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# Investigation of the properties of cast asphalt concrete mixture with the addition of fiber from the fly ash of thermal power plants

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The introduction of new road-building materials with advanced physical and mechanical properties is the trend in contemporary civil engineering, which aims to increase the quality of road surfaces. The use of cast asphalt concrete in the upper layers of road surfaces as a replacement for layers made of traditional fine-grained asphalt concrete will not only increase the pace of construction and repair, but also the durability and quality of the road pavement. However, this method requires operational and economic optimization. Using fiber from the fly ash of thermal power plants is one of the solutions for the design of cast asphalt concrete compositions. The aim of the work is to design the optimal composition of hot cast asphalt concrete and cold cast emulsion–mineral mixtures with the use of fiber from the fly ash of thermal power plants for the construction of thin-layer coatings of highways of all categories and values; to study their properties; and to determine the feasibility of their use as reinforcing and stabilizing additives. The method of GOST 11506, namely, "Method for determining the softening temperature of the ring and ball", with the apparatus "Lintel KiSh-20m-4" was used during the experiments. The use of standard laboratory tests made it possible to analyze the quality indicators of the materials under study and design the optimal compositions of hot cast asphalt concrete, taking into account the delamination of the mixture and the criterion of decomposition, in addition to exploring the properties of the obtained material.

Keywords: *product of coal combustion, properties of asphalt concrete, finely dispersed material, modifying additives, cast asphalt concrete mixture*

## 1. Introduction

Currently, cast asphalt concrete is widely used as an effective material. Cast asphalt is a type of hot asphalt concrete mixture with all its intergranular pores being filled with an asphalt binder. After the mass is laid and compacted, there are practically no residual pores and voids in the monolith; therefore, coatings made of cast asphalt are waterproof [1]. However, urban highways do not withstand today's traffic intensity, heavy traffic, and those alternating loads arising from frequent stops and acceleration of transport when a car is moving in the "urban cycle" mode. As a result, asphalt concrete pavements made from traditional rolling mixes cannot withstand even 3 years of operation [2].

Moreover, along with the sharply increased transport loads, the technogenic impact on the coatings has also intensified: the acid precipitations, the aggressive effects of salt and acid deicing systems, the effect of a polluted atmosphere, and so on [3]. Therefore, it is necessary to radically improve the quality of road pavements and provide an increased density of the pavement, shear resistance, crack resistance, wear resistance, and roughness. Most regions need denser pavements, especially those made of modified asphalt concrete mixtures, which are able to withstand wear, corrosion, and cracking for a long time. One of the modern technologies that allow protection of the upper layers of pavement structures, quickly restoring their transport and operational properties, is the device of thin-layer coatings of hot cast asphalt concrete or cast emulsion–mineral mixtures [4].

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The main task of the thin-layer coatings made from these materials is to extend the service life of existing coatings by sealing cracks and small potholes. The application of the thin-layer coatings also leads to a significant increase in roughness and adhesion properties, as well as evenness of the coating. Apart from that, it prevents cracking and protects the existing coatings from water saturation.

It is important to consider the experience of different countries in solving the problem. An interesting study was conducted by American scholars, jointly with the California Department of Transportation (Caltrans). A 35-year implementation period from 1983 to 2017 was analyzed, including 37 processing strategies, out of which 17 were for asphalt and 20 were for Portland cement coatings (hereinafter, PCC). The top 10 strategies for road surface repair, geographical and temporal variations of repair volumes, as well as operating costs and the state of the road network were identified. Moreover, 10 options were considered for the renovation of the road surface, including recycling, replacement of road slabs, patching, and so on. This large-scale study showed that the replacement of the top strip of the classical asphalt concrete is the easiest to execute. However, every year about 19% of the total asphalt concrete surfaces had to be repaired (in fact, there was a complete change of road surface made of asphalt concrete every 5–6 years), while the repair of the PCC road surfaces constituted about 12%, which indicates >35% savings in operating costs. At the same time, preventive measures on the PCC road surfaces were practically absent. As a rule, this is often associated with the complete replacement of the road coatings and with spot repair in rarer cases. Therefore, the development of new repairable pavements is a very topical trend, especially regarding coatings with strength characteristics that are not inferior to cement-block plates [5].

The operation of the roadway gradually began to move away from patching of pavement defects to an industrial and cost-effective one, namely, preventive protection of the upper layers of pavements. The content of preventive work is reduced to restoring the waterproof nature of the upper layer by continuous distribution of a homogeneous liquid mixture, which consists of binder, fine gravel, cement, and chemical additives, over the surface, while improving the adhesion properties of coatings [6]. Besides, the need to reduce both the consumption rate of binders and the cost of operation is caused by the use of binder in the form of emulsions. As a result, the rate of binder consumption compared to hot asphalt concrete was reduced by 8–10 times, while it decreased by 35%–40% compared to surface treatments on hot bitumen, increasing the transport and operational qualities of the coatings [7].

It is necessary to mention that in the mid-70s of the 20th century, the technology reached a qualitatively new level in terms of the construction of thin coatings from cold cast asphalt concrete using a modified emulsion, termed microsurfacing. This technology was developed by the German company "Rashik" based on an emulsion that was manufactured since 1967 under a French patent. The firm "Kraus" (Robdorf, Germany), for the first time, laid cold asphalt concrete in a thin layer on the pavement surface. Owing to the polymer additives that were used in its composition, the physical, mechanical, and operational properties of the layer material were significantly increased.

Thus, slurry force mixtures became one of the first materials that made it possible to create protective pavement layers in one operation and open traffic within a short period of time [8]. These mixtures became more widespread in developed countries. For example, in Germany, these mixtures became known as Schlämmen, microsurfacing, and in France - cold cast asphalt concrete. In the USSR, SoyuzdorNII developed similar mixtures, based on anionic emulsions called cast emulsion mineral mixtures (hereinafter – CEMM). However, work on the creation of the material and the technical and technological bases for the construction of thin-layer coatings from cast emulsion–mineral mixtures was stopped due to the lack of emulsion with the desired stable properties. As a result, the accumulated production experience was lost [9].

On the other hand, since the 90s of the past century, this technology has been increasingly spreading in Ukraine. However, its spread was not enough due to the fact that the stage of designing the mixture composition has not been sufficiently studied. The main problems of road construction are as follows: the use of mixtures of materials as a decomposition regulator, which reduces the rate of gaining of cohesive strength of the laid cast mixture; the intensive formation and hardening of thin-layer coatings; and the timely opening of traffic.

Studies also considered the influence of pigments, as well as the optical and thermal properties of road surfaces, on the road surface's durability. Thus, the brightness of the color was found to be the dominant reflection factor for visible light, but it did not influence the reflectivity factor in the near-infrared region [10]. Chrome-doped coatings achieved a reflection ratio of about 60%, while the reflectivity in the near-infrared region was as high as the white coating. About 95% of the ratio between the light and visible reflectivity was linear for dark- and medium-colored coatings, while exponential growth was shown for light-colored coatings. Accordingly, road mixtures with more light reflectivity are less likely to be affected by heat and, consequently, to be destroyed and slacked. At the same time, they should have no antireflection properties for the safety of the road. Consequently, antireflection properties can provide a multifunctional composition of road material, and this factor also needs to be taken into account when developing such materials [11].

Therefore, it is especially important to ensure the optimal composition for both hot cast asphalt concrete and cold emulsion–mineral mixtures. The aim of the research is to design the composition and study the properties of hot cast asphalt concrete and cold emulsion–mineral mixture with the use of fiber from the fly ash of thermal power plants for the installation of thin-layer coatings on highways of all categories and values. To achieve this goal, it is necessary to solve the following tasks:

- Analyze the research issues of cast hot and cold asphalt concrete (cast emulsion–mineral mixtures);
- Determine the indicators of quality of raw materials for hot cast asphalt concrete and cast emulsion–mineral mixtures;
- Design the optimal compositions of hot cast asphalt concrete, taking into account the stratification of the mixture and the technological decay criterion;
- Identify the time of formation of the wear layer and the indicator of wear of the coating under wet conditions when used for these types of cast mixtures;
- Determine the feasibility of using fiber from the fly ash of thermal power plants as a reinforcing and stabilizing additive for hot cast asphalt concrete and cast emulsion–mineral mixtures.

The work uses standard research methods and techniques in accordance with Ukrainian regulatory documents [12]. The topicality of this work is the need to improve the quality of asphalt concrete mixtures and develop effective asphalt concrete pavements that would correspond to operating conditions in a variety of environments, overcome the negative influence of numerous factors, and ensure the reliability and durability of highways.

