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Determination of the possibility of using phosphorus slag in the road industry

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The use of crushed, granulated slag is now a rational direction in the use of phosphorus waste in various areas of construction. The modern state of science and technology and the accumulated experience allow to use almost all types of metallurgical slag for the production of road-building materials. The use of slag from other industries will expand the raw material base and improve its geographical location, increase material production and quality, reduce the distance of material transportation and reduce the road construction cost. The use of slag is an environmental task that will have a social impact. The study theoretically proved and experimentally established the feasibility of laying asphalt concrete coatings with phosphorus slag on roadways. The technology of asphalt–concrete mixture preparations and compaction is developed, which ensures high operational properties of road surfaces. It was established that it is possible to produce homogeneous asphalt concrete with phosphorus slag, gravel, mineral powder, and sand, unlike traditional mineral materials of natural origin, such as limestone.

Keywords: *road management, phosphorus slag, asphalt concrete, aggregate, metallurgy waste*

1. Introduction

At present, the use of local building materials, including secondary products of ferrous and non-ferrous metallurgy, i.e., slags, is increasing during the construction, reconstruction, and repair of roads. They are used in all layers of construction of road pavement, including as a mineral filler for asphalt concrete when constructing asphalt concrete pavements for roads of all categories and values. Therefore, it becomes urgent to study the transport and operational indicators of roads when these materials are used in the construction layers, as well as the features of their operation in different periods of the year [1].

The condition of the road is determined by the condition of the carriageway (roadway surface and pavement), the condition of the roadbase and the runway, the presence of elements of road engineering and traffic information, the condition of the artificial and drainage structures, the level of traffic safety, and traffic load [2].

According to DBN V.2.3-4, VBN V.2.3-218-186, calculated load, traffic intensity, and composition, type of surface, climate zone, and hydrological and soil conditions are normalized. The equivalence of the surface and the adhesion coefficient in road safety shall be determined according to DSTU B.2.3-3, RV.2.3-218-02071168-385 and DSTU 218.02070915-102. The roughness and adhesion values of the covered vehicle are reflected

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in DSTU 3587 and are determined in accordance with DSTU B V.2.3-3, DSTU B V.2.3-8 [3].

The level of traffic congestion is calculated as the fraction of the actual traffic intensity to the road capacity according to P-G.1-218-113. Thus, the material of the pavement must correspond to the values of the technical and economic parameters specified in the normative literature. The longer these parameters are maintained at a permissible (normalized) level, the better the material. However, the influence of the structure and properties of layers of the pavement and the kinds of mineral material of the asphalt concrete on the technical and economic parameters of roads is still not sufficiently investigated [3].

When applying new mineral materials that have distinct properties to prepare asphalt concrete, it is obligatory to study not only their physical properties, but also their technical and economic parameters in road performance. The evaluation of the performance of pavements made of asphalt concrete will allow us to explain and underpin with evidence its application in the construction of road pavements.

Of all ferrous and nonferrous types of slag, blast furnace slag is the most suitable for road construction and is less susceptible to various types of degradation. Slag materials with the specific properties desired are produced by adjusting the cooldown speed of the slag conflation. The cooldown speed conditions the chemical activities of the material—its physical and mechanical properties, its structure and composition, and its reactions with bitumen. With rapid cool-down, slag is converted into 0–2.0 mm sand with high hydraulic properties. When the slag is slowly cooled, using thermal energy is prefered for crystallization processes. The material achieves high strength, but to a large extent loses hydraulic binding properties [4].

The production of phosphorus and its compounds in Ukraine is based on phosphate deposits and is associated with large amounts of slag. Currently, the main manufacturer of phosphorus products is Sumychimprom, and it was at this enterprise that the slag shop was designed. The volume of construction materials and products derived from phosphorus slag melts (with a yield of 11 tons per ton of phosphorus) will grow, as will production of the company's main products. In the near future, the amount of liquid phosphorus slag will be about 30% of the blast-furnace slag output [5].

The enterprise operates an industrial facility for the production of rubble stone from cast slag, according to the trench technology scheme. Rubble stone is available in standard fractions of 5–10, 10–20, 20–40, and 40–70 mm. Waste slag from processing consists of slag cuts of the fraction 0–10 mm. At the same time, 10 m tons of unprocessed cast slag into rubble stone have already accumulated in the terricons [6].

The use of crushed, granulated slag is now a rational way of dealing with the phosphorus slag industry in various construction fields. The modern state of science and technology and the accumulated experience allow to use almost all types of metallurgical slag for road building materials production. The use of slag from other industries will expand the raw material base and improve its geographical location, increase material production and quality, reduce the distance of material transportation, and reduce the road construction cost. The use of slag is also an environmentally sound approach that will have a positive social impact [7].

In many regions of Ukraine, the shortage of natural stone materials can be successfully eliminated by using phosphorus slag production as rubble stone, mineral powder, and sand. A reduction in the cost and increase in the quality of road construction can be achieved only by introducing nano materials into the construction and rational use of new durable and cheap local materials, as well as expanding the raw material base through the use of cheap industrial waste and related industrial products. This will not only increase the length of hard-surfaced roads, but also reduce the construction cost and improve road quality, especially in areas where natural stone materials are not available.

In this regard, the purpose of this research is to determine the feasibility of applying phosphorus slag when building roads. To achieve this purpose, the following objectives must be met:

1. study phosphorus slag as a mineral component of asphalt concrete;

2. determine features of asphalt concrete structuring with a complex use of phosphorus slag;
3. analyze the properties of asphalt concrete based on phosphorus slag;
4. develop the technology for construction of asphalt concrete surfaces using phosphorus slag.

2. Materials and methods

The condition of the road is determined by the state of the carriageway, the condition of the subgrade and the right-of-way, the presence of elements of road engineering and traffic information, the condition of the artificial and drainage structures, the level of traffic safety and traffic load.

In order to determine the specific characteristics of road performance created by the addition of slag materials into asphalt concrete, road pavement durability, evenness, and adhesion coefficient should be chosen as the main technical and economic parameters [8]. The speed of traffic flow is taken as an index reflecting the state of highways. One of the asphalt concrete components is rubble stone from cast slag. One of the distinctive features of the gravel examined is its porosity, which is related to the production technology, that is, the gasification of the melt slag is currently subject to directed regulation.

