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PROSPECTS FOR THE USE OF ASH AND SLAG WASTE IN THE CONSTRUCTION OF ROAD PAVEMENT

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Abstract. The relevance of the subject matter is conditioned by the importance of resolving the issues of practical use of ash and slag waste to create a high-quality road surface. The aim of the study is to determine the main promising areas for the use of ash and slag waste in creating a reliable road surface structure during roadway repair. The leading approach in this study is the systematic analysis of the entire complex of issues submitted for consideration, in the context of assessing the importance of the prospects for the practical use of waste in road construction to create a high-quality road surface and the prospects for reducing the cost of its maintenance and possible repair. It has been found that the practical use of ash and slag waste can significantly increase

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the strength of the road surface and increase its service life. Also, it is stated that the use of ash and slag mixture allows for achieving a significant reduction in the cost of building materials. It is concluded that the activating additives should be introduced to reduce cement consumption.

Keywords: road pavement, road repair, building materials, cement, ash and slag mixture.

Introduction

The forecast of an increase in the volume of industrial concrete production in various states, covering the time period up to 2030, assumes the preservation of concrete as the main material for building operations, in particular, for the construction of roads. At the same time, the improvement of the environmental situation implies a reduction in the consumption of natural raw materials in the process of industrial production of concrete, a reduction in energy intensity, and a reduction in emissions of carbon dioxide (CO_2) and dust fractions of less than 0.1 mm during the production of Portland cement. The analysis of technical and patent literature reveals the possibility of partial replacement of Portland cement with various industrial waste (Baishemirov et al., 2016). The prospects of practical use of ash and slag for these purposes are dictated by their properties and low cost. Notably, the main advantage of road coverings created using ash and slag waste in their construction is their relatively lower cost compared to standard asphalt-concrete pavements, with similar strength characteristics and comparable service life (Sharma & Kumar, 2021). In addition, such road pavements require significantly lower repair costs in the future.

For this reason, the study of the properties of concrete mixtures that are used in the road industry with ash and slag with the introduction of modern additives – plasticiser and air entrainment for the construction and repair of road surfaces – remains relevant and guarantees a gradual improvement in the performance of cement mortars and concretes in conditions of saving binder cement and improving overall environmental performance. This includes a concomitant reduction in cement production and a significant reduction in the cost of maintaining ash dumps and using expensive land (Hou et al., 2020).

For the economic development of any country, it is necessary to increase the intensification and efficiency of production, ensure daily savings of resources and environmental protection from pollution. An important role in the implementation of these tasks belongs to solving the problem of recycling large-tonnage industrial waste. Significant accumulations of such waste violate natural ecological relationships and cause environmental pollution (Weiners, 2020). In addition, waste occupies large areas of land that cannot be rationally used in agriculture. It is already known that such waste as phosphogypsum, cement dust, stone screening dust (screening from crushed granite), low-strength limestones, and others are used for the production of road construction materials. But due to the development of the road industry, an increase in the intensity and load of transportation is not enough and the industry requires the development and implementation of other high-quality secondary resources (Chen et al., 2021). One of these resources is energy industry waste. It has been established that according to the main characteristics (chemical, mineralogical and grain composition, time resistance, and others), ash and slag from thermal power plants from coal combustion are mostly valuable raw materials that can be used for the manufacture of many building materials (cement, heavy and light concretes, ceramic and thermal insulation products and products made from them) (Chen et al., 2020; Grigorenko et al., 2020). However, a significant amount of this waste requires the expansion of industries for their use. This explains the need for a qualitative assessment of the prospects for the practical use of waste from thermal power plants. That is why the prospects for the use of ash and slag waste in the construction of road pavement are becoming particularly relevant. The use of ash and slag in road maintenance contributes to the expansion of the range of practical use of waste and the possibilities of creating high-quality road pavement by introducing them into the design.

1. Materials and methods

In the course of this study, the system analysis was used, which allowed for performing a qualitative and comprehensive assessment of the prospects for the use of ash and slag waste in the construction of road pavement. This method involved conducting a study of the stated issues in the theoretical plane, with the definition of the most important theoretical prerequisites and prospects for the practical use of industrial waste when creating a high-quality roadway, empirical studies involving the study of practical experience of specific repair operations, existing regulatory documentation and features of ensuring the proper level of quality of the road surface created with the introduction of industrial waste into its design. Furthermore, the methodology of this study includes approaches for generating statistical data and graphical modelling of the results obtained.

