 50 mm were made from electrically conductive coarse aggregate concrete. Additives of industrial soot suspension - 7% and carbon fiber - 1% were used as modifiers. The additives were introduced individually and in combination. The developed compositions ensure the mechanical compressive strength of concrete on the 28th day of more than 40 MPa. The combined use of modifiers allows the surface of the product to be heated from 21°C to 34°C within 30 minutes. Physicochemical studies of the compositions conducted after 3 cycles of heating and cooling showed optimal homogenization of carbon-containing materials and the absence of chemical interaction between carbon fiber and components of the mineral matrix. The obtained indicators of electrical and mechanical properties prove that it is possible to manufacture products based on the optimal composition that provide repeated heating and are optimal for use in the improvement of urban areas.

1. INTRODUCTION

According to studies conducted in Denmark, Sweden, Norway, Finland, Canada, the USA, and Russia, it has been established that during periods when the average daily ambient temperature is -6.6 °C, icing of the transport infrastructure occurs, leading to disruption of the normal operation of facilities and injuries [1, 2].

In Russia, statistics of injuries due to icing of the transport infrastructure confirms the upward trend in such cases. Among the causes of temporary disability of the population, injuries due to ice account for about 15% and in 15-20% cause disability [3, 4]. In addition, snow and ice are the cause of most road accidents; the accumulation of precipitation and ice on airport runways leads to flight delays [5, 6].

Basically, high-impact transport and urban infrastructure facilities are built from heavy concrete with coarse aggregate. Concrete and reinforced concrete occupy the main place in the volume of production of building materials, so expanding the functionality of these materials is an urgent task.

This problem can be solved through the development of composite materials with enhanced functional properties obtained by modifying the structure and properties.

The authors [7, 8, 9] proposed technological solutions to increase the functional load of products based on high-strength concrete: in the field of transport infrastructure - to ensure snow melting; at energy industry facilities – to provide protection systems against electrochemical corrosion; at industrial and civil infrastructure facilities - as heating systems [10, 11].

The main components for the manufacture of this type of material are high-quality cements, washed classified sands and fine-grained chippings of fractions from 3 to 10 mm, as well as plasticizers and dispersed additives.

In turn, data analysis indicates that CEM I 42.5N and 32.5N cements produced in Russia are often inferior in strength, for example, to German analogues, cements of the CEM I-42.5R and CEM I 32.5R brands. The reduced strength is due to the high content of slag additives used to reduce the cost of the final product [12].

This disadvantage in the production can be mitigated by forming a matrix with dense packing, ensured by optimal granulometry of the components. Similar approaches were suggested and implemented in the development and application of highly efficient self-compacting concrete and fiber-reinforced concrete by Professor V.I. Kalashnikov [13]. Similar methods were implemented by P. Taylor [14].

Deicing measures include the use of chemical additives and mechanical actions, which in turn lead to the destruction of concrete. This necessitates the development of alternative, environmentally friendly, economical, and fast ways to combat icing.

In many countries, various heating systems are used as an alternative to standard methods, such as water heating, resistive cables, and electrically conductive materials [15, 16].

Hydraulic heating systems melt sediment by circulating the heated liquid through pipes built under the road and/or sidewalk surface. In each cycle, the cooled liquid passes through a heat source (geothermal water, boiler or heat exchanger), which reheats it [15]. The disadvantages of hydraulic systems are considered to be the complexity of the design, high installation costs, low maintainability, and dependence on the geothermal potential of the region [16]. In countries with low geothermal activity, this method is not cost-effective.

Using resistive cables embedded in concrete structures shows low performance due to the required high-power density, low maintainability, and high sensitivity to damage [15, 16].

By analyzing the disadvantages of the presented methods, it is possible to determine a general approach to creating such systems, which consists of reducing the material consumption of the proposed solution, independence from the geographical location of the region, and increasing maintainability and economic efficiency. Achieving these criteria is possible when implementing resistive heating systems directly using the material or product involved in the work [17, 18].

A set of criteria can be achieved by using electrically conductive materials based on heavy concrete. Electrically conductive products based on heavy concrete have a number of advantages and make it possible to avoid expensive and material-intensive heating systems.

From a theoretical point of view, the implementation of such systems is determined by the theory of percolation and the Joule effect, the occurrence of ohmic or resistive heating of an electrically conductive network in the structure of a low-conductivity matrix. This solution provides low energy consumption and is characterized by ease of manufacture and installation [19, 20].

As noted in [19, 21], the most effective way to obtain electrically conductive concrete on a mineral matrix is by means of dense packing, selection of the granulometric composition of aggregates, and the use of polymorphic carbon particles. The combination of these factors makes it possible to conduct an electrical charge through a volume of concrete.