The novelty of the research consists in calculating the optimal amount of fiber from the fly ash of thermal power plants in cast hot and cold asphalt concrete mixtures. It is presumed that when mixed with bitumen at an operating temperature range of 180°C–190°C, fiber has a positive effect on the bitumen structure. Apart from that, the recipes for bitumen emulsions for cast emulsion–mineral mixture technology will be developed.

## 2. Materials and methods

The use of cast emulsion–mineral mixtures is a highly efficient and complex technology for the repair and restoration of road surface s, which necessitates specific requirements for the cast emulsion–mineral mixtures. There are two main problems of using this technology. The first problem is the use of mineral materials with high total surface activity (reactivity), which exceeds the permissible value [13]. The other one is the use of bitumen emulsions on bitumen, which do not provide the required rate of gain of the cohesive strength of the laid cast mixture. This bitumen includes highly paraffinic oxidized petroleum bitumen with low acid quantity. These two main problems and the dependence of cast emulsion–mineral mixtures on ambient temperature and humidity limit the use of this technology.

Domestic and foreign researchers have come to the unanimous opinion that distilled bitumen with high acid quantity, which is made from heavy, highly resinous, low paraffinic oil with a naphthenic–aromatic base, is the most suitable for bitumen-emulsion technologies, namely, for cast emulsion–mineral mixtures [14]. The analysis of heavy oil reserves showed that most of the world's reserves are concentrated in Canada, Venezuela, and Turkey. Heavy oils include those that have a density of more than 0.88 g/cm$^3$. This value of oil density was determined and agreed upon on the basis of the classifications and information from databases. This value also corresponds to the border beyond which difficulties occur in the production, transportation, and processing of oil, which leads to an increase in its cost. In general, heavy oils are divided into three classes in terms of density: oil with increased density (0.88–0.92 g/cm$^3$), very heavy oil (0.92–0.96 g/cm$^3$), and bituminous oil ($>$0.96 g/cm$^3$) [15]. Highly resinous oils are considered to be oils with a resin content of $>$13%. The high resin content in oil also leads to technological complications during its production, transportation, and refining. In addition, the high resin content also contributes to the formation of coke during the refining process, which leads to coking of the surface of the catalysts, causing high economic costs [16].

Thus, it can be seen that the production of heavy, highly resinous oils requires significant capital investments. The use of ready-made distilled bitumen can be a solution. The bitumen of Nynas Company has proven itself well in the Ukrainian market, meeting international quality and environmental safety standards. Moreover, this bitumen is certified for use in the territory of Ukraine and is recommended by the State Service of Highways of Ukraine "Ukravtodor" for use in bitumen-emulsion technologies [17]. The bitumen production is carried out by fractional distillation, passing it through a distillation column and a vacuum distillation column under atmospheric pressure. The special design of the vacuum distillation column makes it possible to isolate the necessary fractions in the absence of a low temperature and with a shorter residence time in the column (the "aging" of bitumen is reduced). At the same time, the disadvantage of using such bitumen is its cost [18].

Accordingly, the bitumen based on heavy, highly resinous oils is optimal for cast emulsion–mineral mixture technology, but they are scarce and expensive. To obtain hot cast asphalt concrete using fiber from the fly ash of thermal power plants, the following components were used:

1. Crushed stone from dense rocks (gabbro-igneous intrusive rock): 5–20 mm fraction;
2. Sand from granite crushing screenings according to the requirements of DSTU B V.2.7-30 (State Standards of Ukraine);
3. Limestone mineral powder MP-1;
4. Viscous oil road bitumen BND 90/130 (oil road viscous bitumen); and
5. Fiber from the fly ash of thermal power plants.

The proportional ratio varied depending on the cycles of the experiment [12]. It should also be taken into account that the modern equipment with which the research was carried out passed certification and verification. Standard laboratory tests were used in the work, which confirms the reliability of the results.

The quality of road bitumen is one of the most important factors that determine the service life of roads. The performance of a bitumen binder in asphalt concrete under periodic exposure to shear stresses, compression, and drops in temperature largely depends on the plasticity of the road bitumen. This has led to the need of marking road bitumen by penetration (the depth of penetration of the needle). Thus, the determination of penetration at 25°C ($P_{25}$) and 0°C ($P_0$) was carried out according to GOST 11501-78 on an automatic penetrometer "Lintel PN-10B" (Figure 1). The results of determination of the hardness of the original bitumen are presented in Table 1.

Table 1. Data on the hardness of the original bitumen

| Needle penetration depth, 0.1 mm | Test method | Norm for DSTU 4044 | Actual value |
|---|---|---|---|
| At 25°C | GOST 11501 | 91–130mm | 108mm |
| At 0°C | | Not <28mm | 33mm |

Table 2. Data on the elasticity of original bitumen

| Extensibility of bitumen, cm | Test method | Standard according to DSTU 4044 | Actual value |
|---|---|---|---|
| At 25°C | GOST 11501 | 6.5 | 88 |
| At 0°C | | 4.0 | 5.6 |

Fig. 1. Penetrometer “Lintel PN-10B”


Fig. 2. Apparatus Lintel KiSh-20m-4


Fig. 3. Ductilometer DB-2M

Another test for assessing the deformative properties of bitumen consists of determining the temperature of its softening. It should be noted that due to the multicomponent nature of bitumen, the notion of softening temperature is conditional since bitumen does not have a strictly defined softening point. However, similar to all amorphous bodies, it has a certain softening interval. The determination of the softening temperature was carried out according to the method of GOST 11506 “Method for determining the softening temperature of the ring and ball” on the apparatus “Lintel KiSh-20m-4” (Figure 2). According to these tests, it was found that this indicator corresponds to a temperature of 44°C.

Furthermore, the determination of the extensibility of bitumen BND 90/130 was carried out in accordance with GOST 11505-75 on a laboratory semiautomatic ductilometer DB-2M (Figure 3). The obtained data on the tensile values at 0°C and 25°C are presented in Table 2.

Moreover, it is worth noticing that since elastic deformations play the major role at low temperatures, considerable attention should also be paid to the study of the deformative properties and strength of bitumen precisely at low temperatures. Consequently, the determination of the brittleness temperature is of great practical importance since it gives a definite idea of the lower temperature limit at which the use of this bitumen is permissible. During the experiments, the determination of the brittleness temperature of bitumen BND 90/130

Table 3. Basic indicators of bitumen BND 90/130

| No. | Indicator name | Norm of DSTU 4044 | Actual value |
|---|---|---|---|
| 1 | Flash point, °C, not lower | 230 | 265 |
| 2 | Change in softening temperature after heating, °C, no more | 5 | 5 |
| 3 | Penetration index | From +1 to −1 | −0.8 |
| 4 | Bonding bitumen to marble or sand | Pass the test against the control sample | Withstands the marble test |

Table 4. Composition of crushed stone according to the requirements of DSTU B V.2.7-119

| Indicators | Sieve openings, mm | | | | | |
|---|---|---|---|---|---|---|
| | 25 | 20 | 12.5 | 10 | 5 | 2.5 |
| Private balances | 0 | 0.76 | 54.04 | 6.4 | 36.6 | 1.9 |
| Full balances | 0 | 0.76 | 54.8 | 61.2 | 97.8 | 99.7 |
| Full passes | 0 | 99.24 | 45.2 | 38.8 | 2.2 | 0.7 |
| DSTU requirements | Up to 0.5 | Up to 10 | 30–60 | – | 90–100 | 95–100 |

Table 5. Basic properties of crushed stone of 5–20 mm fraction

| No. | The name of indicators | DSTU B V.2.7-30 requirements | Actual indicator |
|---|---|---|---|
| 1 | Crushed stone moisture, % | Not normalized | 0.15 |
| 2 | Bulk density at natural humidity, t/m$^3$ | Not normalized | 1.47 |
| 3 | Content of flaky and needle-shaped grains, % | From 15 to 25, III group | 22.01 |
| 4 | Content of dust and clay particles, % by weight | Not >1 | 0.37 |
| 5 | Clay content in lumps, % by weight | Not >0.25 | 0 |
| 6 | Crushed stone crushing (grade), % by weight | To 12, including Grade 1400 | 3.9 |
| 7 | Crushed stone abrasion grade, % | To 25, including Grade I1 | 7.4 (I1) |
| 8 | Grain content of weak rocks, % by weight | Not >5 | 2.4 |
| 9 | Crushed stone frost resistance, cycles, weight loss in % | 15, not >2 (F300) | 1.7 (F300) |
| 10 | Specific effective activity of natural radionuclides, Bq/kg | Not >370 | 15.8 |
| 11 | Stability of the structure against decay (loss of mass), % | 0.65–0.9 | |

was carried out in accordance with GOST 11507, along with the addition of Paragraph 3.2 of GOST 22245 on use of the apparatus for determining the brittleness temperature of petroleum bitumen ATX-20 (Figure 4).