The slag melt is poured into a single pit; in this mixture, there are strongly poriferous areas along with dense aggregate. The inhomogeneity of crushed slag cannot be simply considered a disadvantage that must be overcome, because this material has been widely used in industrial and civil construction as one of the potential porous fillers [9].

The following raw materials were examined to achieve the objectives:

1. Phosphorus slag
2. Crushed rock from cast phosphorus slag (a large filler for asphalt concrete mixture)
3. Granulated phosphorus slag as sand (a fine aggregate for asphalt concrete mixture)
4. Mineral powder based on ground and granulated slag
5. Standard asphalt concrete
6. Asphalt concrete with phosphorus slag

The following research methods were used to present more broadly the structure formation in asphalt concrete with phosphorus slag:

1. Consideration of mineralogical, chemical, and petrographic composition of phosphorus slags.
2. Consideration of the process of interaction of phosphorus slag with bitumen in the projected compositions of asphalt concrete.
3. Study of the influence of the composition and the kind of phosphorus slag on the quality of asphalt concrete.
4. Study of physical and mechanical characteristics of the asphalt concrete mixture obtained with phosphorus slag.
5. Study of the operational properties of the asphalt concrete obtained with phosphorus slag.
6. Development of asphalt concrete technology using phosphorus slag.
7. Research and production testing of the results.

In our research, we regard the porosity of cast slag gravel as a large mineral filler for asphalt concrete. There are two main approaches to study the properties of porous fillers: (1) the examination of the average combination of grains; (2) the examination of a separate grain.

In addition to separation in a boiling sand layer, we used a method for separating mesh materials by average grain density in a mixture of organic solvents of different densities. Organic solvents are used because they do not react with mineral compounds [10].

This research continued with the study of the influence of porosity on the characteristics of asphalt concrete and the optimal content of bitumen in mixtures. It was established that, having determined the bulk density of rubble stone in the

laboratory, it was easy to predict any characteristic of its physical–mechanical properties. Hot asphalt concrete mixtures in cast slag gravel were studied, has and it was shown that they have different bulk densities, and hence different components of dense and porous grains [11].

For this purpose, a representative average sample of slag gravel was divided into 10 samples with different bulk densities (from 0.89 g/cm^3 to 1.48 g/cm^3). The sample with a bulk density of 0.89 g/cm^3 consisted mainly of highly porous and pumiceous rubble stone, while a sample with a bulk density of 1.48 g/cm^3 consisted of dense rubble stone without visible porosity. Rubble stone with a greater or lesser degree of porosity was found in the intermediate samples. Then, crushed sand of identical grain composition was prepared from half of the content of each sample.

Based on the mineral material obtained, fine-grained asphalt concrete mixtures were selected and tested. Inactivated slag was taken as a mineral powder for all mixtures. The amount of bitumen ranged from 4.5% to 6.0% of the weight of the mineral part, taking into account the porosity of slag gravel. All studies were conducted with a large number of parallel tests to eliminate accidental errors.

The choice of liquids and the method of separation are stipulated by the features of the rubble stone from the cast slag. Since the average density of individual gravel ranges from 1.95 g/cm^3 to 2.89 g/cm^3, a number of organic liquids with different densities were considered. Tetrabromotan (CHB2 CHB2), with a density of d = 2.952 g/cm^3 and a diluent of acetone (CH3COOCH3) with a density of 0.786 g/cm^3 were the most appropriate. After short-term mixing at any ratio, these liquids form insoluble solutions, resulting in density ranging from 1.95 g/cm^3 to 2.95 g/cm^3. This range is sufficient to divide the material by its average density. In the process of division, glass vessels were installed in the fume hood according to the number of dividing swords, slag separation trays, and a large desiccator with slag gravel which was draught to a constant mass. Vessels with liquids of densities varying from d = 2.95 g/cm^3 to d = 1.95 g/cm^3 with a density interval of 0.2 g/cm^3 were placed successively, from the heaviest medium to the lightest one [12].

In order to separate the rubble stone from the cast slag by average grain density in a liquid medium, an average representative sample of rubble stone of 10–20 mm was taken. Slag gravel from the desiccator was immersed in small portions into the vessel with the densest medium (d = 2.95 g/cm^3), the popped grains were moved into the second vessel (d = 2.75 g/cm^3), the popped grains in the second vessel were moved the third one and so on. Grains, which popped in the medium with the lowest density (d = 1.95 g/cm^3), were transferred to the tray [13]. These are the lightest grains with an average density of less than 1.95 g/cm^3. The bottom grains were transferred to the next tray with a mean density interval of 1.95–2.15 g/cm^3, and from the next vessel with density d = 2.15. r/cm^3, they were moved on a tray with a medium density interval of 2.15–2.35 g/cm^3, and so forth. After vacuuming, which was conducted to remove liquid and odour residues from the pores, the separated slag was dried to a constant mass and used for further research.

After separating each tray, 10 grains of crushed stone were selected, which determined the actual average density of each grain by waxing. The linear relationship between the values of the true average grain density (ρm fact.) and the weighted average grain density obtained as a result of the experiment (ρm dos.) indicates the validity of the experiment. The determination of the percentage of the grains of each average density division by mass to the total mass of the tube showed that the highest grain content lies in the range of 2.55–2.75 g/cm^3 and is 35.9%. The second largest concentration of rubble stone has an average density of 2.75–2.95 g/cm^3. Thus, 66.2% of rubble stone grains have an average density of more than 2.55 g/cm^3. Grains with an average density of less than 1.95 g/cm^3 contain 8.7% by mass, the remaining grains are crushed with to mean density of 1.95 to 2.55 g/cm^3.

A visual examination of the crushed stone with different average densities showed that it had a visible structure. Thus, rubble stone with an average density of more than 2.75 g/cm^3 has a dense structure without visible porosity. Rubble stone

with an average density of 2.55–2.75 g/cm^3 has a barely visible fine-pored structure.

