Materials Science-Poland, 40(2), 2022, pp. 181-195
http://www.materialsscience.pwr.wroc.pl/
DOI: 10.2478/msp-2022-0021

Features of the hot recycling method used to repair asphalt concrete pavements

Andrii Bieliatynskyi[1], Shilin Yang[2,*], Valerii Pershakov[2], Meiyu Shao[2], Mingyang Ta[1]

[1]School of Civil Engineering, North Minzu University, Yinchuan, NingXia, P.R. China

[2]Department of Computer Technologies of Construction and Reconstruction of Airports, Faculty of Architecture, Civil Engineering and Design, National Aviation University, Kyiv, Ukraine

The recycling methods used in the construction and repairing of asphalt concrete pavements are being constantly improved, and the improvements mostly fall under one of the following common avenues of innovation: developing new binders based on bitumen and cement; developing new varieties of asphalt concrete and other materials having an equivalent utility and function; and developing additives that can be used in the production of new types of binders that can enhance the performance properties of the pavements. This article aims to develop the composition and determine the physical-mechanical and structural-rheological properties of asphalt concrete reclaimed by the hot recycling method and reinforced by fiber of fly ash from thermal power plants (TPP). The author of this article developed a mechanism for the interaction between fiber and bitumen in asphalt binder and acquired an optimum composition of hot granular asphalt concrete. During the research, the author evaluated the utility of fiber used as an additive in reclaimed asphalt concrete, studied its effect on the properties of hot reclaimed asphalt concrete, and examined the technological and performance properties and durability of the material obtained. The fiber of fly ash used in the hot recycling method made it possible to reduce the cost and ensure the high quality and durability of the structural layer of road pavement. Our experiments with analyses of the obtained composition indicated that employing it in the construction of the structural layer of road payment would result in superior structural integrity. Hot recycling made it possible to obtain thick bound layers characterized by the homogeneity of the material. For the first time, the author studied the effect of using fiber of fly ash from Chinese TPP in hot reclaimed asphalt concrete, and the results have proved the rationality of using this composition.

Keywords: *hot regeneration, coal combustion product, fiber, thermal profiling, asphalt concrete properties*

1. Introduction

The traditional method of repairing asphalt concrete pavements involves leveling them with asphalt concrete mixture and overlapping them with a new layer of asphalt concrete. As a result, the material of the old layers becomes a source of reflected cracks in the new road pavement. There are hundreds of millions of tons of asphalt concrete in the lower layers of road pavement, and these do not serve any useful purpose; the volume of stone materials exceeds these pavements by 2–3 times in the underlying layers and foundations [1]. Given the constant increase in the shortage and cost of road construction materials during the construction and reconstruction of highways, it is necessary to develop non-material-intensive or non-energy-intensive technologies using available reserves. The authors of this article developed a technical and technological solution to the problems of cost escalation and excessive energy consumption that commonly characterize the restoration of existing road networks. The solution allows reusing the material of the reconstructed roads.

A cost-effective, technological solution, which provides for quality road construction materials obtained from asphalt scraps, is to process them by their secondary products and industrial waste such as granulated slag, nepheline sludge, ash, ash-and-slag mixtures of thermal power plants (TPP), phosphogypsum, cement kiln dust (CKD), etc. [2]. A promising technological solution is to obtain organomineral material from a semi-finished product without heating it by processing the crushed scrap with a mineral binder. However, the use of

* E-mail: yang8083@edu.cn.ua

this method is not always rational and possible, given the long-term formation of the organomineral material structure during the operation of the road under traffic.

The technology of processing asphalt scrap in an installation with heating and the addition of new constituent components is a modern technology that provides a durable asphalt concrete pavement in the upper layer without overlapping it with a layer of road surface treatment. Reheating asphaltic concrete leads to plasticizing the formed bitumen structure, which, in turn, reduces its viscosity and improves the processing properties of the mixture [3].

The viscosity of bitumen increases by 2–3 times in the "old" asphalt concrete due to a decrease in the number of light fractions. The addition of a plasticizer can bring the bitumen penetration to standard values. Such oils as petroleum, coal, or specifically developed oils are often used as plasticizers since they contain many aromatic compounds, and the use of fuel oil or liquid bitumen is rare. Hot technology methods for processing asphalt concrete involve high-temperature heating but do not provide for the restoration of the bitumen properties contained in long-term asphalt concrete; the addition of a new binder with enhanced properties will ensure the durability of the reclaimed asphalt concrete [4]. The method of regenerating "old" asphalt concrete using heating technology is promising since this technology is rapidly advancing in feasibility, and is thus being widely adopted. The hot recycling method can be carried out on the site of manufacture or by transporting the mixture to an asphalt recycling plant. The prolonged service life of pavement from the restored mixture fully pays off a slight increase in the cost of the transportation of milled scrap [5].

The study of performance features of the restored layer of the road pavement made of granular asphalt concrete with the fiber of fly ash under dynamic loading will make it possible to predict its performance properties throughout the entire service life. The assessment of the impact of technological processes of wear layers and the production of repair work on the environment confirms the idea of their relative environmental safety. It is necessary to do the following in order to obtain the results of the impact of the fiber of fly ash:

- to substantiate the possibility of using fiber in granular asphalt concrete, given its composition and properties;
- to study the mechanism of interaction between fiber and binder (bitumen) in the composition of granular asphalt concrete when arranging wear layers of road pavement;
- to examine how granular asphalt concrete with fiber changes its properties under transport loading;
- to study the influence of the technological process in arranging layers of granular asphalt concrete reinforced with the fiber of fly ash (especially the factors of temperature increase and compaction).

This article aims to develop the composition and determine the physical-mechanical and structural-rheological properties of asphalt concrete reclaimed by the hot recycling method and reinforced by fiber of fly ash from TPP. To achieve this aim, it is necessary to complete the following tasks:

- to review and study the existing experience in using the fiber of fly ash from TPP as an additive to reclaimed asphalt concrete;
- to analyze the theoretical foundations of structure formation in bitumen and asphalt binder with the introduction of the fiber of fly ash;
- to study the effect of the fiber on the properties of the hot reclaimed asphalt concrete mixture;
- to study the structural-rheological and technological properties of hot reclaimed asphalt concrete mixture with the fiber of fly ash;
- to study and test the durability of reclaimed asphalt concrete with the fiber of fly ash under laboratory conditions;
- to examine the performance properties of the asphalt concrete material obtained.