According to these tests, it was found that this indicator corresponds to −17°C. The remaining bitumen indicators, determined in accordance with the requirements of GOST 22245-90, are presented in Table 3.

Based on the results obtained, it should be concluded that oil road bitumen BND 90/130 meets the regulatory requirements. Therefore, it is suitable for the preparation of asphalt concrete mixtures.

Fig. 4. Apparatus for determining the brittleness temperature of petroleum bitumen ATX-20

Table 6. Grain size of sand

| Sieve size, mm | Actual results | | |
|---|---|---|---|
| | Private balances, % | Total balances, % | Full passes, % |
| 2.5 | 33.65 | 33.65 | 66.35 |
| 1.25 | 21.664 | 55.29 | 44.71 |
| 0.63 | 18.63 | 73.29 | 26.08 |
| 0.315 | 11.52 | 85.44 | 14.56 |
| 0.16 | 9.29 | 94.73 | 5.27 |
| 0.071 | 3.12 | 97.85 | 2.15 |
| <0.071 | 2.15 | 100 | 0 |

Table 7. Physical and mechanical properties of sand

| No. | Name of indicators | DSTU B V.2.7-30 requirements | Actual indicator |
|---|---|---|---|
| 1 | Bulk density, kg/m$^3$ | – | 1,510 |
| 2 | True density, kg/m$^3$ | – | |
| 3 | Content of dust and clay particles, % | Not >10.0 | 1.46 |
| 4 | Size module | 3.0–3.5mm | 3.34mm |
| 5 | Sand group | – | Increased size |
| 6 | Clay content in lumps, % | Not >2.0 | Does not have clay |
| 7 | Content of grains with size >10 mm, % | Not >5 | 0 |
| 8 | Content of grains with size >5 mm, % | Not >15 | 0 |
| 9 | Content of grains with size >0.63 mm, % | 65–75 | 73.92 |
| 10 | Content of grains with size >0.16 mm, % | Not >10 | 5.27 |
| 11 | Total specific effective activity of natural radionuclides, Bq/kg | Not >370 | 296.6 |

Table 8. Basic properties of mineral powder

| No. | Indicator name | Factual data |
|---|---|---|
| 1 | Grain composition, % sieve 1.25 mm | 100 |
| 2 | Grain composition, % sieve 0.315 mm | 98.8 |
| 3 | Grain composition, % sieve | 74.3 |
| 4 | Swelling by volume, % | 2.40 |
| 5 | Porosity by volume, % | 29.9 |
| 6 | Humidity, % | 0.45 |
| 7 | Specific gravity, g/cm$^3$ | 2.83 |
| 8 | Content of sesquioxides (Al+Fe), % | 1.17 |
| 9 | Water-soluble fraction, % | 2.41 |
| 10 | Active CaO + MgO, % | 2.08 |
| 11 | Loss on ignition, % | 17 |
| 12 | Total specific efficiency of natural radionuclides, Bq/kg | 1,348 |

The main properties of crushed stone for the production of modified asphalt concrete were determined according to DSTU B V.2.7-119 [19]. The data on the grain size composition and the main properties (physical and mechanical) of crushed stone are given in Tables 4 and 5, respectively.

Apart from these, crushed stone from dense rocks (gabbro-igneous intrusive rock; fraction 5–20 mm) meets the requirements of GOST 8267-93 and GOST 9128-2009. Therefore, crushed stone is suitable for the preparation of asphalt concrete mixtures. The data on the grain size of sand and its

Table 9. Fly ash fiber characteristics

| **Name of indicators** | **Physical and mechanical properties** |
|---|---|
| | **Fly ash fiber** |
| Average fiber diameter, µm | 160.0 |
| The amount of nonfibrous additives, % | 2–3 |
| Density, g/cm$^3$ | 2.65 |
| Temperature range of use, °C | −269 to +700 |
| Water resistance, % | 99.6 |
| Chemical resistance, % | 93.4 |
| 0.5H NaOH | 77.3 |
| 2H NaOH | 98.5 |
| 2H $H_2SO_4$ | to 1.0 |
| Hygroscopicity, % | 4,100 |
| Mechanical strength, MPa | 120 |
| Elastic modulus, MPa | 3.1 |

Table 10. Types of CEMM by grain size

| **Sieve diameter, mm** | **Full pass through the sieve, % by weight, for mixtures of the type** | | |
|---|---|---|---|
| | **Type 1** | **Type 2** | **Type 3** |
| 15 | 100 | 100 | 100 |
| 10 | 100 | 100 | 80–94 |
| 5 | 100 | 91–100 | 71–90 |
| 2.5 | 90–100 | 65–90 | 45–70 |
| 1.25 | 67–91 | 46–71 | 29–51 |
| 0.63 | 41–66 | 31–51 | 20–35 |
| 0.315 | 24–41 | 17–29 | 12–24 |
| 0.14 | 14–28 | 9–20 | 7–18 |
| 0.071 | 10–20 | 5–15 | 5–15 |

main physical and mechanical properties are shown in Tables 6 and 7, respectively.

In addition, sand from the screening of crushed stone of Class II meets the requirements of DSTU B V.2.7-30. Therefore, the sand is suitable for the preparation of an asphalt concrete mixture. The main properties of the MP-1 mineral powder are determined according to DSTU B V.2.7-121 and are presented in Table 8.

Moreover, the mineral powder of M-1 grade meets the requirements of DSTU B V.2.7-121 [15]. It can be concluded that all raw mineral materials meet the requirements of regulatory documents and are suitable for preparing an asphalt concrete mixture. The physical and mechanical properties of fiber from the fly ash of thermal power plants are shown in Table 9.

Accordingly, for the preparation of the mixtures, medium- and slow-decaying cationic bitumen emulsions (not modified and modified) of the EKM-60, EKM-65, EKS-65, EKMM-60, EKMM-65, and EKSM-65 brands are used according to DSTU B V.2.7-129: 2013 “Bitumen road emulsions. Technical conditions” [12]. The mass fraction of bitumen with an emulsifier should be 60%–65%. Moreover, for the preparation of cationic bitumen emulsions, it is necessary to use bitumen in accordance with DSTU 4044. The grain size of the stone must also meet the requirements given in Table 10. If the specified limits are exceeded, the stone material is considered unsuitable for use in these mixtures.

To control the decay time of the bitumen emulsion and the plasticity of the mixture, cement is

Table 11. Grain composition of mineral filler

| **Mix component name** | **Content by weight, in %, of mineral grains smaller than a given size, mm** | | |
|---|---|---|---|
| | **0.315** | **0.140** | **0.071** |
| Mineral filler | 90–100 | 75–100 | 67–100 |

used according to DSTU B V.2.7-46 [15]. The use of finely dispersed mineral fillers such as ground limestone, dolomite, basalt, and fly ash, simultaneously with cement or instead of it, according to DSTU B V.2.7-121 is allowed. By carefully choosing the combination of emulsifiers and decomposition regulators, it is possible to control the increase or decrease in the rate of mixture setting. Besides, the grain size composition of the filler should be within the limits given in Table 11.


Fig. 5. Aluminum sulfate: sample A – first grade; sample B – top grade

During the experiments, aluminum sulfate (Figure 5), or rather its 50% aqueous solution, was proposed as an unconventional decomposition regulator or a regulating additive. Aluminum sulfate is a white salt with a blue, gray, or pink tint, in crystalline hydrated form $Al_2(SO_4)_3 \cdot 18H_2O$, that is, it is in the form of colorless crystals, under natural conditions. It loses water if heated and does not melt; if fried, it decomposes into $Al_2O_3$ and $SO_3$. This additive has good water solubility. Technically, aluminum sulfate is obtained by treating clay or bauxite with sulfuric acid. However, the product is cleaner if $Al(OH)_3$ is dissolved in hot concentrated $H_2SO_4$. Furthermore, aluminum sulfate is easily combustible and very hygroscopic – it absorbs water from the environment and retains it in the middle. A 10% aqueous solution of the emulsifier Redicote E-11 (Akzo Nobel, Sweden) was used as a traditional additive for cast emulsion–mineral mixtures.