As the average density decreases, the fine-porous structure becomes medium-pored and spongy. Finally, rubble stone with a mean density of 1.95 g/cm^3 has a pronounced pumiceous structure. Granulated phosphorus slag is an artificial material similar to the grain composition with natural coarse sand. Grains of more than 5 mm are practically absent in the granulated slag. Large slag grains have an extended surface and complex pores and caverns, whereas the tiniest grains have a globular shape [14].

The grain composition of phosphorus granulated slag is as follows. The material fineness modulus ranges from 2.60 to 3.27; the total residue from the grid No. 0.63 is 60.0%–70.0%; the particle content with the No. 0.14 mesh does not exceed 5% by mass; the dust particle number determined by the torsion method is 1.0–2.0%. The following physical and mechanical characteristics of phosphorus granular slag can be singled out:

- absolute density (2.89 Г/СМ^3),
- mean density (1.22–1.29 Г/СМ^3),
- porosity (54–56%),
- organic impurities (absent),

Table 1. Comparison of the characteristics of granulated phosphorus slag and the requirements

Indices	**Granulated phosphorus slag**	**DSTU B V.2.7–149**
Large natural sand size module	2.60–3,.7	>2.5
Total residue on sieve 0.63% by mass	60–70	>50
Grains larger than 10 mm	–	≤0,5
Grains of 5–10 mm, % by mass	1.0	≤5
Number of dust and clay particles, % by mass	1.0–2.0	≤3
Clay, % by weight	–	=0.5

- mass loss in 25 freezing and thawing cycles,
- the adhesion of phosphorus slag to the bituminous cement BND 60/90, BND 90/130, and BND 130/200 is sufficient.

The high content of CaO and a rough grain surface result in sufficient adhesion of bitumen to slag. Thus, granulated phosphorus slag approximates the requirements of VDTU B.2.7–149 for large sands with a size modulus of 25 mm by the grain residue and physical–mechanical properties [15]. Numerous studies of asphalt concrete structure formation made it possible to identify the main structural factors as follows:

1. the grain composition of a mineral structure;
2. properties of stone material surface;
3. properties and quantity of weight applied.

In addition to the main factors listed above, other factors related to the manufacturing process and the brushing of mixtures have a very significant impact on the asphalt concrete structural process. The properties of asphalt concrete mixtures and asphalt concrete compounds are continuously changing from the moment of consolidation, in a mixer, during transportation, stacking, sealing, and also during their performance as a road surface.

Consequently, it is possible to assume that during the construction of asphalt concrete coatings with the integrated use of phosphorus slag, the main structural factors will be the following ones: the grain composition of the mineral structure of asphalt concrete, in which all types of structures (macro-, meso-, and microstructure) will consist of homogeneous components, that is, phosphorus slag (rubble stone, sand, mineral powder) and bitumen [16].

Thus, asphalt will be based on a homogeneous mineral material with the following characteristics:

- phosphorus slag, since it is poriferous and has a large specific surface;
- the surface and structure of phosphorus slag, as well as its chemical and mineralogical composition, will influence its interaction with bitumen and the structure of asphalt concrete in general [17].

All of these factors need to be manifested both in the testing and in the control experiments [18]. In order to examine the interaction of bitumen with slag gravel, sampling of fine-pored, medium-pored, spongy, cellular, and pumiceous structures were chosen. The experiments were conducted with bitumen BCD 60/90 and BND 90/130 by modifying the materials' surface covered with bitumen. The experiments showed that 70% of bitumen film is retained on dense and fine-pored samples, 60% of such a film remains on medium-pored films, and 50% of bitumen film is retained on cellular and pumiceous films.

These results can be explained in the following way: Bitumen, which is the most similar to slag, is sorbed on the mineral surface, and the quality of adhesion is determined by the surface roughness. Less active bitumen is sorbed into small pores of a material. Such components as oils are filtered inside by big pores. In case a bitumen film is washed away by water, bitumen fills cellular and pumiceous structures. Therefore, the surface, which is covered with a bitumen film on dense and fine-pored structures, is more extended than that on spongy ones. As a result, it is quite difficult to establish the adhesion quality of bitumen with slag gravel of different characteristics [19].

Selective adsorption is a more accurate method of determining adhesion quality [20]. This method was used to determine the adhesion quality of bitumen on mineral materials with different chemical and mineralogical compositions.

The results of the studies showed that the adhesion value is proportional to the total amount of surface of the material covered by bitumen. Consequently, with the growth of the initial bitumen surface, the adhesion also grows. Limestone showed the highest adhesion level, while the lowest one was shown by granite. The adhesion of the slag is slightly lower than that of limestone (5–10%) and much higher than that of granite (20–30%) and lies between 70% and 85%.

Hence, the rough surface and composition of the phosphorus slag ensure strong adhesion with bituminous cement [21]. Accordingly, the results of the interaction of the phosphorus slag with bituminous cement prove the legitimacy of the the hypothesis about the intensity of the contact 'bitumen–phosphorus slag' tested by the petrochemical recalculation method [22].

3. Results

3.1. Mineralogical, petrographic, and chemical composition of phosphorus slag

The slag is produced by electrothermal distillation of yellow phosphorus of calcium phosphate with carbonite and silica stone at a temperature of 1350–1550°C in reaction (Eq. 1):

$$Ca(PO4)2 + 5C + 3SiO2 = 3CaSiO2 + 2P + 5CO \quad (1)$$

The principal source material is phosphate. The chemical structure of phosphorus slag corresponds to the regulation of electrothermal phosphorus waste.

Table 2 shows the chemical structure of the cast slag produced by the phosphorus plant in Sumy.

The composition of the main oxides is presented in Table 3.

The chemical structure of the granulated phosphorus slag produced by Guizhou Kailin Co. Ltd. (Guiyang, China) is the same [23] as illustrated by Figure 1.

The chemical test of the water extractor shows that phosphorus slag contains only a few water-soluble salts. The reaction of the water extractor is weakly alkaline. The results of the analysis of the water extractor from the granulated phosphorus slag after a long exposure in water are consistent with the results of the studies. Thus, phosphorus slag has a solid crystal order due to low iron oxide and manganese content and P_2O_5 above 0.25.

