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Mineral Powders for Asphalt Concrete from Granulated Furnace Slags

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***Abstract*—The paper studies the properties of mineral powder, asphalt binders and structural and mechanical properties of asphalt concrete. Asphalt concrete with ground granulated slag as a mineral powder has high heat, water and frost resistance. The use of mineral powders can reduce the consumption of the binder in the production of asphalt mixes by 1-2%.**

***Keywords*—mineral powder; asphalt binder; asphalt concrete; structural and mechanical properties.**

I. Introduction

Nowadays, asphalt concrete pavements are most widely used among the improved ones, as they create maximum comfort for vehicle traffic. These coatings are used on roads of any traffic density.

Mineral powder is finely ground component and the most important structural component of asphalt concrete. Mineral powder in asphalt concrete performs many functions: it participates in the formation of a durable structure of the asphalt binder, increases the surface and adhesion strength of the mineral part and bitumen, provides the optimal thickness of the bitumen film, increases the density, water resistance and heat resistance of asphalt concrete, stabilizes the properties of bitumen and asphalt binder and participates in the formation microstructure of asphalt concrete. All these functions are performed only if the mineral powder is capable of transferring bitumen from a bulk (free) condition to a film (structured) condition [4, 8].

The properties of mineral powders as the most important structure-forming component are mainly determined and depend on the development of specific surface area, porosity, chemical and hydraulic activity. Along with the physic and chemical interaction, an important element of the interaction of bitumen with a porous mineral powder is the selective filtration of bitumen components [4, 5, 7].

The processes of interaction of bitumen with the surface of the mineral powder are decisive in the formation of the operational properties of asphalt concrete. The structuring effect of the mineral powder depends on its mineralogical composition, porosity, grinding fineness and the properties of bitumen [6, 9].

The best interaction with bitumen is shown by carbonate and carbon-containing rocks due to more intensive processes of physical and chemical adsorption on the line of bitumen - mineral material [1, 2, 12].

II. Methods and Materials

Slag materials have a high hydraulic activity, and there is experience of using hydraulically active substances as mineral powders in asphalt concrete [8].

The authors studied mineral powders obtained by grinding granulated blast-furnace slags of the Novolipetsk Metallurgical Combine, as well as the properties of asphalt binders and asphalt concrete mixtures based on them.

The chemical composition of the granulated slag of the Novolipetsk Metallurgical Combine is shown in Table 1.

TABLE I. CHEMICAL COMPOSITION OF GRANULAR FURNACE SLAG

Chemical Composition, %					
SiO₂	***CaO***	***Al₂O₃***	***MgO***	***FeO***	***прочие***
37.91	42.88	11.72	5.72	0.24	1.53

The bitumen of the BND 40/60, BND 60/90, BND 90/130, BND 130/200 grades were used as a binder. In order to compare the research results, limestone mineral powder was used as a reference.

III. Results

The test results of mineral powders according to the State Standard 32761-2014 [3] are given in table 2.

TABLE II. Properties of mineral powders

Indicators	Limestone mineral powder	Ground granulated NLMK slag	State Standard requirements 32761-2014 (MP-3)
Grain composition,% by weight:			
smaller than 2 mm	100	100	100
-//-0,125 mm	98	93	75
-//-0,063 mm	81	72	60
Porosity, % volume	33	43	не более 40
Mixture swelling of mineral powder with bitumen, % volume	1.2	0.98	не более 3.0
Bitumen indicator, g/100 cm^3	48	60.0	не более 80

The increased porosity of ground granulated slag is associated with the content of Al_2O_3 aluminum sesquioxides (not more than 1.7 as per the State Standard 32761-2014), which may adversely affect the water resistance of asphalt binder. The water resistance of asphalt binders is investigated.

The specific surface of mineral powders for the preparation of asphalt binders was 3800–4000 cm^2 / g. The amount of BND 90/130 bitumen for the preparation of asphalt binders was selected in such a way that the initial water saturation was not less than 7-8% by volume. The increased water saturation was taken in order to reveal the undesirable properties of the powders under the action of water. It is necessary to note that it was not possible to achieve the same water saturation (Table 3), but for tests of this kind with increased water saturation, the deviation of 0.8% is not significant.

TABLE III. SELECTION OF BITUMEN IN ASPHALT BINDER ON SINGLE-WATER SATURATION

% bitumen (over 100% of the mineral part)	Granulated blast furnace slag of Novolipetsk Metallurgical Combine	% bitumen (over 100% of the mineral part)	Limestone mineral powder
11	10.1	20	10.5
12 +	8.5	21 +	7.7
13	6.3	22	6.8

Note: + – mixtures accepted for water resistance testing.