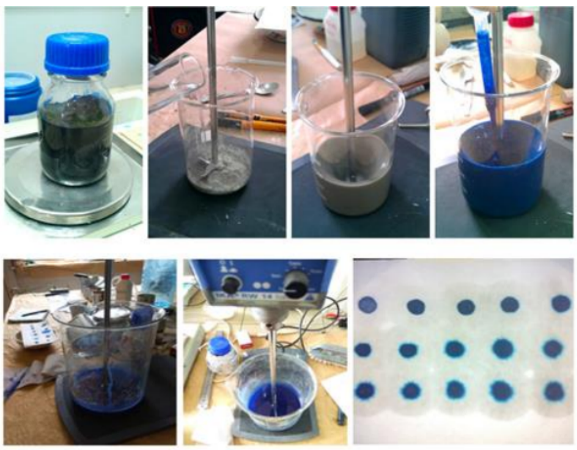

Fig. 6. Test procedure for determining adsorption of methylene blue

To prepare mixtures, it is necessary to use drinking water in accordance with GOST 2874 or industrial water in accordance with GOST 6709 or GOST 23732 without mechanical impurities and with an average hardness not exceeding 6 mg-eq/L. Cast emulsion–mineral mixtures were tested according to international standards (International Slurry Surfacing Association [ISSA] A105, ISSA A143) and domestic ones (Standard Of Organization of Ukraine SOU 42.1-37641918-119: 2014) [19].

In order to develop the recipes for bitumen emulsions, the experiments were carried out taking into account the following indicators: the appearance of the emulsion; the concentration of water ions (pH); the homogeneity of the emulsion; the amount of bitumen content with an emulsifier;


Fig. 7. Components in cast emulsion–mineral mixtures

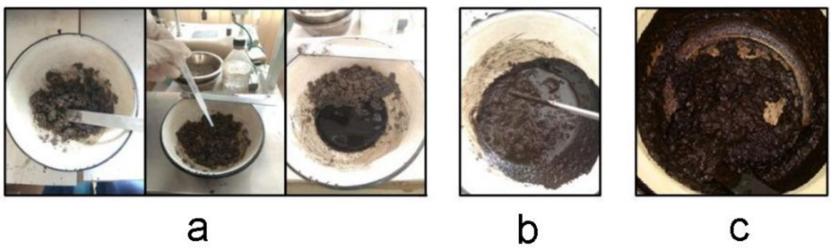


Fig. 8. Determination of CEMM decay

the conditional viscosity; and the adhesion of the binder to the crushed stone surface. This method consists in measuring the ability of the filler to adsorb methylene blue (MB). Since it is adsorbed mainly by clay, organic components, layered silicates, and iron hydroxide, this test provides an indication of the total surface activity of all these components. Figure 6 shows the procedure for performing tests on MB.

It was established that high values of MB and, accordingly, a high surface activity cause an accelerated reaction of the filler with bitumen emulsions and additives, which can lead to premature decomposition or poor adhesion. Therefore, the indicator MB should be in the range of 5–10 mL.

Furthermore, tests to determine the disintegration time of the mixture were carried out in accordance with DSTU B V.2.7-129 [12]. The disintegration of CEMM is a process that occurs from the time of mixing all the mixture components up to the moment in time when it loses its mobility and makes further mixing impossible. The disintegration criterion also determines the time during which the mixture can be made and applied to the thin-layer coating. Thus, according to the decay criterion, the optimal composition of cast emulsion–mineral mixtures can consist of stone material, mineral filler, fiber from the fly ash of thermal power plants produced in China, water, additives, and bitumen emulsion. Such a composition ensures the disintegration of the mixture in no faster than 120 or 180 s, depending on the type of mixture (Figure 7).

The general method for establishing the disintegration of cast emulsion–mineral mixtures is as follows (Figure 8): (a) mixing mineral components, water, regulating additives, and emulsions in an enamel pot (Figure 8A); (b) manual mixing of the resulting mixture with a spatula in an inclined container to assess the mobility of the mixture during the mixing time (Figure 8B); (c) fixing the time of disintegration of the mixture, that is, the time from mixing all the mixture components to the moment when it loses its mobility and the possibility of further mixing (Figure 8C).

Cohesive strength is the strength of the internal structural bonds of a material. Thus, the formation rate of the cast emulsion—mineral mixtures wear layer is determined by testing the established samples after certain periods of time on a modified cohesive device (Figure 9).


Fig. 9. Modified cohesive device: 1 - air cylinder; 2 - cylinder rod; 3 - rubber tip; 4 - a plate of roofing felt(s); 5 - pressure gauge for measuring the pressure in the cylinder; 6 - air pressure regulator; 7 - torque wrench; 8 - regulator for lowering the cylinder rod

The tested samples from the cast emulsion–mineral mixtures are classified according to the nature of destruction and the corresponding values of the torque as follows (Figure 10):

1. “N”– Normal (standard) – characterized by almost complete destruction of the sample with the presence of radial cracks. Equivalent torque is 12–13 kg*cm.
2. “NS”– Normal spin – characterized by the presence of only one radial fracture crack. Equivalent torque is 20–21 kg*cm.
3. “S”– Spin (twisting) – characterized by the absence of cracks, but with chipping of grains of stone material or displacement in a circle. The equivalent torque value is 23 kg*cm.
4. “SS”– Solid spin – characterized by the absence of cracks. The sample is not cracked; the displacement or removal of bitumen particles is possible. The equivalent torque value is 26 kg*cm.

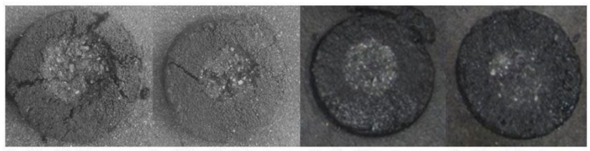


Fig. 10. Destruction of cast emulsion–mineral mixture specimens by type. N, normal; NS, normal spin; S, spin; SS, solid spin

Therefore, according to this classification, the formation stage of the cast emulsion–mineral mixture structure and the possibility of opening the traffic along the arranged road surface were determined (Table 12).

Moreover, the method of determining material loss due to abrasive wear under wet conditions consists in determining the loss of mass of a material impregnated with water from a mixture during mechanical abrasion with a rubber surface for 5 min. This is a test based on wet wear conditions, which are calculated using the following formula:

$$B = (m_0 - m_1) \cdot k \tag{1}$$

where $B$ is the weight loss of the material during wet abrasion, in grams;
$m_0$, $m_1$ – the masses of the sample before and after wear, respectively;

Table 12. Determination of the road surface formation stages from cast emulsion–mineral mixtures

| **Strength characteristics** | | **Stages of forming road surfaces from cast emulsion-mineral mixtures** |
|---|---|---|
| **The nature of the destruction** | **Torque value, kg*cm** | |
| "N" – Normal | 12–13 | Grasping |
| "NS" – Normal spin | 20–21 | Self-sealing (opening movement with a speed limit of up to 40 km/hr) |
| "S" – Spin | 23 | Sealing |
| "SS" – Solid spin | 26 | Hardening (opening movement without speed limit)† |

†After this stage, gaining of cohesive strength begins

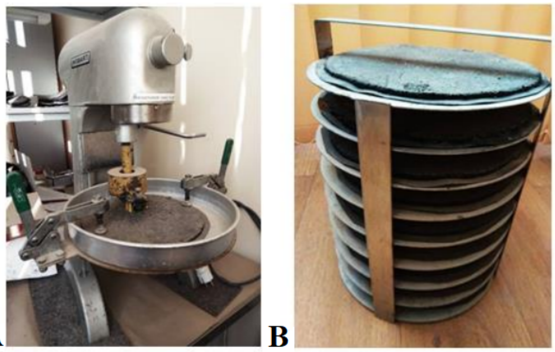


Fig. 11. A - planetary mixer "Hobar C-100"; B - finished samples

$k$ – a conversion factor, which depends on the brand of the mixer and varies in the range from 29 to 35.

In parallel, during the study of bitumen and bitumen-based emulsions, the suitability of stone material for cast emulsion–mineral mixtures was determined by the criterion of total surface activity. Accordingly, the calculated particle size distributions were selected for each of the types of mixtures. According to the criterion of disintegration, the mixture composition contains Portland cement, water, and an additive. Then, cast emulsion–mineral mixtures were analyzed according to the criterion of gaining rate of cohesive strength, which permitted the determination of the optimal compositions of the mixtures, using indicators of the beginning of the gain of the mixture cohesive strength, the mixture formation, the destruction types, the formation stages, and the mixture class. After that, the loss in weight of the coating during wet abrasion and the economic efficiency of the optimal cast emulsion–mineral mixture compositions were determined by the criterion of gain rate of cohesive strength (Figure 11).