It is customary to conventionally divide the slag chemical composition by a modulus that relates the total amount of the principal oxides to the total amount of acidic oxides [24]. The chemical test results demonstrated that the main components of slag (the basicity factor varied between 1.02 and 1.22) contained two major components, i.e., calcium oxide and silica stone, comprising 88% of the composition [25].

In contrast to blast-furnace and furnace slag, phosphorus slag contains such components as P_2O_5

Table 2. Chemical structure of cast slag

Components	SiO_2	Al_2O_3	Fe_2O_3	FeO^+ MnO	CaO	MgO	SO_3	N_2O^+ K_2O^+ TiO_2	CaF_2	P_2O_5
Composition, %	38–43	1.8–4.1	0.3–1.1	0.2–0.4	43–48	2.0–5.5	0.1–0.6	0.7–1.1	3.4–3.9	1.2–2.2

Table 3. Main oxide composition

Components	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaF_2	P_2O_5
Composition, %	44–47	40–44	3–4	up to 1.0	up to 3.0	up to 2.5	0.5–2.0

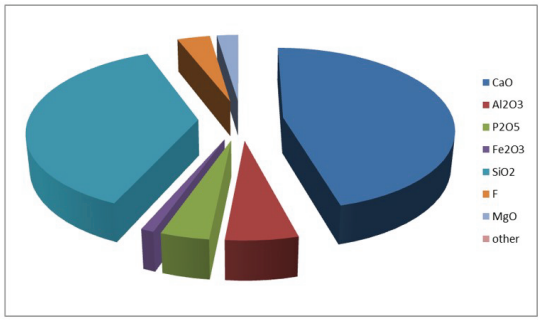


Fig. 1. Chemical composition of slag [Guizhou Kailin Co. Ltd., Guiyang, China]

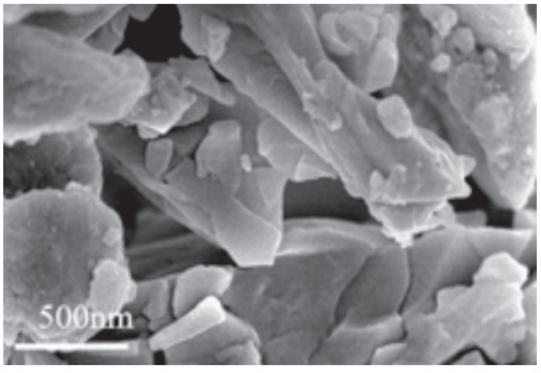


Fig. 2. Micrograph of phosphorus slag

and Fe. High-density alloys (Fe_2O_3, FeO, TiO_2, MnO), which are characteristic of metallurgical slag, are found in low amounts, making it close to natural rocks. Phosphorus slag has low activity with the activity module being within 0.03 and 0.06.

3.2. Mineralogical structure of cast and granulated slag

The mineralogical structure of the crystalline lattice of cast and granulated slag is determined by petrographic and X-ray crystallographic analyses [26].

As can be observed in Figure 2, the structure of cast slag is full-crystal, fine-pored, and homogeneous. Crystallization is clear and complete. There is almost no residual crystalline melt (vitreous phase). The main crystalline phase is pseudo-wollastonite (α-CaO*SiO_2), crystallized as glass-shaped, prolonged, fibrous, uncoloured prisms with large bi-refraction Ng = 1,650; Np = 1600. Its idiomorphic crystals are cut in a homogeneous interlacement and create an intercertal structure characteristic of the effusion basalt rocks. The length of the crystals is up to 0.0016 mm. The ratio of pseudo-wollastonite is 60%–65%.

Melilite is the second crystalline phase (20%–25%), which is manifested in kermanite and gehlenite. Akermanite (2 CaO • MgO * $2SiO_2$) is in the form of plate-like crystals with direct and positive prolongation, Ng = 1.630; Np = 1.600. The double refraction is low. The length of the crystals is up to 0.13 mm [26].

Gehlenite (2 CaO • Al_2O_3 • SiO_2) exists in the forms of light brown or dendritic crystals that form lattice structures that look like pedestrian structures of quartz or feldspar. The index of refraction (N = 1.650) is larger than the index of refraction of kermanite. The double refraction is low. Moreover, glass fills minor gaps in the crystals of pseudo-wollastonite and melilite. Particles of glass range from uncoloured to dark brown; they are amorphous and isotropic (+Ni). The index of

refraction is N = 1.600 + 0.005. In addition, glass also contains tiny incisions of the crystalline phase. Parawollastonite, cuspidine, and apatite crystallize as dendroid structures (5–7%) [27].

Thus, although cast slag is a human-made stone, during the cool-down process it has crystallized minerals of natural rocks. In the study, we regard the porosity of cast slag gravel as a large mineral filler for asphalt concrete. There are two main approaches for studying the properties of porous fillers: (1) the examination of the average combination of grains; (2) the examination of a separate grain.

Research on physical and mechanical characteristics of rubble stone [28] of each division interval found that the rubble stone has the following characteristics: volume density, porosity, water saturation factor, and grinding. Tests of frost resistance carried out by freezing and defrosting proved that frost resistance of rubble stone is conditioned by porosity of its grain (Table 4).

Table 4 demonstrates the tests results of fractional slag rubble stone in sodium sulphate solution received in the laboratory of the phosphorus plant of Sumy. The results of the sodium sulfuric acid freeze test showed no abnormalities in the phosphorus gravel, often found in the test of rubble stone from some natural rock types, showing a sharp incompatibility with the direct freezing method.