The table shows that in order to achieve certain water saturation, less bitumen is required for ground granulated blast furnace slag than for limestone mineral powder. The low bitumen content to achieve the required water saturation for ground granulated slag is explained by better packing of mineral powder grains and a smaller bitumen film thickness.

The results of studies of asphalt binders for long-term water resistance are shown in Table 4.

TABLE IV. EFFECTS OF LONG-TERM WATER-SATURATION ON WATER RESISTANCE OF ASPHALT-BINDING SUBSTANCES

The compositions of asphalt binders and their initial properties	**Curing time in water, day**	**Water saturation % of volume**	**Swelling, % of volume**	**Compressive strength at temperature +20 ° C**	**Water resistance coefficient**
Ground granulated furnace slag of the Novolipetsk Metallurgical Combine - 100%,BND 90/130 bitumen - 12%; R_{20} = 4.8 MPa, B = 8.50%	0.1	8.50	0.98	4.8	1.00
	2	8.60	0.66	5.6	0.96
	7	9.04	1.72	4.4	0.92
	14	11.66	1.96	4.7	0.98
	28	9.80	1.63	5.2	1.08
	40	8.10	1.73	6.4	1.33
	60	7.85	-	6.2	1.31
Limestone mineral powder - 100%, BND 90/130 bitumen - 21%; R_{20} = 7.3 MPa, B = 7.7%	0.1	10.43	1.45	5.5	0.75
	2	13.08	3.96	4.8	0.65
	7	22.09	11.14	2.9	0.31
	14	36.49	21.13	1.2	0.16
	28	38.35	26.29	1.0	0.14
	40	The samples have cracks		1.0	0.14
	60	The samples fall apart		-	-

As it can be seen from the results, the water resistance of asphalt binders based on slag materials is significantly higher than on limestone mineral powder. After prolonged water saturation (28–40 days), asphalt binders on limestone mineral powder lose their bearing capacity and fall apart. Asphalt binder on the mineral powder from granulated furnace slag after prolonged water saturation up to 14 days reduces and then gains strength. The presence of oxides of alkaline earth metals (CaO and MgO) in the composition of granulated slag allows suggesting the hydrolysis and hydration of slag materials, the intense interaction of bitumen with the porous slag surface. The interaction of bitumen with ground slag materials is characterized not only by a developed internal and external surface, but also by the presence of active centers in the form of calcium and magnesium cations, as well as acute-angled peaks on which asphaltenes and resins are adsorbed. The physical, chemical and mechanical processes take place with the formation of strong adhesive bonds at the line between bitumen and mineral material [11].

The strength of the microstructure varies dramatically depending on the content and type of mineral powder, as well as the viscosity of the used bitumen (Fig. 1). When the system is filled with mineral powder up to a certain limit, the strength of the binary system (bitumen - mineral powder) increases, and then sharply decreases. With the increase in the concentration of mineral powder, the distance between individual particles becomes smaller than the sum of the thicknesses of two structured shells on the particles of mineral powder, and the properties of the asphalt binder are determined by the degree of interaction of these layers.

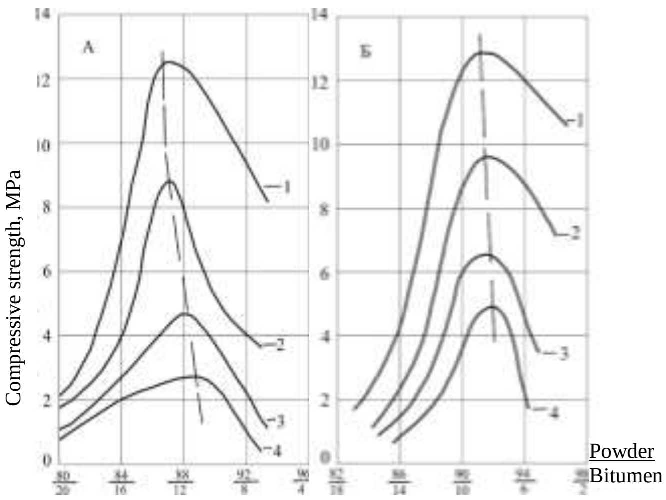

Fig. 1. Strength of the asphalt binder, depending on the degree of filling with mineral powder and the grade of bitumen: A - ground granulated slag; B - limestone mineral powder: 1 - BND 40/60 grade bitumen; 2 –BND 60/90 grade bitumen; 3 –BND 90/130 grade bitumen; 4 - BND 130/200 bitumen

With the increase in the amount of mineral powder above the optimal content, air gaps form in the system, the porosity increases, some particles are not enveloped in bitumen, and solid phase contacts appear. It is necessary to note that the structure-forming concentration of the mineral powder depends on its nature and on the viscosity of the bitumen (Table 5).