## 3. Results

Recent studies have shown that it is necessary to use modified bitumen to ensure durability, and especially shear stability (strength during high summer temperatures), of hot cast asphalt concrete. Generally, bitumen is modified using polymers such as rubber and resin. Modified bitumen is characterized by a number of positive characteristics (wider plastic range, low brittle temperature, and elasticity) [20]. However, the hot cast asphalt concrete requires fairly large amount of bitumen (12%) for its structuring, that is, the introduction of additives that would reinforce bitumen. This will ensure adsorption of bitumen molecules into the solid surface of the grains of both the additive and the mineral material [21].

It is known that adsorbed molecules undergo conformational change, which leads to a change in their mobility. Thus, the higher the adsorption energy, the shorter is the length of free bonds in the bitumen and the greater is the proportion of bound segments. Therefore, it can be assumed that large particles of mineral grains (10 mm) in an asphalt concrete mixture will have stronger adhesion and retain a certain flexibility. This effect will be even more noticeable on small particles (<3 mm) [22].

Previous studies have also established that when adding fiber from the fly ash of thermal power plants to the composition of the bitumen binder, there is a chemical interaction of active par-

Table 13. Structural type according to the HCS criterion

| No. | Bitumen brand | Manufacturer | Production technology | Group chemical composition, wt.% Asphaltenes (A) | Resins (C) | Oils (olives) (M) | Ratio, *100% A/A+C | A/C+M | *C*-th type according to HCS |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Nynas 100/150 | Nynas | Distillation | 12.1 | 29.5 | 58.4 | 29.1 | 13.8 | 2 |
| 2 | Nybit E85 | Nynas | Distillation | 15.9 | 38.1 | 46.0 | 29.4 | 19.8 | 2 |
| 3 | BND 60/90 | Ukrtatnafta | Oxidation | 25.3 | 24.7 | 50.0 | 50.6 | 33.9 | 3 |
| 4 | BND 60/90 with ICR | Ukrnafta | Oxidation | 22.0 | 36.0 | 42.0 | 37.9 | 28.2 | 3 |

ICR, indene–coumarone resin

Table 14. Physical and mechanical properties of bitumen

| No. | Bitumen brand | Name and meaning of indicators $T_{\text{times}}$, °C | $P_{25}$, 0.1 mm | $L_{25}$, cm | $T_{\text{xp}}$, °C | IP, °C | IR | Paraffin contents, wt.% | Glass adhesion |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Nynas 100/150 | 43 | 107 | >100 | −15 | 58 | −1.25 | 0.5 | 20 |
| 2 | Nybit E85 | 47 | 80 | >100 | −11 | 58 | −0.8 | 0.5 | 24 |
| 3 | BND 60/90 | 49 | 72 | 84 | −18 | 67 | 0.6 | 5.4 | 32 |
| 4 | BND 60/90 with IKS | 52 | 62 | 26 | −16 | 68 | −0.21 | 4.0 | 93 |

ticles of fly ash, asphaltenes, and bitumen resins, which ensure the adhesion of bitumen to the grains of the mineral material [23]. It should be taken into account that due to the direct impact of weather, climatic factors, and traffic loads, the working conditions of road surfaces impose corresponding requirements on the structure of asphalt concrete. It must provide shear stability at elevated temperatures, deformability and crack resistance at low temperatures, water resistance, frost resistance, and other performance properties.

Bitumen structured with fiber from the fly ash of thermal power plants, which is a microfiller in asphalt binder, is a composite material with strong bonds. It can provide operational properties to the cast asphalt concrete pavement [24]. In Ukraine, the most common bitumen is oxidized, but distilled ones were also taken for research. This choice is attributed to technologists' opinion that this bitumen is optimal for cast emulsion–mineral mixtures. Recently, doubts have arisen about the correctness of the primary technological method for producing bitumen by oxidizing petroleum feedstock. At the same time, the expediency of manufacturing and using distilled bitumen, obtained by vacuum distillation of heavy feedstock, seems to be quite rational [20]. However, during the manufacture of these mixtures, weather and climatic conditions, the characteristics of the feedstock (light and heavy oils), and the system for assessing the quality of bitumen were not always taken into account [25].

So, experiments were carried out on three oxidized bitumens, such as BND 60/90 produced by PJSC Transnational Financial and Industrial Oil Company Ukrtatnafta (hereinafter - BND 60/90 "Ukrtatnafta"), BND 60/90 manufactured by PJSC Mozirsky Oil Refinery (hereinafter - BND 60/90 "Mozirsky Oil Refinery"), and BND 60/90 "Ukrtatnafta", modified using BND 60/90, and on two distillation bitumens made from heavy oil, such as Nynas 100/150 and Nybit e85 from Nynas (Sweden).

The structural type according to the HCS criterion of bitumen, the content of solid paraffin, and acid quantity were determined at the State Enterprise Scientific Research Institute of Oil Refining and Petrochemical Industry "MASMA" and at the Department of Chemical Technology of Oil and Gas Processing of the National University "Lviv Polytechnic". The group chemical composition of the studied bitumen is given in Table 13.

Analyzing Table 13, it can be seen that in terms of the content of asphaltenes and the ratio A/A + C, A/C + M, the Nynas 100/150 and Nybit E85 bitumens refer to the second structural type (sol), while the Ukrtatnafta bitumen can be attributed to

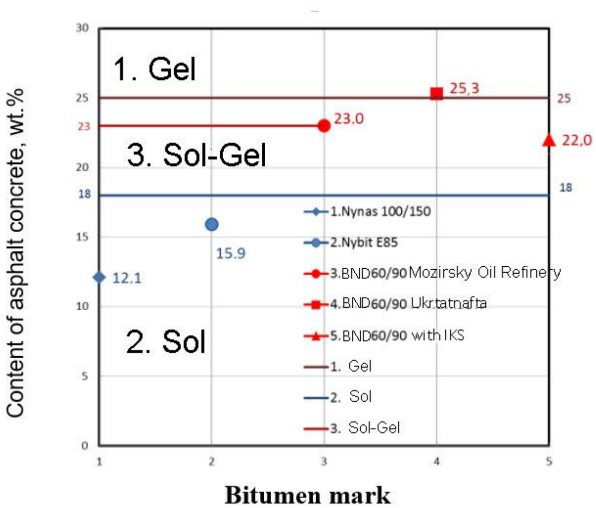


Fig. 12. Quantitative content of asphaltene depending on the bitumen brand

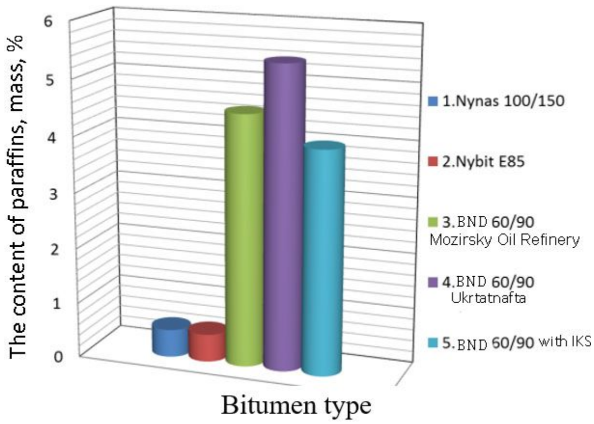


Fig. 13. The content of paraffin in bitumen of different types

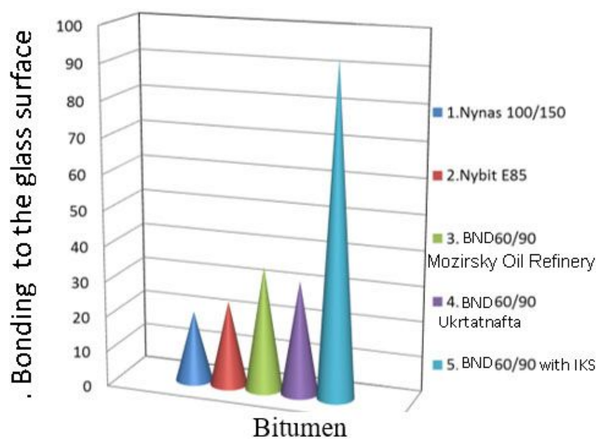


Fig. 14. Adhesion of different types of bitumen to the glass surface

the third type (sol–gel). This distribution into structural types can be explained by the differences in the use of crude oil and the technology used for obtaining this bitumen. Figure 12 shows the effect of the asphaltene on the structural type of the studied bitumen. With an increase in asphaltene, the structural type of bitumen changes in the following sequence: “sol” $\rightarrow$ “sol–gel” $\rightarrow$ “gel”.