2. Materials and methods

The primary indicators of performance reliability of the structural layers of the pavement are structure stability, which depends on the adhesion strength of the bitumen to mineral particles, the bending strength, structure stability to fluctuations in humidity and temperature conditions, the fatigue failure under dynamic loading, etc. The strength of granular asphalt concrete layers depends on the quality of the mixture preparation and the properties of milled asphalt concrete. Loading, climatic, periodic, and one-time impacts cause various processes in the road structure during its everyday performance. The pavement treatment by granular asphalt concrete is generally initiated for roads that are undergoing rapid deterioration, or in cases where the total area of pavement defects has reached 30% before the end of the performance period [6]. When the defects appear on pavements, it indicates low-quality materials and washing out of bitumen from the surface layer [7].

The initialization of the mixture during its rolling is a critical operation in laying the pavement, and it is also the factor that determines the quality of these layers to the greatest extent. When a road roller passes along the pavement, pressure develops in the pavement layers, and numerous physicochemical processes occur under the influence of temperature, which results in the formation of spliced layers of the required strength. Exposure to temperature changes the balance within the materials used, resulting in a nonequilibrium thermodynamic state [8]. The interlayer compression pressure increases, and the internal moisture contained in the bituminous binders and mineral material influences their initiation. The correct choice of mixture compositions and technological conditions for laying ensure high strength and durability of pavements during construction usage, reconstruction, and repair. Temperature also affects the diffusion processes occurring during the formation of new pavement and its subsequent performance [9].

High temperature causes both unevenness of heating and premature aging of the bitumen binder, thus reducing the road strength characteristics. The heat from the compression surface of layers with the granular binder permeates into the lower layers. Excessive pressure appears, which causes the binder to penetrate the depth of the layer, leveling the temperature fields [2]. The curing process flows more evenly over the thickness of the layers, which improves the road strength characteristics. The conditions for the equality of heat fluxes and transfer of the liquid fraction of the binder during the formation of the layer can be expressed as follows:

$$-\lambda \frac{\partial T(x,t)}{\partial x}\Big|_{x=h} = 0, \qquad (1)$$
$$-\alpha_c \rho \frac{\partial U(x,t)}{\partial x}\Big|_{x=h} = 0$$

Therefore, an adequate description of changes in the bitumen concentration in the asphalt layer can be an objective answer to the durability of the road pavement [10]. It is necessary to theoretically substantiate the functional dependence of the bitumen concentration on time and other natural parameters, such as access time for concentration to reach a certain threshold (minimum permissible) value. Such an estimate can be one of the predictive estimates of the pavement service life.

Zolotarev [11] proved that mixtures with optimum density have a high coefficient of relative thermal conductivity. Table 1 shows the temperature effect on the relative thermal conductivity of granular asphalt concrete mixtures with different densities.

According to Table 1, a mixture with a density ranging from 2.2 t/m^3 to 2.4 t/m^3 possesses a higher coefficient of thermal conductivity λ, even when heated to 90°C. The density of granular asphalt concrete with the studied fiber of fly ash should correspond to these optimum values. If the process of uniform bitumen distribution is regulated, it is possible to obtain a layer with high physical and mechanical characteristics. Figure 1 represents the dependence of the penetration rate of the binder in the formed layer.

Figure 2 provides data, generated in the course of the present study, on the dependence of bitumen concentration on the thickness of the coating layer and the service life. The data are given for the

Table 1. Effect of the mixture temperature on the relative thermal conductivity, λ

Temperature	Density of the mixture (t/m^3)						
	1.8	1.9	2.0	2.1	2.2	2.3	2.4
50	0.94	0.94	0.95	0.95	0.96	0.97	0.97
70	0.97	0.97	0.97	0.99	0.99	0.99	1.0
90	1.00	1.00	1.00	1.02	1.03	1.03	1.03

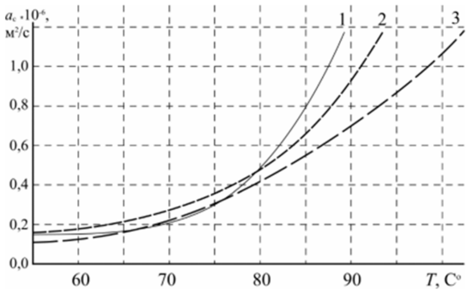


Fig. 1. Temperature dependence of the penetration rate of the binder: 1 – a binder based on bitumen with the fiber in the amount of 4% of the weight of granular asphalt; 2 – a binder based on bitumen with the fiber in the amount of 3% of the weight of granular asphalt; 3 – binder without fiber

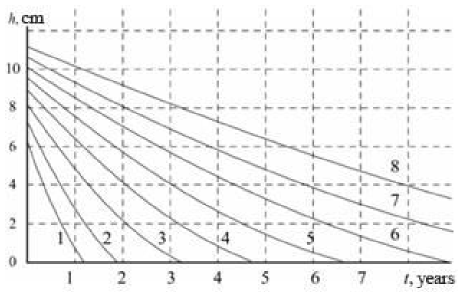


Fig. 2. Dependence of the binder concentration on the thickness of the coating layer and the service life of 1%–8% bitumen in the mixture; 2–7%; 3–6%; 4–5%; 5–4%; 6–3%; 7–2%

amount of bitumen from 8% to 2% by weight of granular asphalt.

The binder concentration constantly changes in the coating layers under atmospheric factors and traffic. There is a constant diffusion into the layer, and the concentration changes from higher (80% or 100%) to lower (20% or 60%). The binder does not fulfill its function when reaching a particular concentration limit, which accelerates pavement destruction. The minimum concentration will obviously be at a later date when the binder concentration is reducing in the upper layer and diffusing into the lower layers of asphalt pavement. It is possible to adjust the road service life based on this provision. The time during which the binder concentration decreases below 70% can be considered the beginning of intensive pavement destruction.