The basis of this research is numerous papers devoted to the practical use of ash and slag waste in the construction of road pavement during the repair of the roadway and the creation of a high-quality road surface, in general. For the sake of creating the highest quality and objective picture of this study and to facilitate the perception of information, all the developments of researchers submitted for consideration of the issues cited in this study were translated into English. Thus, the methodological framework of this study is selected in strict accordance with the specified subject matter, which contributes to the most complete and high-quality coverage of all the issues under study.

The study was carried out in three stages:

1. At the first stage, a theoretical study of research papers available within the framework of the stated topic was carried out to identify the currently formed positions of researchers on the stated problems and the available practical methods for resolving the issues of the use of ash and slag waste in the construction of road pavement.
2. At the second stage, the effectiveness of ash and slag waste in the construction of road pavement during road maintenance and the prospects for expanding the range of applications of such technology were assessed from a practical standpoint.
3. At the final stage, the final conclusions were formed based on the study results. In general, the conclusions summarise all the theoretical and practical developments carried out to create the most complete and objective picture of the assessment of the prospects for the use of ash and slag waste in the construction of road pavement during works to restore damage to the roadway, and are also a complete and systematic display of the results obtained during the research.

2. Results and discussion

The road industry is material-intensive. It is known that 70% of road construction and repair costs are material costs. Solving the issue of widespread use of energy production waste for building different layers of road structures would allow significantly reducing the cost of work, expanding the range of road construction materials, reducing the cost of conditioned materials – crushed stone and sand. This determines the relevance and importance of this study.

Ash and slag mixtures with crushed stone or gravel that meet the requirements for the grain composition of mixtures according to DSTU B V. 2.7-30 (2013) are used as materials for the construction of non-reinforced layers of the road surface base. Ash and slag mixtures are used as the base for transitional and improved lightweight types of pavements on roads of categories IV–V, and the lower layers of the base for improved lightweight and permanent surfaces on roads of category III. The construction of the pavement base layers consists of the following technological operations: ash and slag mixtures of thermal power plants (TPP), stone materials are added to a trapezoidal ditch, on a compacted earth bed, or on the lower layer of the base; they are mixed, distributed, humidified to optimal humidity, and compacted. The minimum thickness of the layers that are laid should not be less than 10 cm, and the maximum should not exceed 25 cm. The bases with a thickness of more than 25 cm are arranged in two layers. It is recommended to compact mixtures with rollers on pneumatic tires or vibratory rollers. Reinforced ash and slag mixtures from different TPPs are used for the construction of the base layers and the pavement coating. The thickness of layers is determined according to VBN B.2.3-218-186 (2004). The physical and mechanical characteristics of reinforced ash and slag mixtures should be in accordance with the parameters given in VBN B.2.3-218-541 (2010). Cement-reinforced mixtures of ash and slag with the addition of stone material must meet the requirements of GBN B.2.3-37641918-554 (2013).

Reinforced milled materials using ash and slag mixtures must meet the requirements of VBN B.2.3-218-545 (2009). Reinforced mixtures using ash and slag mixtures must meet the requirements of the first group according to VBN B.2.3-218-541 (2010) and grades of materials M20, M40, M60, M75 according to GBN B.2.3-37641918-554 (2013), designed for the construction of the upper layers of the bases for improved surfaces of permanent and lightweight types on roads of category I–III, and pavements with protective layers on roads of categories IV–V. Reinforced ash and slag mixtures that meet the requirements of the second group according to VBN B.2.3-218-541 (2010) and have the grades M10, M20, M40 according to GBN B.2.3-37641918-554 (2013) and VBN B.2.3-218-545 (2009) are intended for the construction of the lower layers of the bases for lightweight and transitional types of coatings on roads of categories II–III, and the bases for road pavements IV–V. Reinforced ash and slag mixtures of the third strength group according to VBN B.2.3-218-541 (2010) and grades M10, M20 according to GBN B.2.3-37641918-554 (2013) and VBN B.2.3-218-545 (2009) are intended for the lower layers of the foundations for covering roads of categories III–IV, and for paving on roads of category V. The ash and slag mixtures are distributed into groups according to SOU 42.1-37641918-104 (2013).