The physical and mechanical properties of bitumen were determined in order to define their compliance with the current regulatory requirements and to distinguish the structural type of bitumen by the design criteria. Certain physical and mechanical characteristics of bitumen are given in Table 14.

It can be observed that the investigated distilled bitumen corresponds to grades BND 90/130 and BND 60/90 according to SOU 45.2-00018112-069:2011, while oxidized bitumen corresponds to grade BND 60/90 according to DSTU 4044-2001. A high content of solid paraffinic carbohydrates (paraffin) is observed in oxidized bitumen, being in a lesser quantity in distilled bitumen. The amount of solid paraffin in bitumen is shown in Figure 13. The dependence of the adhesive properties of the bitumen on the amount of paraffin is shown in Figure 14.

Adding IKS and plasticizers to BND 60/90 “Ukrnafta” made it possible to reduce the paraffin content in this bitumen by 1.35 times (Figure 14) and increase the adhesion of bitumen to the glass surface by four times (Figure 15).

The values of the plasticity interval of bitumen are illustrated in Figure 15

The main difference between distilled bitumen made from heavy oil and oxidized bitumen is their acid quantity (Figure 16). The former is characterized by high acid quantity ($\approx$ 3.5 mg KOH/g), while the other one is characterized by low content of acid (0.5–0.6 mg KOH/g).

Having analyzed the data from Table 14, it can be concluded that bitumen of the second structural type (sol) and bitumen of the third structural type (sol–gel) have lower softening points, increased ductility at 25°C (>100 cm), while the content of

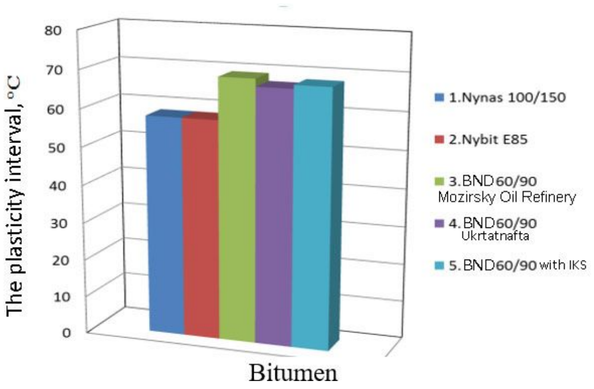


Fig. 15. The plasticity interval of different types of bitumen

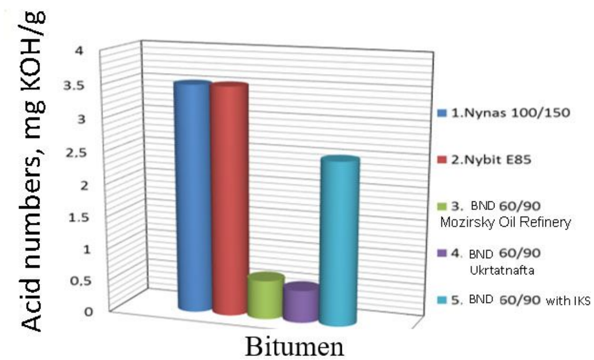


Fig. 16. Acid quantity in different types of bitumen

paraffin in their composition is insignificant. On the other hand, the transitional structural type of bitumen "sol–gel" has a wider range of plasticity due to a low brittleness temperature and a higher softening temperature. Moreover, the modification of BND 60/90 "Ukrtatnafta" and obtaining BND 60/90 from IKS led to a significant increase in the adhesion of bitumen to glass, an increase in the softening temperature of bitumen while maintaining penetration, which corresponds to the 60/90 grade, an increase in the acid amount of bitumen from 0.5 mg KOH/g to 2.5 mg KOH/g, a slight decrease in the brittleness temperature, and a significant decrease in ductility.

Structural types are determined according to the design criteria, which are based on physical and mechanical characteristics. However, they do not fully correlate with the actual structural type of bitumen using the HCS criterion. This makes it possible to conclude that these design criteria have a certain error. Thus, studies of the properties of different types of bitumen have shown that it is possible to use oxidized bitumen, being the most active and having the best adhesive properties. Therefore, for further research, oxidized bitumen grade BND 60/90 "Mozyr Oil Refinery" was used (Table 15).

It is crucial to note that the introduction of fiber increased the gaining rate of the cohesive strength of cast emulsion–mineral mixtures since the fiber chemically interacts with bitumen in the emulsion. The bonds of fly ash particles with the active groups of bitumen by asphaltene do not weaken, but are strengthened, in the presence of aluminum sulfate, which is added as an emulsifier to the emulsion for cold cast asphalt concrete (Table 16).

To determine the physical, mechanical, and hydrophysical characteristics of asphalt concrete mixed with fiber from the fly ash of thermal power plants, standard methods were used. The determination of the strength characteristics was carried out on an electromechanical press DTS 06-50-50 and a universal machine Instron 6637 (Figure 17).

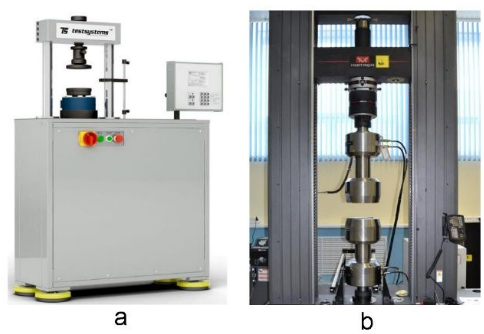


Fig. 17. Equipment for determining the strength and deformation characteristics of asphalt concrete: A – DTS 06-50-50 press; B – a universal machine Instron 6637 (USA)

The results of testing of the asphalt concrete samples of traditional composition and composition with the addition of fiber to bitumen are shown in Table 17. The research results showed that the reinforcement of bitumen by the fiber from the fly ash of thermal power plants causes a change in the properties of asphalt concrete.

Table 15. Structural types of bitumen according to the HCS criterion and design criteria

| No. | Bitumen brand | The structural type by criteria | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | HCS | Plastic interval | | Penetration index | | Indicator V.A. Zolotareva ($K_{sta}$) | |
| | | | PI, °C | *C*-type | PI | *C*-type | $K_{sta}$ | *C*-type |
| 1 | Nynas 100/150 | 2 | 58 | 3 | −1.25 | 2 | 0.07 | 2 |
| 2 | Nybit E85 | 2 | 58 | 3 | −0.8 | 3 | 0.07 | 2 |
| 3 | BND 60/90 | 3 | 69 | 3 | −0.7 | 3 | 0.083 | 3 |
| 4 | BND 60/90 with IKS | 3 | 67 | 3 | −0.6 | 3 | 0.096 | 3 |

Table 16. Calculated selection of the composition of the asphalt concrete mixture

| No. | Name of materials | Mixture composition (bitumen >100%) | The composition of the mixture (bitumen 100%) |
|---|---|---|---|
| 1 | Crushed granite fraction, 10–20 mm | 29.98 | 28.34 |
| 2 | Crushed granite fraction, 5–10 mm | 13.73 | 12.98 |
| 3 | Sand from crushing screenings | 48.29 | 45.64 |
| 4 | Nonactivated mineral powder MP-1 | 4.00 | 3.78 |
| 5 | Fiber from the fly ash of thermal power plants made in China | 4.00 | 11.14 |
| 6 | Bitumen BND 90/130 | 11.80 | – |

Table 17. Physical and mechanical properties of asphalt concrete

| Binder composition, compressive strength | Traditional composition | Composition with the addition of fiber, % | | | |
|---|---|---|---|---|---|
| | | 1.0 | 2.0 | 3.0 | 4.0 |
| At $t$=50°C, MPa | 1.62 | 1.24 | 1.47 | 1.58 | 1.55 |
| At $t$=20°C, MPa | 3.31 | 2.74 | 3.02 | 3.07 | 2.74 |
| At $t$=0°C, MPa | 8.12 | 7.26 | 7.66 | 9.21 | 9.84 |
| Coefficient of temperature sensitivity, $R_{50}/R_0$ | 0.20 | 0.17 | 0.19 | 0.17 | 0.16 |
| Coefficient of temperature sensitivity, $R_{50}/R_{20}$ | 0.49 | 0.45 | 0.48 | 0.51 | 0.57 |
| Water resistance after prolonged water saturation | 0.94 | 0.92 | 0.91 | 0.91 | 0.90 |

Thus, it can be observed that cast asphalt with fiber is less sensitive to temperature. The coefficient of temperature sensitivity is defined as the ratio of the compressive strengths of asphalt concrete at the temperatures of 50°C and at 0°C.

$$K = \frac{R_{50}}{R_0} \tag{2}$$

Therefore, with the optimal fiber content, it increased by 1.5–2 times on average, which allows predicting the increased heat and crack resistance of hot cast asphalt concrete (Figure 18).