Literature sources claim that reinforcing additives reduce the diffusion of bitumen in the underlying layer due to the formation of a structural framework in the bitumen-fiber system [12]. The above is especially typical for fibers with a rough particle surface, such as the fiber of fly ash from TPP.

As the temperature rises, microparticles of the fiber of fly ash interpenetrate into the molecules of the most active part of bitumen, namely asphaltenes. The fixation of particles in the binder reduces the amount of free bitumen, structuring it and thereby preventing the binder from moving deeper into the layer, and increases the strength and durability of granular asphalt concrete in the pavement.

3. Results

The author used the following materials to conduct experimental studies on the composition selection of granular asphalt concrete and determine its physical, mechanical, and performance properties when carpeting with an asphalt concrete pavement by the hot recycling method:

- milled asphalt concrete;
- oil road bitumen BND 60/90;
- mineral material – crushed granite of 5–10 mm fraction;
- stone screening dust of 0–5 mm fraction;
- fiber of fly ash from TPP.

Table 2. Variants of restoration technology for asphalt concrete pavements

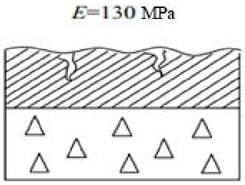
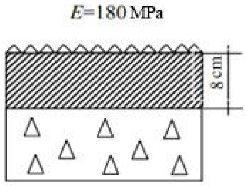
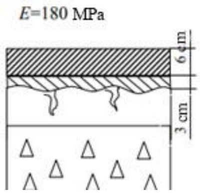
Condition of the pavement before restoration	Methods of restoration	
	1. Hot regeneration with surface treatment	2. Traditional, leveling course (3 cm) and new pavement (6 cm)
		

Table 3. Grain size composition of the granular asphalt

Indicators	Mesh size (mm)										
	20	15	10	5	2.5	1.25	0.63	0.315	0.16	0.071	<0.071
Partial residuals (g)	32	8	88	160	120	52	100	140	116	52	72
Partial residuals (%)	3.40	0.85	9.36	17.0	12.7	5.53	10.6	14.8	12.3	5.53	7.67
Full passes (%)	96.6	75.7	66.3	49.3	36.3	21.0	20.4	5.5	3.2	0.67	
Requirements according to standards	90–100	85–100	75–100	60–70	48–60	37–50	28–40	20–30	13–20	8–14	

Table 4. Indicators of properties of oil road bitumen BND 60/90

No.	Indicator name, unit of measurement	Test result	DSTU 4044 value for BND 60/90 grade
1	Needle penetration depth (0.1 mm)		
	at 25°C	76	From 61 to 90
	at 0°C	23	Not less than 20
2	Ring-and-ball softening point (°C)	50	Not lower 47
3	Elongation (cm)		
	at 25°C	100	Not less than 55
	at 0°C	4.5	Not less than 3.5
4	Brittleness point (°C)	−17	Not higher than −15
5	Flash point (°C)	240	Not lower than 230
6	Change in softening point after progress (°C)	3.5	Not more 5
7	Penetration index	−0.2	−1 to +1

Taking the conditions of Ukraine as a background, the authors justify the usage of the hot recycling method in carrying out restoration of asphalt concrete pavements as part of road repairing works (involving roads containing asphalt concrete pavements). Table 2 presents the variants for the restoration of asphalt concrete pavements.

Table 5. Physical and mechanical properties of the crushed granite

No.	Indicator names	Actual indicators	DSTU B V.2.3-39 requirements
1	Content of crushed grains by weight (not less %)	85	85
2	Content of lamellar (flaky) and needle-shaped grains by weight (no more %)	15	15
3	Content of grains of weak rocks by weight (no more %)	2.8	5
4	Content of dust and clay particles by weight (no more %)	1	2
5	Clay content in lumps (% by weight, no more)	None	0.25
6	Crushing grade (not less)	1,000	1,000
7	Attrition grade	A1	A1
8	Frost resistance grade (not lower)	F150	F150
9	Plasticity grade	Pl1	Pl1–Pl2
10	Water resistance grade	B1	B1–B2
11	Bulk density ρ_n (kg/m^3)	1,318	-

Table 6. Physical and mechanical indicators of the stone screening dust

No.	Indicator names	Actual indicators	DSTU B V.2.3-39 requirements
1	True density (kg/m^3)	2,628	-
2	Average density (kg/m^3)	2,621	-
3	Bulk density (kg/m^3)	1,540	-
4	Content of dust and clay particles, by weight (no more %)	0.96	2
5	Crushing grade (not less)	1,000	1,000
6	Attrition grade	A1	A1
7	Frost resistance grade (not lower)	F150	F150

The following structural and technological scheme was adopted as a compared variant:

- hot recycling of 7 m wide asphalt concrete pavement to a layer depth of 8 cm using a WR-2500 recycler with the introduction of viscous bitumen;
- modulus of elasticity on the paving surface before repair – 130 MPa, after repair – 210 MPa;
- recycling is carried out in three passes across the width of the carriageway, and the overlap of the passageways is 250 mm.

Since hot recycling provides a higher modulus of elasticity and allows carrying out work over the entire thickness of the layer (8 cm), option No. 1 was adopted. The milled asphalt concrete was removed with a milling cutter to a layer with a thickness of 6 cm. Table 3 shows the grain size composition of the granular asphalt.

As can be seen from Table 3, with the exception of the 20 mm fraction, the grain size composition of the granular asphalt fails to meet the requirements of DSTU B V.2.7-119 for all fractions. Therefore, it is necessary to add a new mineral material such as crushed stone and screening in order to ensure the required density of granular asphalt concrete. The author of this article provides indicators of the properties of oil road bitumen BND 60/90 under the requirements of DSTU 4044 in Table 4 [13].

The bitumen used in the present research meets the DSTU 4044 requirements [13]. The author used the crushed granite of the Novopoltavsky quarry (Ukraine) in the research. Table 5 provides its physical and mechanical indicators.