The electrical conductivity of concrete is inversely proportional to the volumetric electrical resistivity [21,22], which ranges for conventional concrete at room temperature from 600 to 1000 kOhm・cm. After drying, this indicator is about 108 kOhm・cm. When wet, concrete is considered a semiconductor, with a resistivity of about 10 kOhm・cm. It has been established [21,22] that in order to conduct electric current through a volume of concrete, its resistivity must be less than 1000 Ohm ・cm.

Reducing the volumetric resistivity and stabilizing the indicator over time is the main task in the development of such products.

In electrically conductive concrete, the heating element is a volumetric electrically conductive network of the solid phase, which, due to the movement of charge carriers induced by the applied voltage and the movement of the charge through micro heating elements, leads to the dissipation of electrical energy into the heat generated by the product [19, 21]. The effect is realized both when supplying alternating and direct current. In this case, the supply of alternating current is carried out by connecting the object to the network directly or through a voltage rectifier. The use of a voltage rectifier is due to the need to control the characteristics of the supplied electric current to avoid premature electrical wear, as well as to regulate the temperature of the product.

To assess the economic efficiency of a product based on electrically conductive concrete, the electrical power consumption (P) must be determined. This indicator can be described as follows, as formula:

$$P = I^2 \times R \text{ or } P = U^2/R \quad (1)$$

where I is the current, R is the resistance, and U is the applied voltage.

Electrical power is a physical quantity that characterizes the speed of transmission or conversion of electrical energy. Studies have shown [23, 24] that in electrically conductive concrete the rate of electric current power consumption is directly dependent on the size, shape, and number of electrically conductive components that act as microheating elements in the matrix.

The use of various types of additives and determination of their effect on the volumetric resistivity indicator are the components of a set of studies required for the introduction of electrically conductive concrete into the practice of construction production.

Electrically conductive components, in accordance with the geometric shape of the solid phase, are classified [24, 25] into dispersed powders with predominantly round particles and particles with relative elongation.

The use of additives with different particle shapes promotes the formation of different types of electrically conductive structures, such as cluster, linear, and mixed.

It is proposed to introduce steel fibers, graphite powder, and carbon particles of various geometric shapes into the concrete mixture as heating microelements-additives. Such additives are introduced in amounts from 0.01% to 20% by weight of the binder. In this case, the range of achieved values of electrical resistivity varies from 500 to 2 × 105 Ohm・cm [11, 19]. The authors of [26] note that the influence of the modifying component on the operational properties of concrete depends on the choice of the type of electrically conductive structure formed. Thus, the use of ultrafine additives based on carbon or iron in an amount of over 10% by weight of the binder leads to a decrease in grade strength by 30-40% [25].

In turn, the use of iron-containing additives as an electrically conductive component can lead to intensification of electrochemical corrosion processes and destruction of concrete [27].

Analyzing the results of work [28] showed that carbon is an effective material for ensuring the electrical conductivity of a mineral matrix based on Portland cement. Carbon-based additives have been used for a long time in construction materials science. They help improve physical, mechanical, and electrical properties [28].

The main types of carbon-containing additives are: industrial soot [16], carbon fiber [9], and carbon nanotubes [18]. From an economic point of view, an effective carbon-containing additive is dispersed industrial soot, obtained as a waste from the oil and gas and mining processing complex. The experience of its use for modifying fine-grained concrete [18, 20, 29] has shown a significant reduction in the specific volumetric resistance of products. At the same time, thermograms of products modified with finely dispersed additives demonstrate low heat generation. It is optimal to use a complex of additives that provide a combination of dispersed particles with larger particles of various morphologies.

Carbon fiber is known as a reinforcing component for composite products. Additionally, in the manufacture of electrically conductive materials, the fiber can act as an electrically conductive additive.

Carbon fiber-modified concrete has improved performance characteristics [9, 15, 17]. However, the use of fiber to modify the mineral matrix requires certain technological solutions, selection of the optimal additive content, establishment of a rational fiber length, and adaptation of the component mixing stage. While ensuring homogenization of the fiber in volume, the additive can significantly influence the electrical conductivity of the matrix.

One of the approaches to increasing the degree of homogenization of fibers is the use of plasticizers, often polycarboxylate [9].

To analyze and evaluate the potential for introducing electrically conductive concrete compositions into construction production, it is necessary to carry out mathematical modeling of the processes that determine the electrical conductivity of the mineral matrix and describe the heating process of products [11, 26].

Currently, there is a need to study the thermal characteristics of samples of electrical products [19, 20] and select the optimal geometric shape of the electrode [8].

To introduce products into the operational process, it is necessary to work out design solutions for connecting and supplying electric current to the product and determine the specific heat release and energy consumption [18, 24].