The composition of reinforced ash and slag mixtures is selected experimentally, considering the properties of the materials used, the weather and climatic conditions of construction, the intensity of automobile traffic, and the purpose of the structural layers of the road surface. The determination of the composition of reinforced ash and slag mixtures is reduced to the choice of such a ratio between the constituent components, in which it is reliably and most economically ensured that the mixtures obtain the specified strength and frost resistance. It is recommended to introduce activator additives to reduce cement consumption, accelerate hardening, and increase frost resistance. The content of needle-like, silty, and clay particles in crushed stone, gravel-sand, and gravel-sand mixtures should not exceed 5 %, including clay particles – no more than 2 %. The frost resistance of the crushed stone and gravel should not be lower than the necessary frost resistance of the reinforced mixture. All types of industrial waste that are used must meet the same requirements (Fang et al., 2021).

Ash and slag mixtures of TPPs in concrete mixtures and cement concrete, depending on the grain composition, can be used in three ways:

- as an additive to replace a part of cement;
- as an additive to replace a part of sand;
- as a constituent component (active micro-filler).

Using an ash and slag mixture, it is possible to regulate the ability to move and the resilience of the concrete mixture (the time interval until the end of the mobility of the mixture), the rate of solidification and strength at a given age, i.e., the structure-forming processes of concrete. These properties depend on the amount of ash in the ash-slag mixture, the specific consumption of the ash-cement binder in the concrete, and the dosage of water.

The optimisation of the composition of concrete with the addition of ash and slag mixture is based on the method of optimal ratios. The criterion of efficiency here is the value of strength, which is provided by a unit of cement mass (Eq. 1):

$$K_{\mathrm{e}} = \frac{R_{\mathrm{st}}}{C}, \tag{1}$$

where K_{e} – the coefficient of efficiency of cement use; R_{st} – the compressive strength of concrete in a given time, MPa; C – cement consumption per 1 m^3 of concrete, kg.

The composition of concrete and the amount of introduction of ash and slag mixture are determined by the calculation and experimental method, considering the specific characteristics of the materials used and the requirements for the structural layers of road surfaces, depending on the operating conditions. For the successful implementation of large volumes of work on road, transport, and industrial construction in Ukraine and all over the world, building materials of various properties and high quality are required. Binders and concretes are in the leading positions in the list of building materials. According to preliminary estimates, the demand of the building sector of Ukraine for cement in 2020 may be at least 80–90 thousand tonnes. However, the production of cement is closely related to the release of:

1. CO_2 – the main component of the greenhouse gas, which is formed during the decarbonisation of the lime component of the raw material mixture;
2. Dust, the fractions of which do not exceed 0.1 mm, when firing a mixture of the raw materials in question in rotating furnaces and under the condition of using dry grinding of this mixture and cement.

Due to the above factors and the need to stabilise the environmental situation throughout the state, the use of industrial energy waste in concrete remains highly relevant. Table 1 presents data on fuel and electricity costs for the production and subsequent transportation of cement of various types and brands, kg to TOE (tonne of oil equivalent).

1. The cost of extraction and preparation of raw materials – 50% of the total cost;
2. The cost of energy – 30% of the total cost;
3. Financial investments and labour resources – 20%.

When using industrial waste instead of natural mineral raw materials, it is really possible to reduce the energy intensity of products by 1.4 times, and the material intensity by 1.5–2.0 times. Since modern concrete plants are often mobile and can be placed directly at the construction of facilities, the use of such waste heat energy as ash and slag mixtures is advantageous from a technological standpoint and economically feasible for the preparation of concrete mixtures.

Table 1. Fuel and Electricity Costs for the Production and Subsequent Transportation of Cement of Various Types and Brands

Cement type	300	400	500	550	600
Portland cement	–	279.7/118*	290.9/123	321.5/136	344.8/145
Portland cement with mineral additives	–	236.9/100	258.1/109	306.9/129.5	334.9/141
Portland blast-furnace cement	140/59	163.1/69	193.5/82	–	–

* Note: the numerator indicates the cost of making cement; the denominator indicates the cost of transporting cement.

Table 2 presents the classification and characteristics of technogenic additives currently used in the construction of road pavement during maintenance.