Analyzing the data in Table 18, it can be seen that the introduction of fiber from the fly ash of thermal power plants has a positive effect on the resistance of asphalt concrete to deformation loads at low temperatures. Thus, when fibers from fly ash are added to the asphalt concrete composition, the deformation at −5°C is higher by 30% on average compared to traditional asphalt concrete.

As is known, the interaction of cationic bitumen emulsions with the acid mineral material during the road surface formation depends on the following indicators of cohesive strength setting speed: the decay of mixture and the beginning of cohesive strength setting. These indicators affect the formation of the cast asphalt concrete mixture, that is, the mix's grasping, sealing, and hardening. Accordingly, the speed of formation of cast emulsion–mineral mixtures can be divided into certain stages

Table 18. Deformation of cast asphalt concrete during its compression at maximum load at low temperatures, obtained on Instron 6637 (USA)

| Binder composition for asphalt concrete | | Displacement at maximum load, at temperatures, mm/mm | | |
|---|---|---|---|---|
| | | 5°C | 0°C | 5°C |
| BND 90/130 | | 0.750 | 0.734 | 0.728 |
| Fly ash fiber | 1.0 wt.% | 1.022 | 0.812 | 0.789 |
| | 2.0 wt.% | 1.025 | 0.983 | 0.774 |
| | 3.0 wt.% | 0.712 | 0.914 | 0.766 |
| | 4.0 wt.% | 0.892 | 0.861 | 0.720 |

Table 19. Requirements for cohesive strength set speed of cast emulsion–mineral mixtures

| Time necessary to achieve required cohesive strength, hr | Durability properties | | | Stages of formation of cast emulsion-mineral mixtures |
|---|---|---|---|---|
| | Nature of destruction | Torque value, kg*cm | Ultimate shear strength, mPa, not more | |
| Not more than 0.5 | "N" – Normal | 12–13 | 0.26 | Grasping |
| Not more than 1.0 | "NS" – Normal Spin | 20–21 | 0.42 | Self-sealing (the opening of traffic with a speed limit of 40 km/hr) |
| - | "S" – Spin | 23 | 0.48 | Sealing |
| Not more than 4.0 | "SS" – Solid Spin | 26 | 0.55 | †Hardening (the opening of traffic without speed limits) |

†After this stage, the final cohesive strength setting occurs (additional sealing)

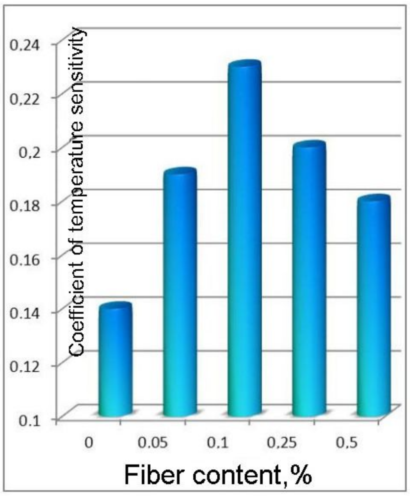


Fig. 18. Coefficient of temperature sensitivity depending on the amount of fiber in the mixture

with corresponding properties of durability and time-span (Table 19).

The introduction of fiber should increase the cohesive strength setting speed of the cold emulsion–mineral mixtures since it reacts chemically with bitumen in the emulsion. The connections of fly ash particles with active groups of bitumen (asphaltene) are not weakened but increased due to the presence of aluminum sulfate, which is added as an emulsifying agent to the cold cast asphalt concrete emulsion [6].

Hence, the use of fiber from the fly ash of thermal power plants is expedient for use in cast emulsion–mineral mixtures and is more cost-effective than the traditional analogous method. Its use leads to a decrease in the price because the additives are a domestic product, and the fiber is made from the waste of power plants. This will significantly reduce the cost of road surfaces with cast emulsion–mineral mixtures. In addition, its technical effect is undeniable in comparison with other foreign analogs.

## 4. Discussion

One of the modern options for increasing the rate of gaining of the cohesive strength of cast emulsion–mineral mixtures is the use of special polymer additives or active fillers in bitumen emulsions. “AkkzoNobel Surface Chemistry”, a company whose products are popular in Ukraine, purposefully developed the emulsifiers Redicote 505 and Redicote 540 for their use in emulsions based on oxidized bitumen. The inclusion of these emulsifiers in the aqueous phase in a certain amount, together with standard emulsifiers, makes it possible to accelerate the rate of gaining of the cohesive strength of cast emulsion–mineral mixtures. At the same time, the competitor of “AkkzoNobel Surface Chemistry” company in the European market is the French company CECA, which has also developed a line of special emulsifiers called Stabiram. The problem of increasing the cohesive strength in this line is solved by the product Stabiram ms8, which is based on derivatives of fatty amines [8].

Another traditional way to increase the rate of gaining of the cohesive strength of cast emulsion–mineral mixtures for the Ukrainian market is the use of various polymer modifiers to improve the quality of oxidized bitumen and cationic bitumen emulsions. The most common modifiers for bitumen and bitumen emulsions are polymers, such as natural rubber, styrene–butadiene copolymer, styrene–isoprene copolymer, isobutylene–isoprene copolymer, polychloropropene, and others [19]. The most common polymers for cationic emulsions in Ukraine are the following ones: synthetic latex Toptex A and Toptex B, natural latex Algoltex C from Algol Chemicals (Finland/Sweden), and Butonal NS 198 from BASF (Germany). Toptex A and Toptex B are styrene–butadiene synthetic rubber (SBR) latex polymers, while Algoltex C is a modified natural rubber latex. Latex Butonal NS 198 belongs to the class of SBR-type thermoplastic elastomers and is a water dispersion of styrene–butadiene copolymers. However, the use of these modifiers is also quite expensive [12].

Studies also show that indene–coumarone resin (ICR) is one of the substances that are characterized by high adhesive and emulsifying properties, which can be used as a modifier of bitumen and bitumen emulsions. ICR is a copolymer of indene, coumarone, styrene, and their derivatives, and their cost is significantly less than the price of modifiers [26]. Moreover, the studies carried out proved the possibility of using ICRs for modifying bitumen in order to increase their softening temperature and adhesion to mineral materials. One of the byproducts of coke production – indene-coumarone fraction (ICF), which is often called “heavy benzene” – can serve as a raw material for the production of ICRs. Furthermore, IKF is a product of distillation of gasoline fractions, which, in turn, are obtained as a result of thermal destruction of the organic part of coal during its coking [14]. The use of ICR for modifying petroleum bitumen will make it possible not only to improve its operational properties but also allows to effectively use one of the byproducts of coke production (the ICF). In addition, the properties of bitumen modified by ICR indicate the possibility of improving the rate of gaining of the cohesive strength of cast emulsion–mineral mixtures.

Studies were also carried out on the use of slags. However, these additives were used in powder form, which were introduced into the mineral powder (up to 5% by weight of the mineral material). They were not evenly distributed and required an increase in mixing time. In this regard, they did not receive wide distribution. We propose the use of fiber from the fly ash of thermal power plants as an additive to mineral powder, which, in a mixture with polymeric substances, will show an increase in the strength and durability of a layer of cold cast asphalt concrete. It is important that the properties of bitumen confirm the previous studies and show the positive effect of fiber from the fly ash of thermal power plants on the structural and mechanical properties of oil binder [7].

When fiber is introduced into the composition of an organic binder, a chemical interaction occurs, which improves the technological properties of bitumen, its structure, and group composition. In hot cast asphalt concrete, an increased amount of bitumen with the addition of fiber will increase the physical, mechanical, and operational properties of hot cast asphalt concrete. An increase in the fiber content to an optimum of 4.0% of the mass of the mineral powder is accompanied by an increase in strength at 50°C by 65% in comparison with the traditional composition. With a decrease in the test temperature to 20°C, the increase in strength in the optimum zone is 33% in comparison with the traditional composition. Further stabilization of the increase in strength is explained by an increase in the number of elements of the dispersed phase of bitumen and the high sorption qualities of the active elements of fly ash included in the composition, which reduce the volume of film bitumen in the composition of the composite.