As part of the presented research, the compositions of electrically conductive coarse aggregate concrete were optimized, carbon-containing additives were selected, laboratory products were manufactured, and the possibility of their use as heating products for the improvement of urban areas was assessed.

2. METHODS

The components of the compositions of electrically conductive heavy concrete were conductive materials (heating microelements) in the form of modifying additives and metal electrodes. Heating of products is due to the presence of modifiers and the supply of electric current through built-in electrodes.

A feature of the presented work is the use of a basic control composition and a control composition modified with a polycarboxylate plasticizer as control compositions. Two control samples are used in order to optimize rheological properties of the compositions.

2.1 Mix design and materials

The following components were used to prepare the compositions:

Portland cement, produced by Novoroscement JSC, CEM I 42.5N. Chemical composition of cement: CaO – 66,73%; SiO_2 – 23,22%; Al_2O_3 – 5,16%; Fe_2O_3 – 4,42%; SO_3 – 0,47%. Mineral composition of cement: C_3S – 65%; C_2S – 13%; C_3A – 4%; C_4AF – 18%.

Aggregates: fine aggregate - sand with a particle size modulus of Mk = 2.25 (residue on sieve No. 063 mm - 42%); coarse aggregate - chipping (fraction from 5 to 20 mm).

Industrial soot suspension UPC-MIX-1, produced by Novy Dom LLC. The suspension was introduced to form a cluster structure of industrial soot particles that act as heating elements. The suspension is a macromolecular concentrate of the components: industrial soot - 34%; water - 20%; propylene glycol - 10%, special additives - 8%. In the study [30], the granulometric composition of particles in suspension was determined, represented by a wide range from 0.03 to 10 µm.

Monsterfiber C carbon fiber is chopped carbon thread obtained through multi-stage heat treatment of PAN fibers (polyacrylonitrile-based fibers) at temperatures up to 3200℃, Table 1. The introduction of fiber was carried out to form an electrically conductive frame in the structure of the mineral matrix, combining clusters of carbon particles of industrial soot.

Table 1. Specifications.

Name	Specification
Fiber tensile strength, MPa, not less	3000
Elastic modulus when fiber subjected to tensile load, GPa, not less	230
Density, g/cm³	1,68-1,80
Fiber elongation at break, not less	0,80%
Water content	0,1 %
Storage period	Not limited
Production certified according to standards	ISO 9001, OHSAS 18001, ISO 14001
Fiber length	6 mm

Stahement-2000-M, hyperplasticizer based on polycarboxylates, produced by Stakhema-Volga JSC. The additive is produced in liquid form according to TU 800013176.004-2011 and complies with European standards EN 934-2:2010. It is used to uniformly distribute carbon fiber in a concrete mixture and achieve optimal mobility parameters, ensuring the workability of the mixture.

Calcium nitrate, corresponding to calcium nitrate GOST 4142-77, was used to stabilize electrical conductive properties. The additive was introduced by preliminary dissolution in the mixing liquid.

2.2. Mixture design and specimen production

The components used in the prepared mixtures are presented in Table 2. The ratios of the components were taken based on previous studies [1,9,19].

Table 2. Table of experimental compositions (per 1 kg/m³) and mixture properties.

<table>
<tr><th>Mix code</th><th>CEM I 42.5, kg/m³</th><th>Coarse aggregate, kg/m³</th><th>Quartz Sand, kg/m³</th><th>Industrial Soot, kg/m³</th><th>Carbon fiber, kg/m³</th><th>Stahement-2000-M</th><th>Calcium Nitrate</th><th>Water-to-Cement Ratio</th><th>Density</th><th>Slump, cm</th></tr>
<tr><td>Reference</td><td>410</td><td>1000</td><td>820</td><td>-</td><td>-</td><td>-</td><td>-</td><td>0,45</td><td>2,4</td><td>15</td></tr>
<tr><td>Reference sample 2</td><td>434</td><td>1063</td><td>868</td><td>-</td><td>-</td><td rowspan="4">2,2</td><td>-</td><td>0,35</td><td>2,5</td><td>14</td></tr>
<tr><td>ECON 1</td><td>435</td><td>1066</td><td>869</td><td>31,8</td><td>-</td><td>4,5</td><td>0,35</td><td>2,6</td><td>11</td></tr>
<tr><td>ECON 2</td><td>449</td><td>1102</td><td>899</td><td>-</td><td>4,5</td><td>4,5</td><td>0,35</td><td>2,6</td><td>12</td></tr>
<tr><td>ECON 3</td><td>454</td><td>1131</td><td>909</td><td>31,8</td><td>4,5</td><td>4,5</td><td>0,3</td><td>2,7</td><td>13</td></tr>
</table>

Analysis of the rheological properties of the resulting mixtures established that using a hyperplasticizer ensures a low water-cement ratio and provides the P3 mobility grade for the control and modified compositions. This grade of mobility ensures the use of the mixture in the manufacture of reinforced products and structures. Subsequently, all experimental compositions were made using a hyperplasticizer.