As can be seen from Table 5, the crushed stone used fully meets the DSTU B V.2.3-39 requirements [14]. Stone screening dust is from the same quarry, and its physical and mechanical indicators are given in Table 6.

As can be seen from Table 6, the used stone screening dust fully complies with the DSTU B V.2.3-39 requirements [14]. The preparation of bitumen with the addition of fiber was as follows. The reinforcing additive, the fiber, was introduced into the bitumen, heated to 150°C, and stirred therein by hand until uniform. The distribution of fiber in the bitumen was quick and uniform within 10 min. The firm compression of the granules caused the poor distribution of Topcel, Antrocel, and Chrysotopes in the bitumen without preliminary destruction. Therefore, they were mechanically destroyed in a porcelain mortar that was operated by hand, and thus reduced to a fluffed state. After that, it was possible to achieve a uniform distribution of additives in the bitumen. The appearance of the bitumen with the fiber of fly ash added is a mobile, mushy mixture (without lumps) with a black gloss. At the same time, the viscosity of bitumen increased.

The author prepared the granular asphalt concrete with the fiber of fly ash in the following way. Dosed components of the mixture were heated to the required temperatures: crushed stone and screening dust to 175°C, and bitumen to 155°C. The heated temperature of the inner surface of the laboratory mixer was 140°C. The author added crushed stone and screenings to the mixer with the prepared mixture and mixed it for 30 s. Then, the fiber was loaded and mixed for 1.0 min; bitumen was added thereafter and mixed for 1.0 min until the bitumen completely covered the mineral material, and a homogeneous mixture was formed.

The total mixing time was 4.5 min. Before manufacturing the samples, the mixture was maintained for 20 min at a temperature of 150°C. Samples from the granular asphalt concrete mixture were made in accordance with GOST 12801-98 [15]. Samples were tested in accordance with GOST 12801-98, GOST 31015-2002, and VBN B.2.3-218-002-95 [15–17].

The author studied the microstructure of the fiber with an Axioskop 2 MAT microscope with a series of EC Epiplan-Neofluars lenses for improved color correction. The electron microscopic images were processed to obtain quantitative information about structural elements and their relative position in space. The geometric parameters of the additives were measured, and their appearance, the nature of their mutual arrangement, and the distribution of bitumen were studied. Color micrographs were obtained by photographing the pre-prepared fiber of fly ash of TPP. Figure 3 shows the appearance of the fiber used.

Fig. 3. Fiber

The physical and mechanical properties of the used fiber of fly ash are as follows:

- average diameter of the fiber is 160.0 µm;
- amount of non-fiber additives is 3%;
- density is 2.65 g/cm^3;
- water resistance is 99.6%;
- modulus of elasticity is 120 MPa; and
- elongation at break is 3.1%.

The relative humidity of cellulose and mineral fibrous additives was determined according to GOST 16483.32-77 “Wood. Method for determining the limit of hygroscopicity” [18]. The hygroscopicity of fibrous stabilizers with natural humidity was determined by keeping the fiber for a day in a hermetically sealed desiccator at a relative humidity of 98% and a temperature of 20 ± 3°C. The author placed a weighed sample (in a pre-weighed weighing bottle) above water poured into a desiccator, where the room temperature was at 20 ± 3°C. The weight of samples of additives in the desiccator was measured in a day.

The degree of swelling and linear expansion of cellulose additives were determined according to GOST 7516-75 “Cellulose. Swelling method”

[19]. The author determined the degree of swelling through the change in the weight of the additive samples after keeping them in water at 20 ± 3°C, by weighing the samples by weight method before and after their swelling. Prepared samples of cellulose additives were immersed in water for 1 day. Then, they were removed and kept on a mesh tray until free water flowed off the surface of the additives.

The author determined the linear expansion of cellulose by the increment in the height of the cellulose additive samples in water and expressed it as a percentage. Linear expansion was measured simultaneously with the degree of swelling of the cellulose by weight. The above presupposed the height of the cylinder with the additive to be measured. The discrepancy between the results of three parallel determinations should not be more than 0.5% (in absolute value). The result was the arithmetic mean of three parallel determinations, rounded to the first decimal place.

The flowability of all studied additives was determined according to GOST 25139-93 “Plastics. Methods for determining flowability” [20]. The outflow rate of stabilizing additives characterized their flowability. The outflow rate was determined on the developed model of the receiving hopper for stabilizing additives (Figure 4). A plastic hopper had an outlet through which the additives passed. The fixation of the hopper was in an upright position on a tripod. The outlet was closed with a pawning device.

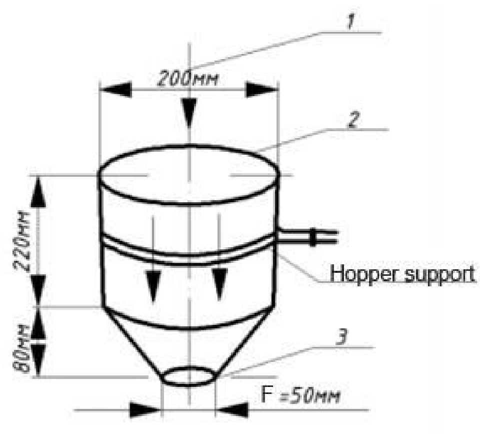


Fig. 4. Model of receiving hopper for stabilizing additives. 1 – direction of additives loading; 2 – inlet opening; 3 – outlet opening

To check compliance with GOST 31015-2002 and GOST 9128-2009, the authors studied the characteristics obtained as a result of the addition of the fiber of fly ash to bitumen, asphalt binder, bitumen fiber, granular asphalt, and granular asphalt concrete [16, 21]. The author used Vibra AJ 2200 CE laboratory electronic balance to weigh the dosing of crushed stone, screenings, bitumen, and fiber when preparing a mixture of asphalt binder and the asphalt concrete mixture. A drying oven was used to heat the mixture components; mixing was carried out in a laboratory mixer SL - AB. The temperatures of the heated materials were monitored with an OPTRIS SIGHT MS pyrometer having a temperature measurement range from −32°C to 420°C. A vacuum setup with a filter moisture separator and a Wigem vacuum pump was used to determine the water saturation and strength of the samples in a water-saturated state.