It was also found that with the introduction of an optimal amount of nanoadditives, the coefficient of temperature sensitivity increases. The introduction of fiber increases the coefficient of temperature sensitivity to a greater extent, which is due to the high concentration of fillers in the additive. The results of calculating the coefficients of temperature sensitivity also correlate with the values of the plasticity interval of modified bitumen with the addition of fiber to the mixture. This is due to a decrease in the amount of bitumen in the bulk state, that is, a more complete transformation of bitumen into a structured state. Therefore, asphalt concrete will remain in an elastic–plastic state in a wider temperature range, undergo less cracking, and withstand a greater number of alternating air temperature fluctuations.

The resistance to waves, sagging, rutting, and other shear deformations is contributed by the shear stability of asphalt concrete. The data indicate an increase in the shear stability of asphalt concrete when using bitumen reinforced with 4% fiber from fly ash compared to traditional asphalt concrete [3]. This is due to the increased cohesive strength and toughness of structured bitumen. All this will make it possible to create an asphalt concrete pavement with increased strength and high shear resistance. The resistance to destructive loads is initially caused by the formed aggregates, consisting of active particles of fly ash and asphalt concrete. Thus, with increasing ultimate loads, the force begins to be transferred to the easily mobile molecules of the maltene fraction. At this moment, the dispersed aggregates begin to move into the mass of maltenes, which will lead to deformation of the asphalt concrete samples.

Analyzing the results obtained, it was established that with the introduction of an optimal amount of fiber from the fly ash of thermal power plants into the composition of asphalt concrete, there is an increase in the strength characteristics at 20°C and 50°C. However, it does not significantly affect the strength characteristics at 0°C. During the operation of asphalt concrete, the effects of dynamic loads, in combination with weather and climatic factors, cause rupture of intermolecular bonds in the binder, microcracks, and dislocations in the structure of the material. Upon contact with water and the transition of temperature through the zero mark, the destruction of asphalt concrete occurs due to the action of water during crystallization. The appearance of such internal stresses, together with the load from a moving vehicle, leads to the premature destruction of the composite.

The structure of cast asphalt concrete made using bitumen reinforced with fly ash fiber from thermal power plants made in China becomes denser. This leads to a decrease in the rate of water penetration into the interface between the binder and the surface of mineral materials through the film of composite bitumen, in comparison with cast asphalt concrete without fiber [9]. Increasing the water resistance of asphalt concrete favorably affects the durability of the road surface using structured fiber from the fly ash of thermal power plants with bitumen. Analyzing the changes in the basic mechanical and deformative properties of asphalt concrete, it is obvious that the introduction of fiber from the fly ash of thermal power plants into the composition of bitumen, and the further production of asphalt concrete based on it, favorably affects the improvement of these characteristics. It was also established that the introduction of fiber from fly ash significantly improves the operational properties of asphalt concrete in the entire temperature range.

## 5. Conclusion

Previous studies have established that when adding binder fiber from the fly ash of thermal power plants to the composition of bitumen, a chemical interaction of the active particles of fly ash, asphaltenes, and bitumen resins occurs. This ensures the adhesion of bitumen to the grains of the mineral material. At the same time, the theoretical studies have shown the necessity of introducing a structuring filler into the composition of hot cast asphalt concrete. In this work, experiments were carried out to establish the possibility of introducing fiber from the fly ash of thermal power plants into cast emulsion–mineral mixtures.

Therefore, the raw materials used for hot and cold cast asphalt concrete were analyzed using standard laboratory tests in accordance with the requirement of DSTU B.V.2.7-129: 2014. The main stages of interaction of a cohesive bitumen emulsion with an acidic mineral material in the process of road surface formation were identified. Moreover, the method for assessing the gain of the cohesive strength of cast emulsion–mineral mixtures using two new indicators (the beginning of the gain of cohesive strength and an express indicator of the formation of the mixture) was proposed.

It was found that the addition of fiber from the fly ash of thermal power plants to the hot cast asphalt concrete made it possible to distribute evenly an increased amount of bitumen (up to 12%) on the grains of the mineral material. Moreover, it reinforced the binder structure and increased the strength, shear resistance, and roughness of the coating layer made of this material. It was also established that the addition of fiber from the fly ash of thermal power plants has a positive effect on the properties of cold cast asphalt concrete, combined with an emulsifier, and contributes to an increase in the cohesive strength and density of the mixture. Thus, aluminum sulfate $(Al_2O_4)_3$, in a bitumen-emulsion binder, helps to strengthen bonds in the active groups of bitumen, i.e., asphaltenes and resins. Moreover, the use of fiber from the fly ash of thermal power plants as part of the hot cast asphalt concrete leads to an increase in the strength and shear resistance of this layer. Accordingly, it provides the required durability and quality of the repairs performed.

Furthermore, the laboratory tests demonstrated that the optimal amount of fiber from fly ash in cast hot asphalt concrete is 4.0% of the mass of the mineral powder. Fiber is mixed with bitumen at an operating temperature of 180°C–190°C without losing its activity and has a positive effect on the structure of bitumen, which is in an amount of up to 12% above the mass of the mineral material. Besides, experimental studies of cold cast asphalt concrete with the addition of fiber from the fly ash of thermal power plants also gave positive results. Consequently, recipes for bitumen emulsions for cast emulsion–mineral mixture technology were developed.

Moreover, the grain composition of stone materials and their correspondence to types of cast emulsion–mineral mixtures were defined. Furthermore, optimal cast emulsion–mineral mixtures compositions were designed according to the decay criteria. Apart from that, it was established that the use of an unconventional additive, namely, $Al_2(SO_4)_3$, with fiber from the fly ash of thermal power plants positively influences the formation of cast emulsion–mineral mixtures and slows their decay.

Furthermore, the time of road surface formation of the designed cast emulsion–mineral mixtures compositions was determined. Thus, the mixture with an identical content as a 10% solution of Redicote E-11, namely, $Al_2(SO_4)_3$ with fiber, showed a faster increase in cohesion by 1.5 hr. Consequently, it was concluded that cast emulsion–mineral mixtures with additive with fiber from the fly ash of thermal power plants are characterized by better abrasion under the action of water, displaying the best adhesion and cohesive properties. Compared with the use of a traditional additive, it reduces the indicator by about 50%.

In addition, when using $Al_2(SO_4)_3$ with fiber, a certain cost-effectiveness is achieved due to the fact that aluminum sulfate is cheaper than Redicote, and fiber from the fly ash of thermal power plants is a waste of industrial production. The research showed the possibility and rationality of using fiber from the fly ash of thermal power plants for the preparation of hot cast asphalt concrete and cold cast asphalt concrete (cast emulsion–mineral mixtures). It can be explained by the fact that the fiber in the hot asphalt concrete cast structure allows an increased amount of bitumen in the mixture, contributing to the strengthening of the bonds of the active particles of fly ash and asphaltene bitumen and forms temperature-resistant (180°C) units.

It is also necessary to mention that hot cast asphalt concrete with fly ash fiber is characterized by high physical, mechanical, and operational properties, which will ensure the strength and durability of the coating. The study of bitumen of different structural types showed that it is possible to use oxidized bitumen, which have better adhesive properties in comparison with distilled ones, for the preparation of emulsions for cold cast asphalt concrete. Furthermore, compositions of bitumen emulsions for ECM-60 and ECMP-60 grades were developed according to DSTU B V.2.7-129 on oxidized bitumen.

It was also determined that the emulsifiers Redicote 505 and Redicote 540 and the domestic bitumen modifier ICR are optimal in terms of the cohesive strength of cast emulsion–mineral mixtures. This is attributed to the fact that cast emulsion–mineral mixtures with these accelerators and the optimal stone material belong to mixture Class 4, which is characterized by fast setting of the mixture ($\leq 0.5$ hr) and fast self-compaction ($\leq 1.0$ hr). Therefore, these accelerators make it possible to reduce the opening time for traffic with a speed limit of up to 40 km/hr to 1 hr, while the opening time for traffic without restrictions is 2.5–3.0 hr. In addition, cast emulsion–mineral mixtures based on oxidized bitumen modified with ICR are characterized by 8.5 times lower weight loss of the coating under wet conditions than cast emulsion–mineral mixtures based on oxidized bitumen with emulsifiers for bitumen emulsion.

Besides, it was revealed that the rate of gaining of cohesive strength, regardless of both the nature of bitumen (distilled or oxidized) and the type of mixture, is influenced by the properties of the stone material. Finally, the economic feasibility of using cast asphalt concrete (hot and cold) with the addition of fiber from the fly ash of thermal power plants is attributed to a decrease in cost, since fiber is a cheap waste material, an increased service life of the coating due to the structure of bitumen with fiber, and an increase in the safety of movement by creating increased roughness of the coating surface.

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## Conflict of interest

The authors state no conflict of interest.

## Availability of data and materials

Data will be available on request.

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