TABLE V. EFFECT OF VISCOSITY OF BITUMEN AND TYPE OF MINERAL POWDER ON STRUCTURE-FORMING CONCENTRATION

Type of mineral powder	**Structure-Forming Concentration (mineral powder / bitumen), %, bitumen of grades**			
	BND 40/60	***BND 60/90***	***BND 90/130***	***BND 30/200***
Limestone	91.5 / 8.5	91.7 / 8.3	91.8 / 8,2	92 / 8
Ground granulated furnace slag	86.5 / 13.5	87 / 13	88 / 12	89 / 11

The results presented in Table 5 show that for bitumens saturated with asphaltenes (BND 40/60 bitumen), the structure-forming concentration shifts towards the decrease in the mineral powder content and, conversely, for bitumens with a lower asphaltenes content (BND 130/200 bitumen a) structure-forming concentration of the mineral powder increases.

Each binder has its own optimum film thickness, depending on the physic and chemical properties of the material. In asphalt binder, prepared on bitumens of different viscosity, the dependence of strength on the viscosity of the binder is clearly seen.

The difference in the optimal amount of bitumen can be explained by the structure of bitumen films. In less viscous bitumen, the content of oils is higher than that of resins and asphaltenes. The oils diffuse into the pores of the mineral material, while the resins and asphaltenes remain on the surface.

In the most viscous bitumen, the thickness of the bitumen film will always be greater than in less viscous bitumens. Thus, in an asphalt-binding substance with optimal structure, bitumen and mineral powder are in the best ratio. The violation of this ratio leads to the sharp decrease in the strength of asphalt binder. The strengths of asphalt binders on ground slag and limestone mineral powder are almost the same. Therefore, the structuring ability of mineral powders is comparable to each other.

The high strength of the asphalt binder of the optimal structure is due to the fact that the bitumen film is completely in the zone of action of the surface forces of the mineral grains.

The optimum thickness of the bitumen film, calculated by the formula of I.V. Korolev [8], is given in table 6.

TABLE VI. OPTIMAL THICKNESS OF THE BITUMEN FILM OF ASPHALT BINDER

Mineral powder	**Optimum bitumen film thickness, mcm, bitumen of grades**			
	BND 40/60	***BND 60/90***	***BND 90/130***	***BND 130/200***
Limestone	0.39	0.37	0.36	0.34
Granulated furnace slag	0.39	0.34	0.31	0.28

For limestone mineral powder and ground granulated slag, the film thickness on the particles is about the same for more viscous bitumen. With the decrease in the viscosity of bitumen, the thickness of the bitumen film on the ground granulated slag decreases.

Insufficient corrosion resistance is the most common cause of premature destruction of asphalt concrete pavements. Asphalt concrete is destroyed mainly by prolonged or periodic watering, and especially as a result of alternate freezing and thawing.

Table 7 shows the physic and mechanical properties of asphalt concrete mixtures of the selected particle size distribution depending on the storage conditions.

The analysis of the results shows that asphalt concrete mixtures on mineral powders from granulated furnace slag require an optimal composition of 1% of bitumen less than limestone mineral powder. In asphalt mixtures on mineral powders from granulated blast furnace slag, heat resistance and water resistance are significantly increased after prolonged storage in air, humid and water conditions.

With the course of time, the process of structure formation continues in asphalt concrete. The fluctuations in compressive strength can be explained from the standpoint of the diffuse theory of adhesion and the processes of physicochemical interaction of slag materials with bitumen. In the initial period, asphalt-concrete mixture is prepared, selective diffusion of bitumen components occurs in the pores of ground granulated slag.

Oils, as the most mobile part of bitumen, diffuse into the pores of the slag material, and resins and asphaltenes adsorb on its surface [11].