The author determined the strength of asphalt binder and asphalt concrete by hydraulic presses P-50 and IP-100, providing an error in measurement of no more than 1%. The possibility of adjusting the rate of application to the sample was within 0.2–0.6 MPa/s. The choice of hydraulic presses is motivated by the expectation that the breaking load should be 0.2%–0.8% of the maximum force. When investigating the properties of bitumen with the added fiber of fly ash from Chinese TPP, the author used the following equipment: a ductilometer DMF-1480 No. 06, which is a viscometer for determining the relative viscosity of the bitumen. Table 7 provides the indicators of the properties of bitumen with the added fiber, and Figures 5–7 show the dependence of these indicators on the content of additives in the bitumen.

Analysis of the data in Figure 5 shows that an increased amount of fiber decreases the viscosity of the bitumen, i.e., the stiffness increases.

According to Figure 6, the fiber structures the bitumen since the indicators of the needle penetration depth are high even at 5% of its introduction.

According to Figure 7, the elongation of the bitumen with the fiber added decreases at 25°C, i.e., binder stiffness increases. The calculation of the

Table 7. Indicators of properties of the bitumen with additives

No.	Indicator name, unit of measurement	Additive content in bitumen (%)	BND 60/90	Fiber
1	Needle penetration depth (0.1 mm)			
	at 25°C	0	76	-
	at 0°C		23	
		2	-	47.0
				23.4
		3	-	40.2
				25.8
		4	-	37.4
				25.3
		5	-	36.3
				23.3
2	Ring-and-ball softening point (°C)	0	50	-
		2	-	64
		4	-	67
		5	-	75
		7	-	78
3	Elongation (cm)			
	at 25°C	0	100	-
	at 0°C		4.2	
		2	-	43.3
				3.5
		4	-	30.5
				4.0
		5	-	27.2
				4.2
		7		5.3
				3.6
4	Brittleness point (°C)	0	−17	-
		2	-	−18
		4	-	−25
		5	-	−22
		7	-	−19

amount of new crushed stone in the granular asphalt concrete mixture depends on the amount of the bitumen in the granular asphalt. Based on the ratio, the authors determined the amount of binder in the granular asphalt by burning the mixture to the amount of new binder. We can calculate the amount of crushed stone added to the granular asphalt concrete according to the following formula:

$$M = \frac{Z}{X_0} \cdot 100\% \qquad (2)$$

where Z is the amount of binder in the granular asphalt;

$$X_b = 7 - Z \qquad (3)$$

where 7% is the bitumen content in the granular asphalt concrete according to DSTU B V.2.7-119. Then,

$$X_b = 7 - 4 = 3\% \qquad (4)$$

The ratio obtained is:

$$M = \frac{3}{4} \cdot 100\% = 0.75 \cdot 100 = 75\% \qquad (5)$$

The calculation of the amount of addition of new crushed stone (G) is as follows:

$$G = 100\% - M \qquad (6)$$

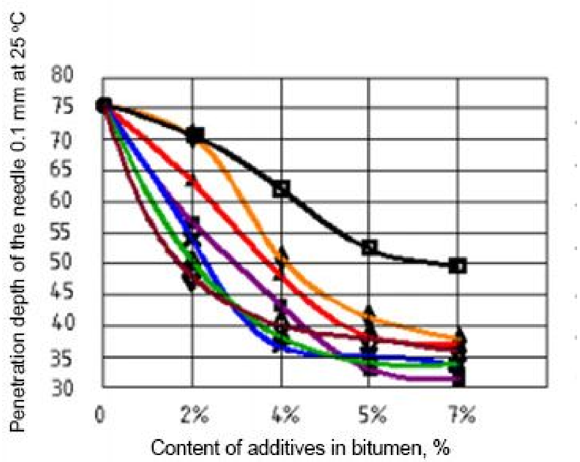


Fig. 5. Dependence of the indicators of the needle penetration depth into the bitumen on the content of the additive at 25°C

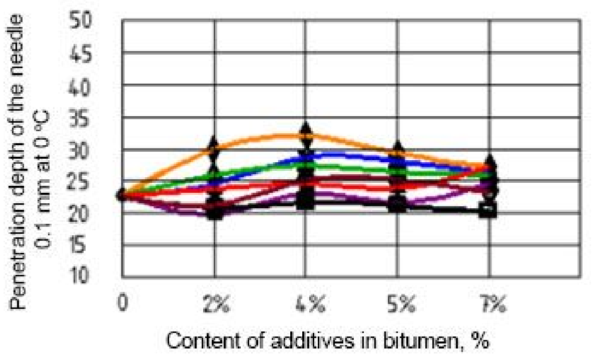


Fig. 6. Dependence of the indicators of the needle penetration depth into bitumen on the content of the additive at 0°C

where 100% represents the composition of the granular asphalt concrete;

$$G = 100\% - 75 = 25\% \quad (7)$$

However, it is necessary to remember that the granular asphalt concrete mixture (P) consists of crushed stone (G), bitumen (X), and fiber (F). The addition of fiber is in an amount of 4% above the weight of the mineral part:

$$P = G + X + F \quad (8)$$

To accurately calculate the amount of new crushed stone, we subtract the bituminous fiber from the total composition of the granular asphalt concrete mixture.

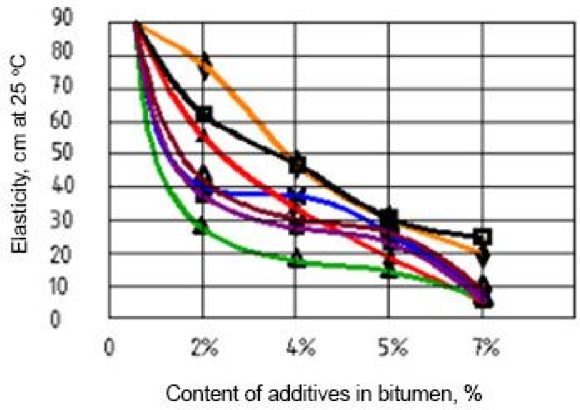


Fig. 7. Dependence of the indicators of the bitumen elongation on the content of the additive at 25°C

$$P_1 = G - X - F \quad (9)$$

$$P_1 = 100 - 3 - 4 = 93\% \quad (10)$$

Then, the amount of the granular asphalt in the mixture will be as follows:

$$K_a = 75 \cdot 93 = 69.75 = 70\% \quad (11)$$

The amount of new crushed stone added will be as follows:

$$K_{cr} = 100 - 69.75 = 30.22 = 30\% \quad (12)$$

Thus, the following granular asphalt concrete mixture (shown in Table 8) was adopted for further research.