The data on frost resistance of rubble stone by freezing and defrosting are similar to the data obtained at the laboratory of the phosphorus plant in Sumy. Studies of the physical and mechanical characteristics of the average samples presented of rubble stone from cast slags of the Sumy phosphorus plant showed the following results:

Table 4. Results of direct freezing and thawing of slag rubble stone

Average grain density, g/cm^3	**Mass loss, % after test**				**Frost resistance grade**
	Number of cycles				
	50	100	150	200	
2.9	1.0	1.5	2.9	3.0	F200
2.8	2.0	2.3	3.2	3.9	F200
2.6	3.0	3.2	3.6	4.4	F200
2.4	3.4	4.0	6.0	–	F100
2.2	5.3	7.0	–	–	F25
2.0	6.8	7.0	–	–	F25

- absolute density 2.89–2.92 g/cm^3
- average grain density 2.40–2.83 g/cm^3
- porosity (average) 3–16%
- test mass loss: compression in dry gravel cylinder 8%–20%
- water saturation 10–27%
- abrasion test mass loss 20–30 %
- compressive strength
- dry samples 90.0–158.0 mPa
- water-saturated 80.0–130.0 mPa
- fluxing coefficient for
  - pumiceous grains 0.70
  - dense grains 0.95

No impurities are observed in the rubble stone. Dust particles do not exceed 2% of the total mass. The grain content of the plate form is 13–15%, the content of weak (pumiceous) grains is 8–10% by weight. Content of P205 is 2% by mass.

The interruption or modification of the technological procedure involves the modification of all physical and mechanical characteristics of the rubble stone. As Table 4 shows, it is evident that with the change of mean density of the raw material both physical and mechanical characteristics of the rubble stone also change. Methods involving complex study of the physical and mechanical characteristics of both rubble stone and raw material allowed us to analyse the following:

1. patterns of changes in physical properties of rubble stone and the raw material;
2. patterns between the physical and strength characteristics of the rubble stone and the raw material;
3. relationships between the strength properties of the rubble stone and the raw material, with strict consistency of physical properties. A starting characteristic, for example, may be such a determinant of the properties of rubble stone as bulk density [29].

Table 5. Physical and mechanical characteristics of rubble stone after experiments

Physical and mechanical characteristics	Numerical values of sample characteristics					
	2018			2022		
	Experimental	By nomogram	% divergence	Experimental	By nomogram	% divergence
Bulk density, g/cm^3	1.26			1.29		
Average density of grains, g/cm^3	2.39	2.39	0	2.44	2.43	0.4
Open porosity, %	6.0	6.5	9.1	5.7	5.9	3.5
Closed porosity, %	12.8	11.8	7.8	11.5	10.5	8.7
Divisibility in cylinder, % mass loss	12.6	12.4	1.6	11.6	10.6	0.6
Drum wear, % mass loss	26.2	2.60	0.8	24.7	25.2	2.1

The comparison of physical and mechanical characteristics of crushed slag materials obtained experimentally (15 samples taken at different times) with data of physical and mechanical characteristics according to a nomogram (using only bulk density) showed a variation of up to 10 relative units, which is acceptable (for illustrative purposes the results for 2 samples are presented in Table 5).

Experimental studies and analysis allowed us to classify crushed rock into cast phosphorus slag by structural traits and durability properties. Thus, it was established that the Sumy phosphorus plant produces rubble stone of four marks, with a predominance of the brand '1000' and corresponding physical and mechanical properties (Table 6).

In order to produce the mineral powder, granulated slag was milled in the laboratory ball mill for 5 hours, then the grain composition was cleaned (Table 7). Properties corresponded to the existing requirements for the nonactivated mineral powder.

As can be seen from the table, the mineral powder obtained by grinding phosphorus granulated slag meets the requirements for aerated mineral powders. Thus, phosphorus slag can be used as sand powder for asphalt concrete mixtures.

We also considered activated mineral powders based on ground granulated slag. The activation

Table 6. Classification of rubble stone by physical and mechanical properties

Type of slag concrete by structure	Mass loss with drum wear, % by mass	Mass loss during a cylinder divisibility test, % by mass	Grade of rubble stone by strength
Dense	>20	8–12	1200
Fine-pored	20–25	12–15	1000
Medium-pored	25–5	15–20	800
Pumiceous	35–45	20–35	600

of mineral powder was realized via grinding layer mills of phosphorus granular slag along with activating a mixture of surfactant with BND 60/90 bitumen. The grinding and activation process continued until the powder was finely ground and uniform in colour [30].

Since chemical slag is intermediate between acidic and base rocks, anionic and cationic activators were selected as follows:

1. Cotton goudron (gosipolian resin) is an anionic active carboxylic acid in the form of a viscous black substance produced by recycling cotton oil. The acid number is

Table 7. Comparison of slag mineral powder properties with current requirements

Indicators	**Properties of inactivated slag powder**	**DSTU B V.2.7–121**
Grain composition, % by mass		
<1.25	100	100
<0315 MM≥	99.7	90
<0.071 MM≥	85.1	70
Porosity, % by volume ≤	34.7	35
Swelling of a mineral powder mixture with bitumen, % by volume ≤	1.0	2.5
Bitumen capacity ≤	59.6	65
Humidity, % by weight ≤	0.3	1.0

55 mg KOH/g, the purification number is 150 mg KOH/g.

2. BP-3 is a cationic agent that exists in the form of a light brown paste. The acid number is 6.72 mg KOH/h, purification number is 0, and neutralization number is 340 mg NCl/h.
3. Carboxylamine is a cationic agent in the form of salt-like mass with a dark color. It is produced by the reaction of cotton goudron with triethanolamine, which functions as a low molecular nitrogenous base. The neutralization number is 670 mg NCl/h.

In order to grind slag, the laboratory ball mill was set to produce a fraction less than 0.071 mm within 70%–80%. To produce a waterproof mineral powder, the degree of waterproofing of powders with different ratios of activators was established: 1.5%, 1.0%, and 2.5%. As a result, the waterproofness of mineral powder is stable at 2.5% of any mixture. Only if a mixture of bitumen with cotton goudron is used, can its quantity be reduced to 2.0%. Based on the results, all activating mixtures must be 2.5% by mass [31].

Moreover, activated mineral powders possess the following physical and mechanical characteristics: The 40 Mpa porosity values for all their types are 15%–30%, which complies with the standards. The powder activated by the mixture of bitumen and cotton goudron results in a denser structure under loading as a result of its higher flexural properties. The bitumen capacity index for all mineral powders does not exceed 40 g, which complies with the existing standards.