The introduction of the latest road construction technologies opens up broad prospects for the use of ash and slag waste in the construction

Table 2. Classification and Characteristics of Technogenic Additives Currently Used in the Construction of Road Pavement during Maintenance

Classification	Chemical and mineral composition	Physical characteristics
1. Possess astringent properties: quickly cooled slags.	As a rule, silicate glass (amorphous silica), with the inclusion of calcium, magnesium, aluminium oxides. The crystalline components can be represented in a small volume.	The material that is not fully prepared for use is presented in the form of granules and includes 5–15% moisture. Before use, it is dried and crushed to particles of no more than 45 microns. The particles have a rough surface, the specific density is 350–500 m^2/kg.
2. Possess astringent and pozzolan properties: high-calcium fly ash (Ca>10%).	Mainly silicate glass (amorphous silica), with the inclusion of calcium, magnesium, aluminium oxides. Crystal components in the form of quartz (may be present in small amounts).	Contains from 10% to 15% of particles larger than 45 microns. Most of the particles have a spherical shape with a diameter of less than 20 microns. The surface of the particles is mostly smooth, but not as clean as that of low-calcium fly ash. The specific surface area is 300–400 m^2/kg.
3. Possess high pozzolan activity: microsilicon.	Consists mainly of microsilicon of non-crystalline (amorphous) modification.	Ultrafine powder consisting of spherical particles mainly with a diameter of less than 0.5 microns. The specific surface area is about 20 000 m^2/kg.
4. Possess normal pozzolan activity: microsilicon.	Mainly silicate glass (amorphous silica) containing aluminium and iron oxides. The crystalline components are mainly in the form of quartz, mullite, magnetite in a small amount. Carbon is usually less than 5%, but sometimes it can be 10%.	Contains from 10% to 15% of particles over 45 microns. Most of the particles have a spherical shape with a diameter of less than 20 microns. Specific surface area is 250–350 m^2/kg.
5. Other: slowly cooled slags; wet ash discharge, boiler slags.	They contain mainly crystalline silicate minerals and a small amount of non-crystalline components.	Additionally, they are crushed to impart astringent or pozzolan properties. The crushed particles have a rough surface.

of road pavement during maintenance (Rahgozar et al., 2018). It can be assumed that the use of a high-quality fly ash additive causes a decrease in cracking and the economy of cement mortar. In world practice, there are several main and secondary methods of using fly ash: application as a raw material for the production of Portland cement and a pozzolanic additive in the manufacture of finished cement in factory conditions; use in concrete to replace part of cement; production of bricks; filler for asphalt concrete; production of light aggregates for concrete; road construction; use in agriculture as a fertiliser for the soil deoxidation; use of ash to obtain rare elements.

A review of papers in recent years has shown that fly ash is actively used as a binder, as a component of a polymer-concrete mixture, in general-purpose concrete compositions, concrete for obtaining high compressive strength, cement compositions for the manufacture of concrete and mortar (Faraca et al., 2019; Skorokhod et al., 1994). In the manufacture of heavy concrete and mortar, fly ash is recommended to be used to save aggregates, improve the technological properties of concrete and mortar mixtures, and quality indicators of concrete and mortar, to save cement (Sreenivasan et al., 2020; Abdullah et al., 2021).

Ash and slag waste can be used as a substitute for sand, which is used as a filler for concrete and mortar. If the lime content is sufficiently high, it should be used instead of cement. According to the scale of possible applications, concrete is the main direction that can qualitatively solve the problem of ash and slag waste elimination through their perfect disposal (Abdullah et al., 2021; Hodul et al., 2021). In addition, it can be used instead of aggregates in the production of “light” concrete, and to create heat and sound insulation. Building materials are the most obvious, but far from the main areas in the practical use of ash and slag. They can become an extremely important source of metals. Metals are already present in coal as part of various minerals and organometallic compounds. In the process of burning coals, a significant part of them turns into ash. Iron in coals resides mainly in the composition of the minerals pyrite (FeS_2) and siderite ($FeCo_3$), while a large proportion can also occur in the form of organo-iron compounds (Wang et al., 2017). In the process of burning coal, at fairly significant temperatures of about 1500 °C, there is a conversion of all available compounds into the mineral magnetite ($Fe3O_4$). Being in the molten, sprayed, and suspended state in the flue gas jet, the magnetite droplets have the shape of blobs. Possible areas of the practical application of magnetite microbeads are the manufacture of dyes, concrete filler capable of shielding electromagnetic radiation, powder metallurgy, and naturally alloyed iron ore concentrates (Fig. 1).