Mixture production

To homogenize carbon-containing additives, a method for producing a mixture in three stages was developed:

Mixing chemical additives with the mixing liquid. In compositions with carbon fiber, a hyperplasticizer was first introduced into the mixing water, then fiber. After that, dispergation was carried out. For all other compositions, chemical additives were mixed using a submersible mixer with a forced mixing method.

Mixing of dry components - Portland cement, crushed stone, and fine aggregate - was carried out using a submersible mixer with a forced mixing method.

Mixing of the pre-mixed dry components with the produced mixture of water and modifiers was carried out using a submersible mixer with a forced mixing method.

This sequence makes it possible to obtain a composition with specified properties, both in laboratory conditions and in the conditions of concrete plants and construction sites.

Samples geometry

Electrical resistivity and mechanical compressive strength were determined using cube samples with geometric dimensions of 70x70x70 mm.

To determine the thermal characteristics, samples were made in the form of slabs with dimensions of 500x500x50 mm. The choice of geometric dimensions is determined by the experimental studies presented in [18, 24], as well as by the correspondence of the dimensions of the experimental product, i.e. the slab, to walkway slabs manufactured according to GOST 17608-2017.

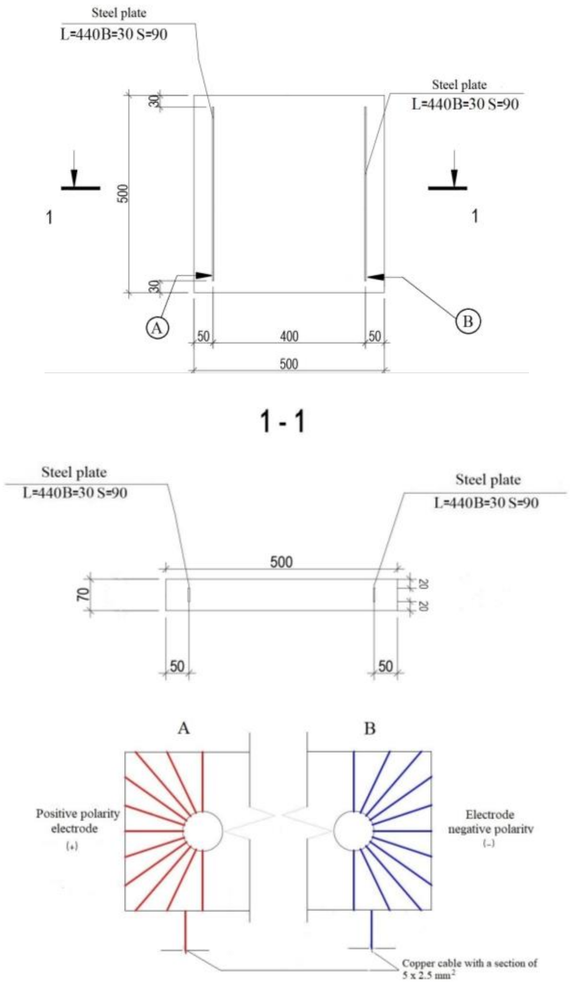


Fig. 1. Layout of steel plates in the experimental product of a slab.

In the sample slabs, the location of the embedded elements and the cable connection were carried out according to the diagrams presented in Fig.1. In the presented diagram in Fig.1, 2 metal steel plates with dimensions of 3 mm x 30 mm and a length of 440 mm are used, as well as a copper cable with a cross-section of 5 x 2.5 mm2, Fig.1. A protective layer of concrete of 5 and 3 cm provides both the operational properties of the product and electrical insulation.

Electrode types for thermal performance evaluation

The thermal characteristics of the developed products were assessed by using electrodes of hot-rolled low-alloy steel intended for metal structures, GOST 4543-2016, with dimensions 440 x 30 mm and a cross-sectional area of 90 mm2.

2.3. Experimental Process

Compressive Strength

Mechanical compressive strength was determined at the age of 7, 14, and 28 days of hardening on a hydraulic press PGM-100MG4-A with a loading rate of 0.5–0.8 MPa/s. For each composition, a series of six samples was made, based on the test results of which the average value was determined.

Electrical resistance measurement test methods

Specific resistance was determined at control test periods after 7, 14, and 28 days of hardening using a two-point uniaxial method.

Electrical resistivity was calculated by as formula (2)

$$\rho = R \times \frac{A}{L}, \Omega \times cm \qquad (2)$$

where ρ is the resistivity of the sample; R is sample resistance; L is distance between probes; A is the cross-sectional area of the sample. The resistance index R was determined using an E7-20 immittance meter.