The swelling test of the mixture of a mineral powder with bitumen withstands all kinds of activated mineral powders when bitumen is matched. Swelling above 1.5% is not detected in any sampling, including in the mixture with a lower content of bitumen having increased porosity (7–10%). In addition, activated powder withstands the swelling test even if bitumen has a high residual porosity level.

Therefore, the analysed types of activated mineral powders obtained from granulated phosphorus slag meet the requirements for limestone mineral powders according to physical and mechanical properties. The results showed that by varying the content of bitumen in mixtures, that is, by achieving an optimal content, it was possible to obtain asphalt concrete that met the existing requirements, using slag gravel of any structural variety [32]. However, the obtained characteristics of the asphalt concrete varied widely. Therefore, there is a question about whether characteristics of asphalt concrete significantly affects the porosity of slag gravel. By analysing each obtained set of asphalt concrete characteristics for all 10 samples and processing the results with mathematical statistics, the data shown in Table 8 were obtained.

The variation coefficient of both dry and water-saturated samples tested at +20°C is 12–13%, indicating that the open porosity of the cast slag did not significantly affect the mechanical properties of the asphalt concrete. All open pores are filled with asphalt material, which provides sufficient strength for the whole asphalt concrete composition.

At a temperature of 0°C, the proper strength of the asphalt concrete varies slightly. However, at a temperature of +50°C, as shown in Table 8, the variation coefficient of strength of asphalt concrete samples is within the permissible limit. This shows the influence of the porosity of the mineral material and quantitative content of bitumen in mixtures on heat resistance of the asphaltenes [20]. It was

Table 8. Asphalt concrete characteristics

Asphalt concrete characteristics	Absolute range	Average value	Root-average-square deviation	Coefficient of variation, %
		X	S	V
R_{20}, mPa	4.00–6.50	4.965	0.668	13.46
R_{20} water, mPa	3,53–5.28	4.427	0.548	12.38
R_{50}, mPa	1.42–2.98	2.079	0.426	20.49
R_0, mPa	7.87–9.95	9.058	0.720	7.94
K_B	0.66–1.04	0.91	0.07	8.36
Water saturation, %	0.67–7.00	2.79	1.66	59.49

not possible to obtain a clear relationship between the strength limit of asphalt concrete samples at +50°C and the bulk density of slag gravel used in mixtures. The analysis of the physical properties of all the compounds studied showed the following: there is no swelling, which is due to the chemical composition of phosphorus slag.

Based on the analysis of the relationship between the water saturation of asphalt concrete and the quantity of bitumen in mixtures, it became possible to determine the optimal content of bitumen for mixtures prepared from cast phosphorus slag with different bulk densities.

Table 9 shows the recommended bitumen consumption for asphalt concrete mixtures with different bulk densities of the cast slag gravel provided that the crushed sand is from the same crushed gravel. Thus, asphalt concrete mixtures are prepared on the basis of rubble stone with a medium porous and pumiceous structure, requiring a higher content of binder compared with asphalt concrete mixtures of dense and fine-pored rubble stone by 2–2.5%, which leads to an increase in the cost of road construction. Bitumen consumption in mixtures increases as the content of gravel grains with increased porosity and lower strength increases [30]. Therefore, it is quite natural to raise the requirements for homogeneity of cast slag gravel, as well as look for possible ways to reduce the per cent of bitumen content in mixtures.

It was determined that in the case of long-term water presence in asphalt concrete pores, hydro-adaptation of the pores' connectivity occurs, followed by the penetration of water under a bitumen film. The intensity of this process depends on the bitumen viscosity and stone properties. The water resistance of the pavement is evaluated by testing the asphalt concrete samples for long-term water resistance.

Table 9. Recommended bitumen consumption for asphalt concrete mixtures

Limit values, bulk density, g/cm^3	Recommended bitumen consumption of mineral part mass, %
0.8–1.5	from 7.0 to 7.5
1.15–1,25	6.0–7.0
1.25–1.35	5.0–6.0
1.35–1.48	5.0

The results of tests on water and frost resistance of asphalt concrete are indicative of the effectiveness of the activation of mineral powders [3]. Studies to determine frost resistance were carried out on asphalt concrete samples containing phosphorus slag. Mixtures were prepared in two types: with gravel and with sand. Bitumen BND 60/90 was used. Samples after one-day saturation under vacuum water passed long tests with alternate freezing in refrigeration chambers (4 hours per day) with temperature regimes of 0°C, −10°C, and −20°C and subsequent thawing in warm water. After 25, 50, and 75 cycles, the water saturation and strength of the samples were determined.

Resistance of asphalt concrete to deformation by bending was established on $4 \times 4 \times 16$ cm beam samplings. Asphalt concrete beams measuring $4 \times 4 \times 16$ cm were made from fine-grained composition of type B and sand composition of type D using rubble stone, crushed sand, and mineral powder to determine the influence of slag

gravel, granulated slag, and sand on deformation properties of asphalt concrete [8]. All samples were examined at a fixed bending voltage of 0.0188 MPa and a fixed temperature of +20°C. In addition, the samplings were studied at +50°C and +70°C with a bending voltage of 0.00625 MPa.

As a result, asphalt concrete of medium rubble stone with cast slag, rubble sand gravel, limestone powder, and mineral powder demonstrated the same resistance to deformation at all temperatures. Thus, at a temperature +20°C, the mean viscosity values for both mixtures are within 2.06–304.30; at a temperature of +50°C it is within 4.64–6.34; and at a temperature of +70°C, it is within 0.64–0.68. Accordingly, the time from the start of deformation to the beginning of destruction for both mixtures is also the same.

The substitution of granulated slag in the asphalt concrete mixtures of crushed sand dramatically increases the viscosity of asphalt concrete. Hence, its mean value is 1010 cpr at the test temperature of +20°C, 23.78 cpr at a temperature of +50°C, and 5.39 cpr at a temperature of +70°C. In contrast, the application of crushed sand in the medium-rubble stone mixtures reduces viscosity of asphalt concrete at temperatures +20°C and +50°C. Thus, at the same temperatures, the mean values are 72.10 and 2.77, respectively. However, at +70°C, the samples were not deformed at all.