The most original and most important components of ash are aluminosilicate hollow microbubbles (AHM). Externally, these are completely hollow, almost perfect in shape silicate balls with a smooth surface. Their concentration in ash and slag waste is usually several tenths of a percent, while their "production" at large thermal power plants in different countries can reach several thousand or tens of thousands of tonnes per year (Consoli et al., 2021). Ash and slag waste, which is formed during the burning of coal at TPPs, is a large tonnage waste. Hydraulic ash handling systems are used for their transportation. In this case, a significant part of such waste is transported in the form of low-concentration pulp for placement in hydraulic dumps, which are one of the main sources of environmental pollution in the production of electric energy (Rahgozar et al., 2018).

The problem of practical use of various industrial waste is extremely acute in many developed and developing countries, where the total amount of electricity generated by burning coal in the total energy balance is measured in the range of 35% (Zhou et al., 2020). The construction materials industry allows using absolutely all the variety of industrial waste, including the most massive – waste of heat and power while solving issues of resource conservation and environmental protection (Sangiorgi et al., 2018). On their basis, cement, concrete, and mortars are produced, and used in road construction and ceramics production. Industrial production of concrete and reinforced concrete

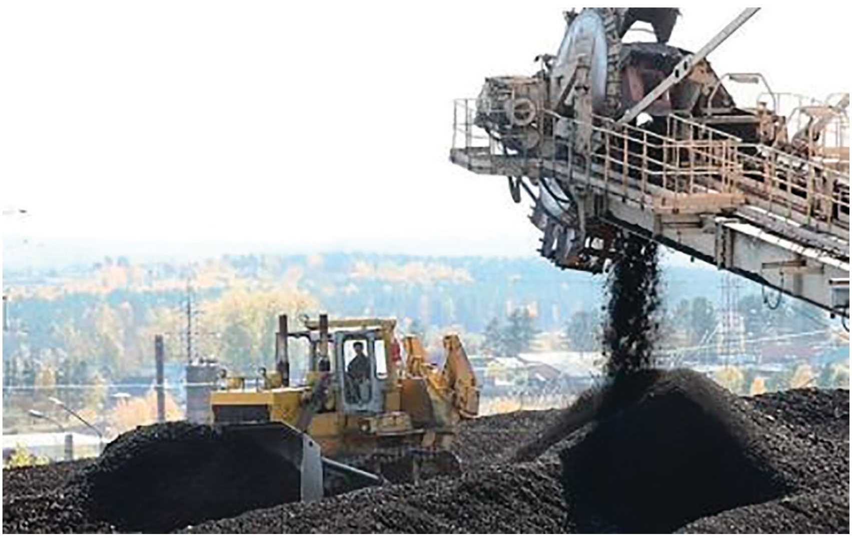

Figure 1. Utilization and processing of ash and slag waste

products and road construction have become the most effective areas of the practical application of such recoverable resources.

When burning at a thermal power plant, depending on the furnace temperature (1200–1600 °C) and the size of the particles, the mineral part of the coals either melts completely or melts from the surface. During cooling, a vitreous phase of the material is formed. Ash particles are deposited in electric filters and removed from them by dry (fly ash or dry removal ash) or by wet (hydraulic removal ash) method. Fly ash is endowed with higher properties and is widely used in cement and concrete technology. Most TPPs have hydraulic removal systems, the ash produced in them is most often used as a fine aggregate for concrete in the production of expanded clay and gypsum concrete, low-grade concrete, in road construction. In order to use TPP ash more effectively, as an active additive in the manufacture of concrete mixes, dry ash collection units are being built (Bekbauov et al., 2017). Thus, today there are broad prospects for the practical application of ash and slag waste in the construction of road pavement (Fig. 2).