Physicochemical characteristics

Assessment of the degree of distribution and nature of interaction of carbon-containing additives in the mineral matrix was carried out by a complex of physicochemical research methods.

Thermogravimetry–Dierential Scanning Calorimetry (TG–DSC) Analysis

DSC analysis was used to obtain additional information on the phase composition. DSC data were obtained on a TGA/DSC1 device by Mettler-Toledo Vostok JSC, Mettler-Toledo Vostok CJSC, Switzerland, temperature range from 60 to 1100°C at a temperature increase rate of 30°C/min in air atmosphere.

Microstructure and EDX examination

Scanning electron microscopy was used to study the morphology and distribution of modifiers. EDX was used to analyze the distribution of various elements. Photography on Thermo Fisher Scientific Quattro S was carried out in low vacuum mode from 20 to 30 kV, without sputtering, at a pressure of 50 Pa.

Thermophysical properties of concrete

Thermograms were used to determine the temperature gradient and establish the thermophysical properties of the product surface. Thermal changes on the surface of the slabs were recorded using a Guide D192M thermal imaging camera. D series smart thermal camera is equipped with a 4-inch-high brightness touch screen, IR resolution 192×144, detector type 25μm, VOx, spectrum 7.5~14μm, temperature range: -20°C~150°C, 100°C~650 °C, 650°C~1500°C, accuracy: ±2°C or ±2% of reading (at ambient temperature 15°C to 35°C and object temperature above 0°C).

The choice of method is based on the results presented in a number of works [18, 24]. The slabs, Fig.1., based on the developed compositions, were tested by supplying a direct electric current with U = 60V and I = 3A. The product was heated by a potential difference applied to two electrodes for 30 minutes.

3. RESULTS AND DISCUSSION

3.1. Electrical test results

The obtained indicators of the specific volumetric electrical resistance of the samples are shown in Fig.2. It was established that the resistivity indicators of the samples correspond to the indicators given in the literature [19 - 22] and amount to 0.8 kOhm・cm on the 28th day for samples with the addition of industrial soot (ECON 1), which is 99% lower, than that of the control composition. Compositions with carbon fiber (ECON 2) and compositions modified with a complex additive of fiber and industrial soot (ECON 3) provided volumetric resistivity of 0.7 and 0.5 kOhm・cm, respectively. The obtained indicators are probably due to the fact that the percolation transition zone in the mineral matrix is a densely packed system, provided with a rationally selected granulometric composition of the components. Also, the indicators are ensured by the introduction of carbon fiber pre-dispersed in the mixing fluid with a plasticizer, which significantly improved the distribution of fiber in the volume of concrete. At the same time, it should be noted that the electrical conductivity of all compositions decreases over time due to an increase in volumetric resistivity during strength gain, which is caused by the processes of crystallization and recrystallization [32]. Studies [1, 9] have confirmed that the resistivity value of the ECON-3 composition containing carbon-containing additives (fiber - 1% and industrial soot suspension - 7%) does not increase significantly over time and largely depends on the breakdown voltage.

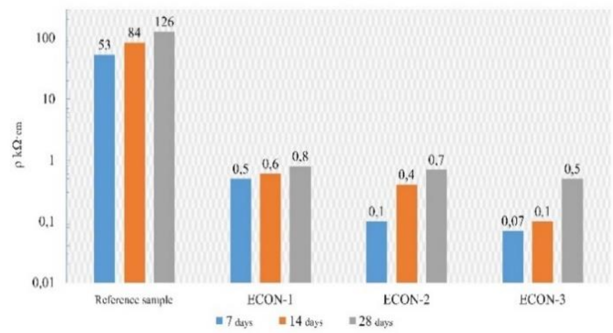


Fig. 2. Change in electrical resistivity of samples of the studied compositions over time

The mechanical compressive strength of the samples of the studied compositions, modified with carbon additives with different morphological structures, was assessed in control periods of 7, 14, and 28 days, Fig.3. The mechanical compressive strength on the 28th day of curing for ECON - 3 samples was found to be 25% higher than that of the control composition and ECON -1 composition; and 18% higher than that of the ECON-2 composition.