The tests of sand asphalt concrete beams with granulated slag and mineral powders evidenced the high resistance to deformation. Consequently, the mean viscosity value is 839.15–1010.30 at a temperature of +20°C; at a temperature of +50°C, it is 11.63–14.79, and at a temperature of +70°C, it is 1.04–1.51.

Thus, a comparative evaluation of the resistance to deformation of asphalt concrete with mineral slag had a favourable impact. The ash powder also had a positive influence on the deformity of asphalt concrete [12]. The extended surface of the granulated slag increases the overall surface of mineral components within asphalt concrete and extends the contact area with bitumen. However, asphalt concrete with phosphorus slag demonstrated better outcomes (Figs. 3 and 4).

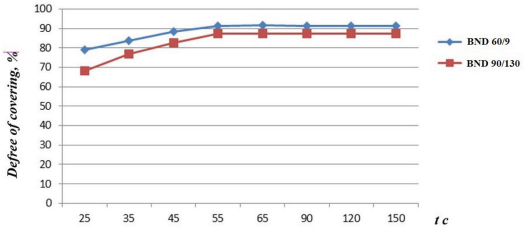


Fig. 3. Dependence of bitumen coating of mineral material on mixing time

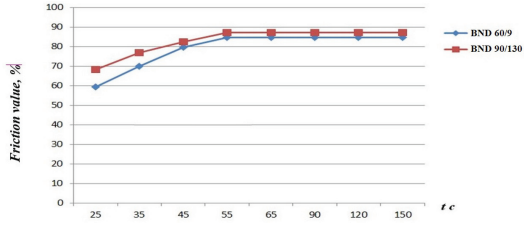


Fig. 4. Adhesion of bitumen to mineral material depending on mixing time

As can be seen from Figure 3, increasing the time over 65 sec in BND 60/90 and 45 sec in BND 90/130 does not improve the results. Moreover, the amount of adhesion is proportional to the bitumen coating intervals (Fig. 4). One of the most important elements of the mixing technology is mixing mineral materials with bitumen. The influence of phosphorus slag characteristics on adsorption of asphalt concrete mixtures was assessed by the level of coating of mineral elements with bitumen, applying the methods of dyeing, and changing the physical and mechanical characteristics of asphalt concrete.

Moreover, the influence of wet mix time on the characteristics of asphalt concrete can be seen in a change in the water resistance coefficient (Table 10). If mix time is less than 45 seconds, asphalt concrete made from bitumen BND 60/90 has a low water resistance coefficient. Meanwhile, asphalt concrete made from bitumen BND 90/130 obtains a required water resistance level if mix time is 35 seconds. Therefore, a reduction of the mix time is due to a higher wetting property of less bituminous concrete and a more intense coating of mineral slag that contains bitumen, as shown in Table 10.

Table 10. Bitumen adhesion to a mineral material coating

Bitumen grade	Mixing time, sec	Initial coating, %	Adhesion value, %
BND 60/90	25	79.2	59.3
	35	83.7	70.1
	45	88.4	79.8
	55	91.5	84.6
BND 90/130	25	84.3	68.2
	35	87.8	76.8
	45	93.0	82.6
	55	96.1	87.3

The roughness of the coating made from the slag minerals and its porosity somewhat impede the wetting because the viscous liquid sinks heavily in the coating. As a result, an air slab is created, preventing the adhesion. As the mix time increases, the encasing of the bitumen-based mineral material also grows. However, mixtures made with bitumen BND 90/130, the primary coating, grows higher than was predicted.

Consequently, the best mix time of asphalt concrete containing slag constituents and BND 60/90 bitumen is 45–65 sec, while the best duration of the mixture with BND 90/130 bitumen is 35–45 sec. The reduced bitumen viscosity results in a reduction of the required mix time and, therefore, reduced energy expenditure for preparing asphalt concrete, and increased productivity of asphalt mixers [29].

4. Discussion

Studies in the United States dwell upon the experiments carried out in 1994 in Oregon to evaluate the feasibility of applying slag in hot asphalt concrete (NMAS). These studies covered the supervision of the experimental areas over a period of five years concerning the condition and physical and mechanical properties of asphalt concrete roads with 30% steel slag. Thus, the preparation of asphalt concrete is not complicated if crushed steel slag is applied as an aggregate. In addition, the total production cost of asphalt concrete reinforced with steel slag can grow owing to the reduction of a coating area as a result of the heavier mixture used. In this regard, the test showed that the coating area made with 30% steel slag was 15% smaller than with the usual asphalt–concrete mixture type B [33].

Studies carried out by Turkish scientists demonstrate the influence of steel slag on the characteristics of a hot asphalt concrete mixture. In order to examine this, four distinct types of asphalt concrete mixtures were selected to make Marshall's samples and establish the best bitumen composition. Physical and mechanical properties of four mixtures were assessed for Marshall's resistance, tensile strength, and elasticity modulus. The mixtures, then, were tested for electric susceptibility. Finally, it was established that steel slag enhanced the physical and mechanical characteristics of asphalt concrete [34].

Research conducted by Jordanian scientists was designed to study the efficiency of using mineral material from steel slag to improve physical and mechanical characteristics of asphalt concrete. Jordan has three main steel mills. The by-product of these plants, steel slag, is randomly deposited in open areas, causing major environmental problems. The research was launched with the evaluation of the toxic effects and chemical and physical characteristics of steel slag. Subsequently, 25%, 50%, 75%, and 100% of the quantity of limestone in mixtures was changed for steel slag. The steel slag filler efficiency was assessed in terms of improvement of tensile strength, elasticity modulus, road resistance, and fatigue durability of asphalt concrete. As a result, it was proved that replacing up to 75% of large limestone with steel slag filler enhanced the characteristics of asphalt concrete. In addition, it was proven that a 25% change was optimal [35].