An increase in the plasticisation effect of the concrete mixture when using fly ash is achieved due to the rounded shape of fly ash particles, and a decrease in its delamination is a consequence of obtaining a more coherent structure due to the small grain sizes of less than 0.16 mm located together with cement in the voids of the aggregate (Zhou et al., 2018; Guo et al., 2018). For the economic development of any country, it is necessary to increase the intensification and efficiency

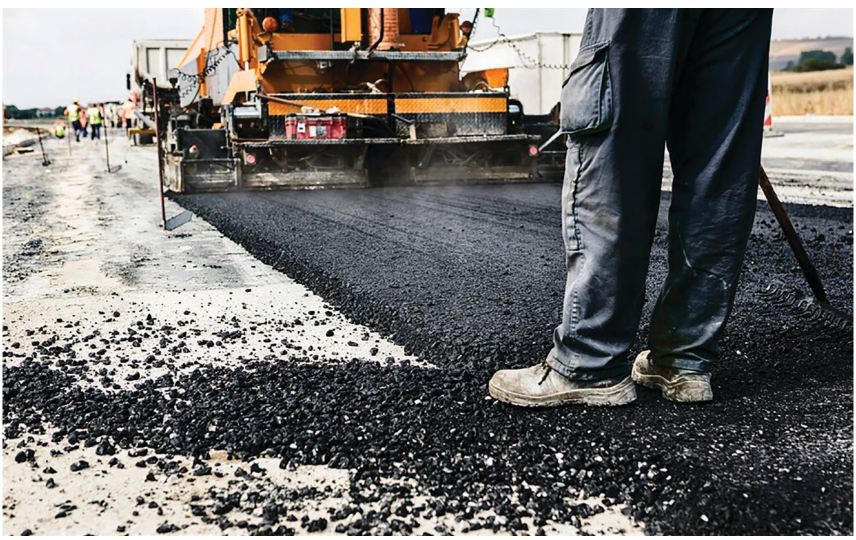

Figure 2. Use of ash and slag waste in road maintenance and construction

of production, ensure daily savings of resources and environmental protection from pollution. An important role in the implementation of these tasks belongs to solving the problem of recycling large-tonnage industrial waste. Significant accumulations of such waste violate natural ecological relationships and cause environmental pollution (Weiners, 2020). In addition, waste occupies large areas of land that cannot be rationally used in agriculture. It is already known that such waste as phosphogypsum, cement dust, stone screening dust (screening from crushed granite), low-strength limestones, and others are used for the production of road construction materials. But due to the development of the road industry, an increase in the intensity and load intensity of transportation, the available resources are not enough and the industry requires the development and implementation of other high-quality secondary resources.

The discussion of the results of this study in the context of comparing them with the results and conclusions obtained by other researchers on the issues submitted for consideration clearly demonstrates the relevance of conducting further scientific research in this line. The possibilities of using ash and slags in concrete are associated with making a decision that it is preferable to mix them with cement beforehand and use them as ash cement or add them as an additive when mixing concrete, due to the need to take into account such factors as the type of structure, the scale of construction work, the market conjuncture formed in relation to cement with the addition of fly ash, and other circumstances. The qualities that should be characteristic of concrete can be determined in accordance with each specific construction object. Therefore, in order to prepare high-quality concrete that is best suited for a specific facility, it is necessary to choose fly ash of a certain quality and find out how much it needs to be applied so that the appropriate cement is at the output, considering the conditions of concrete retention and a number of other related factors.

Conclusions

According to the results of the conducted research, it has been found that the practical use of ash and slag waste can significantly increase the strength of the road surface and increase its service life, which is important from the standpoint of the increased cost of road maintenance. In addition, the use of ash and slag mixture allows for achieving a significant reduction in the cost of building materials used in road repairs. The similarity of the chemical and mineralogical composition of ash and slag waste with materials produced in the silicate industry makes them very promising from the standpoint of use in the manufacture of mineral wool, ash ceramics, silicate bricks and other materials that can be successfully used during road maintenance. The results of this research demonstrate a significant practical benefit from the use of energy waste in the form of ash and slag in the construction of pavement on the roadway, which is extremely important in the context of assessing the prospects for the development of such technologies and their practical implementation in various road works.

Thus, there are serious prospects for the use of ash and slag waste in the construction of road pavement of various levels of complexity and practical orientation. Further study in this direction will contribute to expanding the understanding of the areas of application of ash and slag waste in road repair and construction works and will help to find new, rational possibilities for their practical use in repairing high-quality road pavements that have been damaged during prolonged operation.

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