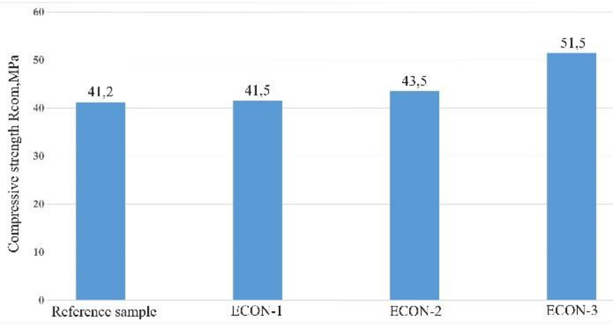


Fig. 3. Results of compression testing of the samples of the studied compositions on the 28th day of hardening. The coefficient of variation is 11.2%

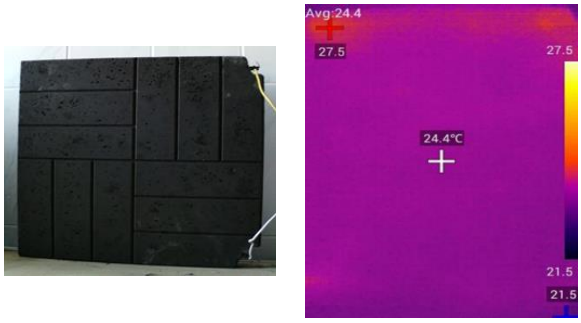
Based on the analysis of studies of the electrical and physical and technical properties of the developed compositions, it was found that ECON-3 is a promising composition. The brand strength of this composition corresponds to concrete class B40 and is 51.5 MPa on the 28th day. Specific volumetric electrical resistance is within the range of up to 1 kOhm・cm and is 0.5 kOhm・cm on the 28th day.

Based on the results obtained, the ECON 3 composition was subsequently used to determine the thermophysical and physicochemical properties.

3.2. Study of the thermophysical properties of the product

Fig. 4 shows the results of testing a product in the form of a slab with geometric dimensions of 50x50x5 cm based on the ECON 3 composition. The electrodes in the product were located according to Fig. 1. By analyzing the results, the parameters of the direct current supplied to the metal electrodes were determined as I = 3A, U = 60V. These characteristics are cost-effective and safe for use in industrial and civil construction. As a result of supplying direct current with the specified characteristics, the temperature of the product gradually increased. Heating continued for 30 minutes. After 30 minutes, the surface temperature of the product was 33.7 °C, which is 13.4 °Chigher than the initial temperature of the product. At the same time, the average power consumption was 68 W/h per 1 m².

The sample was heated within the control periods on the 7th, 14th, and 28th day of hardening, Fig.5. The growth dynamics of the thermophysical characteristics of the matrix is observed, which is due to an increase in the density of the material due to an increase in the volume of the crystalline phase of the cement stone. An increase in density is accompanied by a decrease in the content of chemically free water, while the increase in the electrical conductivity of the material over time is compensated by the tunneling effect due to the close proximity of particles with different morphological structures with low breakdown voltage. In turn, it can be noted that complex modification with industrial soot and carbon fiber further increases the efficiency of fiber distribution in the volume of the mineral matrix, which leads to an increase in mechanical strength.

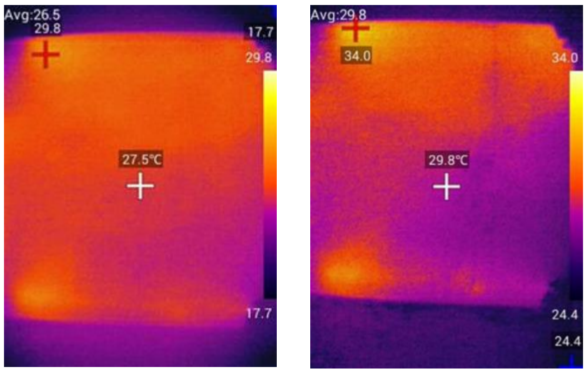


(a)

(b) Emission coefficient – 0.75;

Ambient T = 20 °C;

Average T of slab surface temperature = 24.4 °C



(c) Emission coefficient - 0,75

Ambient T = 20 °C

Average T of slab surface temperature = 27,5 °C

(d) Emission coefficient - 0,75

Ambient T = 20 °C

Average T of slab surface temperature = 29,8 °C

Fig. 4. Thermal camera images taken with a 10-minute heating interval: (a) type of product during testing; (b) 10 minutes; (c) 20 minutes; (d) 30 minutes.

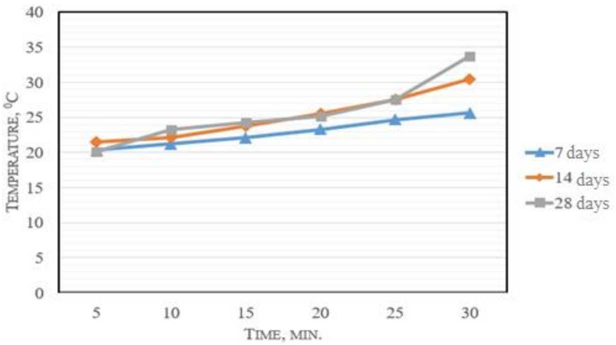


Fig. 5. Dynamics of heating of the slab product within the target time frame.