Table 8. The composition of the granular asphalt concrete mixture

Mixture components	Amount (%)
Granular asphalt	69.75
New crushed stone	30.22
Fiber of fly ash from TPP in China	4.0
Bitumen BND 60/90	3.0

TPP, thermal power plants.

In order to compare the research results, the author also tested the granular asphalt concrete mixture without the fiber of fly ash.

4. Discussion

According to the data presented in the figures, the fiber of fly ash has a positive influence on the water resistance and compressive strength at 20°C and 50°C. Indicators of water saturation increase with the addition of the fiber to 2.5%, and thus the mixture is not dense. An increase in the amount of fiber up to the calculated 4.0% and even up to 5% leads to a decrease in water saturation. Thus, a mixture with a dense structure has been obtained, in which the bitumen completely covers the grains of the mineral material.

The hot granular asphalt concrete with the fiber added has higher strength at 20°C and 50°C than the traditional composition. The ultimate strength and density of the mixture are achieved by introducing the fiber in the amount of 5% of the weight of the mineral part. However, it increases the amount of bitumen, which is undesirable. Therefore, our calculated threshold of a 5% fiber content is judged prescient in ensuring that optimal strength and density parameters are obtained for the mixture, while keeping the amount of bitumen within an acceptable limit. Figure 8 shows how water resistance k_w and water resistance at long-term water saturation k_{ws} of the hot asphalt concrete depend on the content of the fiber of fly ash at the optimum bitumen content. Figures 9 and 10 present the compressive strength at the optimum bitumen content.

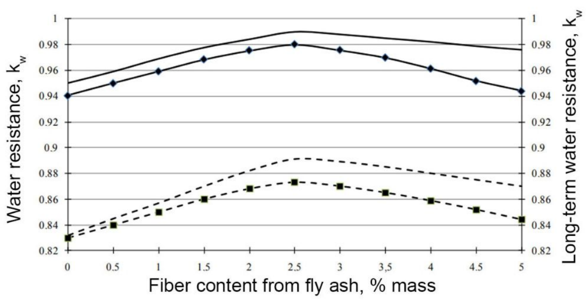


Fig. 8. The dependence of water resistance k_w and water resistance at long-term water saturation k_{ws} of the hot granular asphalt concrete on the content of fiber of fly ash at the optimum bitumen content

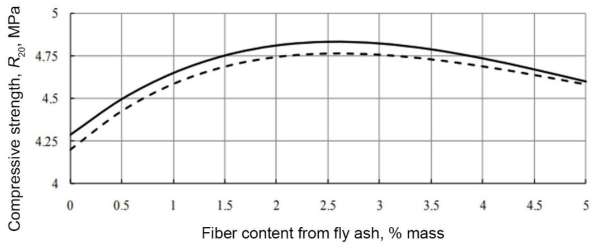


Fig. 9. Compressive strength R_{20} versus the content of fiber of fly ash at the optimal bitumen content

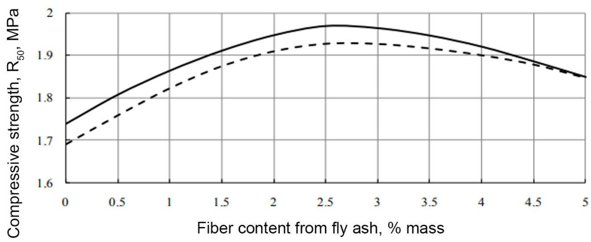


Fig. 10. Compressive strength R_{50} versus the content of fiber of fly ash at the optimal bitumen content

The selection and observance of the optimum temperature conditions for preparation are critical for obtaining high-quality asphalt concrete mixtures [22]. When unloading from the mixer and laying, the temperature of the hot granular asphalt concrete, depending on the bitumen binder used, must correspond to the values specified in Table 9.

The author determined the effect of temperature of mixing (T_{mix}) granular asphalt concrete mixture on the physical and mechanical properties by assessing the strength indicator (R_{20} and R_{50}) and water resistance (k_w and k_{ws}) of the fiber-reinforced granular asphalt concrete samples, prepared at various mixing temperatures. The temperature of mixing was varied in increments of 5°C, and the temperature variation interval was 140–155°C. Table 10 presents the obtained physical and mechanical properties of hot granular asphalt concrete.

According to the test results, the hot granular asphalt concrete mixture with the fiber prepared at a temperature T_{mix} 145°C possessed the highest strength and water resistance indicators. An increase in the mixing temperature decreased the strength and water resistance indicators and in-

Table 9. Temperature of the hot granular asphalt concrete depending on the bitumen binder

Needle penetration depth, 0.1 mm, at 25°C	Temperature (°C)	
	When unloading	When laying, not less
40–60 incl.	150–160	140
60–90 incl.	145–150	145

Table 10. Influence of the temperature of mixing (T_{mix}) on the physical and mechanical properties of the fiber-reinforced granular asphalt concrete

Indicator	Temperature of preparation (°C)							
	Granular asphalt concrete with fiber				Granular asphalt concrete			
	140	145	150	155	140	145	150	155
Compressive strength (MPa):								
at 0°C, R^0	8.07	8.64	8.35	8.21	7.59	8.2	7.89	7.76
at 20°C, R_{20}	4.3	4.71	4.55	4.42	3.37	3.78	3.62	3.53
at 50°C, R_{50}	1.7	1.9	1.83	1.79	1.04	1.19	1.85	1.82
Water resistance (k_w)	0.89	0.96	0.93	0.92	0.8	0.87	0.84	0.84
Water resistance during long-term water saturation (k_{ws})	0.81	0.87	0.84	0.82	0.74	0.8	0.7	0.76
Water saturation (W, % by volume)	2.28	2.2	2.16	2.1	2.68	2.72	2.97	2.99