TABLE VII. WATER RESISTANCE OF ASPHALT-CONCRETE MIXTURES OF THE MATERIAL GRANULOMETRIC COMPOSITION DEPENDING ON THE STORAGE CONDITIONS

Compositions of asphalt concrete mixtures	**Storage periods, day**	**Storage conditions**								
		dry			**moist**			**water**		
		Limits of compressive strength, MPa, at a temperature of ° C		***Water resistance coefficient***	***Limits of compressive strength, MPa, at a temperature of ° C***		***Water resistance coefficient***	***Limits of compressive strength, MPa, at a temperature of ° C***		***Water resistance coefficient***
		20	***50***		***20***	***50***		***20***	***50***	
Quartz sand - 88%, limestone mineral powder - 12%, BND 90/130 bitumen - 7%	10	2.9	1.2	0.93	2.4	1.2	0.89	2.4	1.2	0.86
	20	2.9	1.3	0.93	2.5	1.2	0.92	2.4	1.2	0.88
	40	2.7	1.3	0.92	2.5	1.1	0.94	2.3	0.8	0.86
	60	2.6	1.4	0.92	2.5	1.1	0.92	2.2	0.8	0.86
Quartz sand - 88%, ground granulated slag - 12%, BND 90/130 bitumen - 6%	10	3.0	1.3	0.80	3.1	1.3	0.95	3.6	1.4	0.98
	20	3.6	1.4	0.91	3.7	1.4	0.95	3.6	1.6	0.98
	40	4.4	1.5	0.94	4.7	1.5	0.94	4.8	1.7	0.95
	60	5.4	1.6	0.99	5.6	1.7	0.95	5.7	1.8	0.98

In this case, the surface layer is enriched with resins and asphaltenes. Further, the processes of physic and chemical interaction of bitumen with the surface of the slag material occur, organic-mineral compounds of the type Me-O-O C R and organosilicon compounds of the Si – O – R type are formed, which has been proved by infrared spectroscopy methods [10].

The formation of organic compounds, insoluble in water leads to the creation of a structural-mechanical barrier, which has a shielding effect and reduces the selective filtration of bitumen components into the pores of the mineral material [11].

Thermodynamic balance is established between the resins and asphaltenes adsorbed on the slag surface and the oils diffused into its pores. Under the influence of the difference of thermodynamic potentials and capillary forces, the back diffusion of oils into resins and asphaltenes occurs. The surface layer is enriched with them and becomes more plastic. The addition of active mineral powder not only improves structural bonds and increases the density of asphalt concrete, but also provides a more homogeneous fine-pore structure of this material, characterized by a large number of closed pores, which play the role of micro-shock absorbers, absorbing the pressure of freezing water.

Slag is hydraulically active mineral material. It has a microporous structure, and therefore it can be assumed that asphalt concrete with mineral powders from slag materials will have sufficient frost resistance.

The authors conducted the studies of the structural and mechanical properties of asphalt concrete in finely divided form as a mineral powder.

The research results are presented in Table 8.

TABLE VIII. INFLUENCE OF FREEZING-THAWING ON THE STRUCTURAL AND MECHANICAL PROPERTIES OF ASPHALT-CONCRETE

Compositions of asphalt concrete mixtures	**Number of freezing-thawing cycles**	**Average density, g/cm^3**	**Water saturation, % volume**	**Swelling, % volume**	**Limits of compressive strength, MPa, at a temperature of ° C**			**Frost resistance coefficient**	**Water resistance coefficient**
					20	0	50		
Quartz sand - 88%, ground granulated slag - 12%, BND 90/130 bitumen - 6%	0	2.30	1.51	0.20	3.37	5.87	1.56	-	1.00
	25	2.30	0.84	0.20	3.62	6.25	2.08	1.07	1.04
	50	2.30	0.67	0.00	3.87	6.50	1.77	0.85	1.03
	75	2.32	0.13	0.20	4.12	6.75	1.67	1.22	0.94
Quartz sand - 88%, limestone mineral powder - 12%, BND 90/130 bitumen - 7%	0	2.30	1.10	0.00	4.20	6.30	1.87	-	1.00
	25	2.29	1.69	0.40	4.00	7.00	1.87	0.96	0.86
	50	2.29	0.79	0.30	3.62	7.00	1.77	0.86	0.81
	75	2.28	1.19	0.80	3.50	6.75	1.77	0.83	0.78

The analysis of the results presented in Table 8 indicates that frost resistance of asphalt concrete with mineral powder from granulated furnace slag is increased in comparison with asphalt concrete on limestone mineral powder.

The increased frost resistance of asphalt concrete with mineral powders from slag materials is explained by its specific properties that are absent in natural stone materials, the processes of structure formation and the physic and chemical interaction of slag materials with bitumen.

IV. Conclusion

1. Ground granulated furnace slag can be used as a mineral powder in the manufacture of asphalt concrete mixtures.

2. The use of mineral powders from slag materials reduces binder consumption in the production of asphalt mixes by 1-2%.

3. Asphalt concrete on slag mineral powders has high heat, water and frost resistance.

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