3.3. Study of physical and chemical properties

The microstructure of electrically conductive heavy concrete samples is shown in Fig.6. Photographs of the experimental compositions were taken on the 28th day of hardening and visualize the morphology of the chip surface. The mineral matrix of the modified compositions is characterized by dense packing of crystalline and amorphous phases. In the structure of the sample of the ECON-1 composition, Fig.6.b, carbon-containing plate-like formations are observed, corresponding to the formation of electrically conductive clusters of carbon black; similar new formations were noted in works [33, 34]. In turn, in the ECON – 2 (Fig.6.c) and ECON – 3 (Fig.6.d) compositions, a uniform distribution of fiber grains is observed, while no chemical interaction is observed between the mineral matrix and the fiber. It should be noted that there were no manifestations of deformation and shrinkage processes in the matrix modified with carbon-containing components after three cycles of heating and cooling.

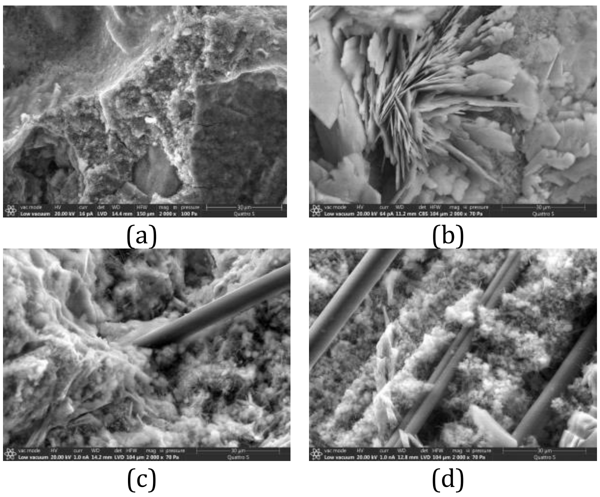


Fig. 6. SEM images of samples of the studied compositions on the 28th day of hardening, after heating and cooling cycles: a. Control composition; b. ECON 1; c. ECON 2; d. ECON 3.

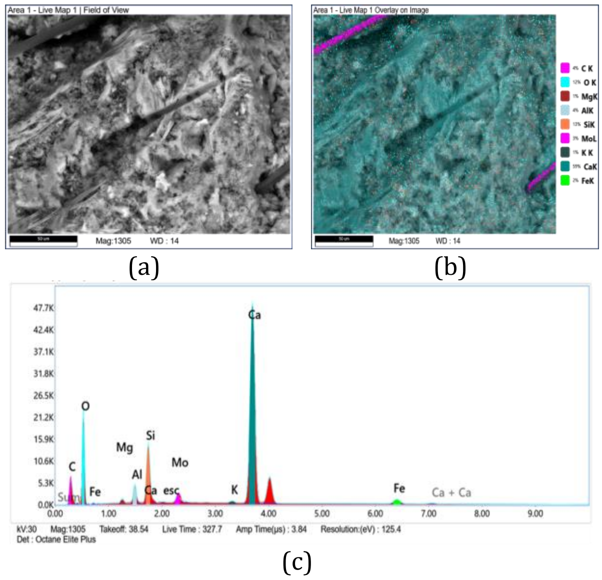


Fig. 7. Results of energy dispersive analysis of the ECON 3 sample on the 28th day of hardening, after heating and cooling cycles (a. microstructure of the ECON 3 sample; b. mapping of elements in the microstructure; c. ratio of elements in the ECON 3 sample.

Despite the low degree of precision (error of 1-1.5%) of this method in construction materials science, mapping within the framework of energy dispersive analysis makes it possible to evaluate the morphological features of the contact zone of the cement matrix formed along the carbon fiber Fig.7. The results confirm the absence of chemical interaction between the mineral matrix and carbon additives [35].

To interpret the morphological features and justify changes in physical and technical properties, differential scanning calorimetry was performed in an oxygen atmosphere; the resulting temperature curves and mass loss data are presented in Fig. 8.

A comparative analysis showed that at temperatures up to 400 C, all samples exhibit an endothermic effect associated with the decomposition and dehydration of cement stone hydration products. In this case, peaks in the region of 150 C are associated with the dehydration of gel and crystalline products of the hydration of the binder. The presence of peaks in the temperature range from 100 C to 300 C, as well as a shoulder at about 300 °C, indicates the presence of ettringite in the compositions.