Table 11. Test results of hot granular asphalt concrete mixtures

Indicators	First option		Second option	
	Granular asphalt concrete with fiber	Granular asphalt concrete	Granular asphalt concrete with fiber	Granular asphalt concrete
Compressive strength (MPa):				
at 0°C, R^0	4.52	4.01	4.54	4.07
at 20°C, R_{20}	1.65	1.37	1.7	1.40
at 50°C, R_{50}				
Water resistance (k_w)	0.96	0.83	0.94	0.84
Water resistance at long-term water saturation (k_{ws})	0.84	0.72	0.8	0.70
Water saturation (W, % by volume)	2.1	2.41	2.35	2.4

creased water saturation. If T_{mix} decreases below 165°C, the strength and water resistance decrease significantly, and the water saturation indicators practically do not change.

The traditional hot asphalt concrete mixtures are prepared according to the technological scheme, which involves the simultaneous supply and mixing of crushed stone, sand, mineral powder, and bitumen [23]. The better part of bitumen combines with mineral powder due to the high surface activity of its grains, and as a result, the surface of crushed stone and sand with bitumen gets wet to a worse extent.

According to research, the introduction of mineral powder into the mixer simultaneously with crushed stone and sand worsens the wetting of crushed stone and sand grains with bitumen due to the adhesion of mineral powder particles to their surface. Crolley [24] believes it is possible to improve the wetting of stone material with bitumen by introducing a mineral powder after mixing crushed stone and sand with bitumen. The result is a perfect distribution of the asphalt binder, which increases the system density, strength, and water resistance.

In order to improve the technology for preparing hot granular asphalt concrete mixture, the author examined how the sequence in introducing the components of granular asphalt concrete influenced its properties. The preparation of hot granular asphalt concrete was carried out in two ways:

Option 1: Mineral aggregate, fiber of fly ash, and bitumen would be heated to the required temperature and dosed, followed by feeding into the mixer and mixing all components.

Option 2: The mineral aggregate and bitumen, heated to the required temperature and dosed, would be fed into the mixer and mixed; and then, the dosed amount of fiber would be added to the mixer.

Samples were made from hot granular asphalt concrete mixtures prepared according to the proposed options. Then, the samples were tested for compressive strength at 20°C and 50°C (R_{20} and R_{50}), water resistance (k_w and k_{ws}), and water saturation (W). The test results are presented in Table 11.

According to the data in Table 11, the hot granular asphalt concrete prepared according to the first option has the highest strength and water resistance indicators. Thus, the sequence involved in introducing the components of hot granular asphalt concrete into the mixer according to the first option, which involves mixing the mineral material with fiber and bitumen, is the most rational.

Thus, the conducted studies of the technological properties of hot granular asphalt concrete showed that the addition of fiber does not complicate the process of preparing asphalt granulometric concrete and is carried out by combining the constituent components with bitumen. The resulting mixture is characterized by homogeneity, that is, uniform distribution of fiber and bitumen on the grains of the mineral material. There are no lumps and uncoated surface of grains of mineral material. Analyzing the data, the author of this article posit the following arguments:

- the use of the fiber of fly ash provides sufficient water and crack resistance to hot granular asphalt concrete;
- the introduction of the fiber makes it possible to obtain higher indicators of strength than it is with the traditional asphalt granulometric concrete;
- the studies on water and frost resistance confirm a high quality of the obtained hot granular asphalt concrete with fiber. The coefficient of water and frost resistance increases while water saturation and swelling decrease.

All these confirm the rationality of using fiber as a reinforcing additive when restoring asphalt concrete pavements using the hot recycling method.

5. Conclusion

The conducted review of the available literature data indicates that the restoration of asphalt concrete pavements by the hot recycling method must be performed on roads that can be categorized into a high level of damage owing to the presence of a significant number of defects and substantial destruction. Processing of granular asphalt in a plant with the addition of a new binder and mineral material will ensure its higher technical, physical, and mechanical characteristics than when using other methods of restoring the transport and operational properties of non-rigid pavements. The theoretical studies carried out prove the possibility and feasibility of using fiber of fly ash to improve the quality and durability of granular asphalt concrete prepared from milled asphalt by hot recycling.

The introduction of fiber of fly ash into the granular asphalt mixture contributes to the uniform distribution of new bitumen on the grains of the mineral material throughout the entire layer thickness due to the combination of fiber microparticles with bitumen and structuring of the binder. Experimental laboratory studies have shown that the use of fiber of fly ash in hot granular asphalt concrete makes it possible to obtain a material with higher strength characteristics and lower water saturation and swelling.

The mechanism of interaction of fiber with bitumen in asphalt binder has been developed. A feature of the interaction is that interactions occur in bituminous layers between grains of mineral material, and microfibers of the fiber are in the zone of action of the forces of active groups of bitumen. The process of distribution of microparticles of fiber in hot granular asphalt concrete with stirring has been studied, as well as the mechanism of interaction between the components of granular asphalt concrete at all stages of its preparation (heating, mixing). The conducted studies of the mixture of fiber and bitumen fully confirm the theoretical premises on the chemical interaction of these substances by combining fiber microparticles of fly ash and the most active part of bitumen – asphaltenes and asphaltenic acids.

The design of the composition of hot granular asphalt concrete in terms of adding new crushed stone was carried out in relation to the ratio of bitumen in the milled granular asphalt and the amount of added binder, and showed that the optimal amount of mineral material that can be introduced is up to 30%. Based on the study of the structure and chemical composition of bitumen, it can be argued that the interaction of the binder with microparticles of fiber occurs according to the type of chemical compound present as the active components of these substances.