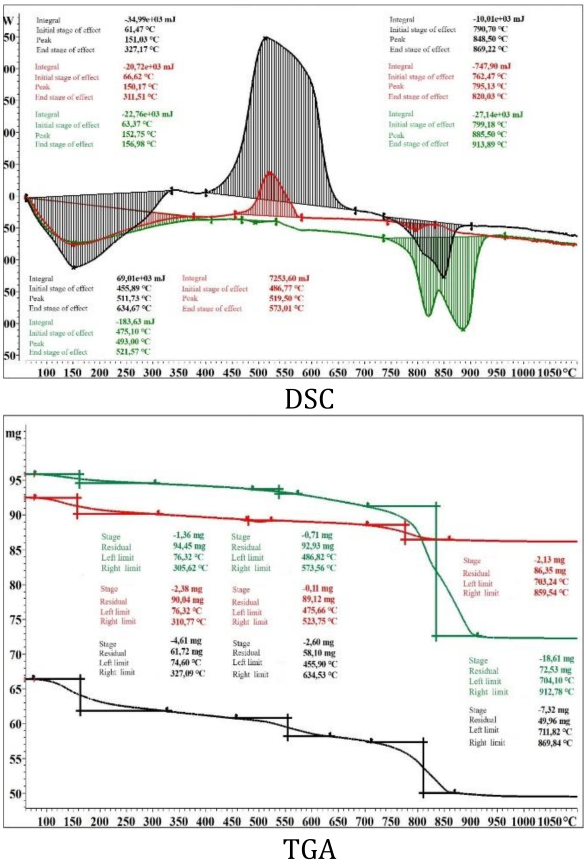


Fig. 8. Thermal analysis of samples on the 28th day, after heating and cooling cycles: Black (ECON 3), red (ECON 1), green (Reference sample)

In addition, exothermic effects with maxima in the region of 455 - 635°C are observed on the DSC curves of the ECON 1 and ECON 3 compositions. The temperature at which the exothermic effect begins depends on the dispersion of the additives, and at a heating rate of 30 degrees/min it is 511.73 and 519.50°C for particles with sizes of 5 and 150 microns respectively. In this temperature range, there are no phase transformations of carbon with the release of heat [35], so the resulting effects probably reflect the interaction of carbon with oxygen to form carbon oxides, which are desorbed from the surface of the particles. In the indicated temperature range, the ECON 1 sample experiences a mass loss of about 0.6%. The absence of a significant difference in the total mass loss of the samples is determined by the dispersity of the carbon additives and indicates that the main part of the oxygen is not on the surface of the particles, but in the interplanar networks of graphite, forming interstitial compounds. In turn, the weight loss of the ECON 3 sample is 3.9%. This loss of mass is due to the presence of a contact zone between the surface of the fiber and oxygen, and therefore a significant part of the oxygen is on the surface and forms carbon oxides, which are desorbed from the surface of the fiber.

The endothermic effect in the region of 475.10 - 521.57°C and the peak at 493°C in the control composition graph can be attributed to the thermal decomposition of calcium hydroxide. The endothermic effect in the temperature range 790.70 - 913.89 °C, accompanied by a mass loss of 19.4%, is associated with the stepwise decomposition of ettringite and calcium carbonate.

4. CONCLUSION

This study is aimed at assessing the feasibility of electrically conductive heavy concrete in the form of products capable of providing heating and snow melting. A prototype of a heated paving slab was manufactured based on a rationally optimized ECON 3 mixture. A diagram of the connection of the product and the characteristics of the supplied current were proposed, which suggests the possibility of scaling the results during practical implementation.

Key findings from the study:

The optimal composition was determined to be ECON 3, for which a complex modification with industrial soot and carbon fiber was applied, providing mechanical strength for 28 days of 51.5 MPa, specific volumetric resistance of 0.5 kOhm · cm. The results obtained fully correlate with the indicators presented in the works [2, 5, 11, 16, 29].

Similar resistivity values for complex modification and modification with industrial soot are due to the high density of the samples and the uniform distribution of additives in the mineral matrix, which is achieved by optimizing the process of manufacturing electrically conductive concrete.

Analysis of the results of the physicochemical properties of the optimized composition suggests the absence of new formations and chemical interaction between the fiber and the components of the mineral matrix, the absence of cracking and deformation in the contact zone between the carbon fiber and the mineral matrix after heating the product.

Stable heating values typical for ECON 3 have been established, which are accompanied by optimal power consumption. Calculation of the economic efficiency of the project implementation on the territory of the Russian Federation, with an average power consumption of 816 Wh per 100 m^2, amounts to 2,600 rubles per month. At the same time, the cost of the mixture was 49,044 rubles per 1 m^3.

It is worth noting the need for additional research to optimize the contact zone of cement stone and carbon fiber, to ensure the possibility of increasing the adhesion of fiber to crystalline hydrates, to improve physical, mechanical, and electrical characteristics.

Additional research is required on the effect of cyclic and long-term exposure to electric current on carbon-containing components and the structure of electrically conductive concrete.

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