There is a diffuse penetration of a viscous liquid – bitumen – into the structure of fiber particles, which is facilitated by the presence of pores and a rough surface of the particles. The use of fiber of fly ash is an extension of the range of additives that are used in granular asphalt concrete and shows the possibility of its use in traditional asphalt concrete compositions. Technological solutions have been tested that increase the performance of the pavement structure, which is ensured by the introduction of fiber of fly ash into the composition. As a result, dispersed-reinforced structures with increased crack resistance at low temperatures and resistance to the formation of plastic deformations in the summer are obtained.

The use of fiber of fly ash, either when carrying out restoration of asphalt concrete pavements using the hot recycling method or when implementing the same technology using the cold method, makes it possible to reduce the cost and ensure that the completed work results in a high-quality and durable structural layer of pavement. The resulting composition indicates the structural integrity of the formed pavement. Hot recycling allows cohesive layers of great thickness to be obtained, which are characterized by homogeneous material. This eliminates the need for liquid binders between thin layers of pavement, which is required in traditional garments.

The addition of fiber of fly ash to the asphalt concrete mixture shows a direct reduction in the cost of materials and construction work involved in the hot recycling method, since the use of fiber as a reinforcing additive increases the structural and mechanical properties of the milled asphalt concrete mixture and provides an increase in the operational properties and durability of the asphalt concrete pavement, which can be restored using suitable recycling methods.

References

[1] Pan Y, Liu G, Tang D, Han D, Li X, Zhao Y. A rutting-based optimum maintenance decision strategy of hot in-place recycling in semi-rigid base asphalt pavement. J Clean Prod. 2021;297:126663.

[2] Stimilli A, Virgili A, Giuliani F, Canestrari F. In plant production of hot recycled mixtures with high reclaimed asphalt pavement content: a performance evaluation. In: Canestrari F., Partl M. editors. 8th Rilem International Symposium on Testing and Characterization of Sustainable and Innovative Bituminous Materials, Vol. 11. Dordrecht: Springer; 2016. pp. 927–39.

[3] Stimilli A. New method to estimate the "re-activated" binder amount in recycled hot -mix asphalt. Road Mater Pavement Des. 2015;16: 442–59.

[4] Xu X, Gu H, Dong Q, Li J, Jiao S, Ren J. Quick heating method of asphalt pavement in hot in-place recycling. Constr Build Mater. 2018;178:211–8.

[5] Britchenko I, Savchenko L, Naida I, Tregubov O. Areas and means of formation of transport regional complexes and mechanisms for managing their competitiveness in Ukraine. Ikonomicheski Izsledvania. 2020;29(3):61–82.

[6] Rezvantsev VI. New method of asphalt concrete regeneration: materials of VII All-Union meeting of road builders. In: Acceleration of scientific and technical progress, increase of labour productivity and quality of road works. Moscow: Nauka; 1981; 124-136.

[7] Xunyi GK. Regenerated road asphalt concrete. Moscow: Transport; 1984.

[8] Glet W. Kaltbau weiseneinneuer Weg der Wiederver-

wendung und zur Einkapseltungkritischer Stofte. Die Asphaltstrasse. 1990;6:31–5.
[9] Sun TS. Heat transfer analysis of microwave hot-recycling for asphalt pavement. J Eng. 2020;3:1–5.
[10] Jing H, Cong Y, Zhang Y, Song L, Romanovich M. Mix ratio optimization design method for hot in-place recycled asphalt mixtures. Eng J Dyna. 2020;95:553–60.
[11] Zolotarev VA. Surface phenomena in disperse systems. Moscow: Nauka; 1999.
[12] DSTU B.2.7-46:2006. General construction cements. Technical conditions. 2006. https://dnaop.com/html/44199/doc-%D0%94%D0%A1%D0%A2%D0%A3_%D0%91_%D0%92.2.7-46-96. Accessed 19 Dec 2021.
[13] DSTU 4044. Viscous petroleum bitumen for roads. Specifications. 2001. http://online.budstandart.com/ru/catalog/doc-page.html?id_doc=45957. Accessed 19 Dec 2021.
[14] DSTU B V.2.3-39. Guidelines for the construction of pavement layers of stone materials. 2016. http://online.budstandart.com/ua/catalog/doc-page.html?id_doc=65407. Accessed 11 Feb 2022.
[15] GOST 12801-98. Materials on the basis of organic binders for road and airfield construction. Test methods. 1998. https://docs.cntd.ru/document/1200003974. Accessed 19 Dec 2021.
[16] GOST 31015-2002. Asphalt concrete mixtures and crushed stone mastic asphalt concrete. Technical specifications. 2002. https://docs.cntd.ru/document/1200031204. Accessed 19 Dec 2021.
[17] VBN B.2.3-218-002-95. Design and construction of road foundations and pavements made of stone materials, industrial wastes and cement reinforced soils. 1995. http://online.budstandart.com/ru/catalog/doc-page?id_doc=24956. Accessed 13 Nov 2021.
[18] GOST 16483.32-77 Wood. Method for determination of hygroscopicity. 1978. https://files.stroyinf.ru/Data1/20/20722/index.htm. Accessed 13 Nov 2021.
[19] GOST 7516-75 Pulp. Method for determination of swelling. 1975. https://files.stroyinf.ru/Data/354/35419.pdf. Accessed 15 Dec 2021.
[20] GOST 25139-93 Plastics. Methods for determination of flowability. 1993. https://docs.cntd.ru/document/1200020928. Accessed 13 Nov 2021.
[21] GOST 9128-2009. Asphalt concrete road mixtures, aerodromes and asphalt concrete. Technical specifications. 2009. https://docs.cntd.ru/document/1200078690. Accessed 20 Nov 2021.
[22] Savchenko L, Achkevych O, Achkevych V, Slipukha T. Development of system for stabilizing movement of power unit with rear mounted mower. Paper presented at the 20th International Scientific Conference Engineering for Rural Development; 2021pp. 750–5.
[23] Maryshev BS, Gopin OB. Regeneration of road pavement. Recyclers. Technol Technol. 2006;3:20–2.
[24] Crolley AV. New on-site hot mix asphalt resurfacing in Mississippi. Mississippi: US Transportation Research Administration; 1999.

Received 2022-04-26
Accepted 2022-07-01