Investigations carried out by American and Australian researchers assessed nickel-plated, air-cooled slag as a filler in hot asphalt concrete mixtures in road construction. Nickel-plated, air-cooled slag is a liquid by-product of nickel production, solidifying at ambient temperature. The laboratory studies carried out to characterize the nickel-plated air-cooling slag included physical and mechanical tests, petrographic studies, and the selection of the hot asphalt concrete mixture [36].

Studies carried out by scientists from Oman were focused on the laboratory studies of copper slag as a filler in an asphalt concrete mixture. The mixtures were selected from different mixtures containing up to 40% copper slag aggregate. The storage modulus was tested as the main index of properties in accordance with the *Manual of Mechanical-Empirical Pavement Design* at distinct frequencies (0.1–16 Hz) and at distinct temperatures (25–60°C). Reference curves and storage modulus displacement factors and slurry mixtures were prepared. Moreover, developed curves were studied in comparison with the predicted Witczak model for 2 and 3 MO-PDG. As a result, a decline in strength was observed while slag increased [35].

Therefore, the steel slag filler is a 100% recycled product due to its physical and chemical properties, and it has a prospective role in road construction. Asphalt concrete with steel slag fillers is characterized by a higher level of porosity and adhesion due to its surface structure and chemical composition. High porosity improves waterproofness of asphalt concrete mixtures and is skidproof, while bitumen adhesion prevents penetration of water into the lower layers of road surface [37].

These characteristics enhance the quality of asphalt concrete mixtures and road surfaces, benefiting their utilization and safety. Research indicated that incorporating steel slag fillers into asphalt concrete can enhance its resistance to roughness and spalling strength. In addition, from an economic standpoint, the inclusion of steel slag can lead to cost savings by reducing the processing of natural minerals.

The steelmaking sector has the potential to decrease the expenses associated with processing and managing substantial quantities of slag. This not only extends the lifespan of roadways but also minimizes maintenance costs for road surfaces, freeing up additional resources for other ventures. From an environmental perspective, incorporating slag generated during steel production offers a direct reduction of the reliance on natural additives and the extraction of raw materials. Furthermore, integrating steel slag into asphalt concrete may lead to a reduction of the land area designated for waste disposal [38].

Although asphalt concrete with slag materials offers several beneficial characteristics, various authors pointed out the detrimental effects of slag gravel porosity on asphalt concrete. The preferential diffusion of volatile bitumen fractions into the mineral material causes its premature aging, thereby enhancing the rigidity of asphalt concrete and diminishing its ability to deform. Researchers observe the gradual strengthening of the pavement as a drawback of asphalt concrete with slag, which leads to wintertime road surface cracks.

To improve the resistance to cracking of asphalt concrete surface containing slag at low temperatures, it is advisable to employ asphalt bitumen with lower viscosity. This choice, while maintaining asphalt concrete strength, can augment its ability to withstand deformation and postpone its aging. Oxidative bitumen does not negatively affect the structural and mechanical properties of asphalt concrete with slag materials, such as increased strength, elasticity modulus, and ageing. The presence of volatile fractions of bitumen, oils, and resins in the pores of mineral material contributes to the processes of bitumen regeneration in asphalt concrete in summer.

Thus, having analysed the scientific works of many authors on the use of slag as an additive for the preparation of distinct asphalt concrete mixtures, it can be concluded that all the work was aimed at determining the possibility of using slag materials in the upper layer of road pavement. The characteristics of asphalt concrete were studied; in addition, the mechanism of interaction of bitumen with slag material was analysed to determine the optimal composition of asphalt concrete.

Observations of research sites were carried out to study the formation conditions of the surface and its resistance to cracking. However, there is no published research looking into the properties of asphalt concrete roads with slag materials during statutory service life and in different seasons. The nature and duration of changes in properties of asphalt concrete coatings with slag materials for forecasting physical and mechanical properties are not fully disclosed. Solving these problems is of greater interest as road safety and safety requirements increase [39].

In order to refine the construction technology of asphalt concrete surfaces using phosphorus slag as rubble stone, sand, and mineral powder, three test sites were built:

1. the construction of an asphalt concrete surface using cast phosphorus slag as a substitute for gravel and sand;
2. the construction of an asphalt concrete surface using ground phosphorus slag stored as mineral powder;
3. the construction of an asphalt concrete surface from evaporated phosphorus slag in the form of rubble stone, mineral powder, and sand.

The construction of test sections No. 1 and No. 2 was carried out on Sumy-Okhtyrka motorway (the technical category P) during its reconstruction.

Section No. 1 was built in 2007 (from km 499 + 800 to km 501 + 600), section No. 2 was built in 2008 (from km 493 + 800 to km 493 + 150). The development of the technology was mainly limited to refining the prescription of the activating mixture. It was experimentally established that a mixture of cotton tar and bituminous concrete with a ratio of components of 1:5:1 was the most effective. Asphalt concrete mixtures were prepared in domestic mixers, mixing for 45 sec and at temperatures 150–160°C. The temperature of mixtures before installation was from 140 to 150°C. Laying was done by asphalt stacker DC 100. The mixtures were pumped at temperatures of 120–100°C, using 3 rollers: 7 t (5–6 passes), 10 t (8–10 passes), and 12 t (12–18 passes).

Constructed sites were monitored and periodically surveyed, including the following:

- visual observation;
- testing of unbroken and undisturbed structure cuts with the determination of average density, water saturation, swelling, and compression strength of samples;
- the determination of road pavement elasticity modulus and vehicle cohesion coefficient.

The first two test groups were carried out at both sites in accordance with the applicable standards. A visual survey of the sites was conducted twice a year (in spring and autumn).

The examination of the section No. 1 showed that the coating was flat, without visible traces of destruction and peeling, and there were no signs of surge and shearing, indicating a fairly large intraabdominal friction of the mixtures, due to the roughness of slag gravel and sand and good adhesion of their surfaces to bitumen [40]. At the test site, the roughness of the surface is well preserved, which can be explained by the uneven wear of various types of slag gravel. The cuts taken from the surface showed that the strength of the asphalt concrete increased, and the rest remained at the point of requirement DSTU B V.2.7-119. The visual examination of sections No. 2 and No. 3 also showed that they were in good condition, with no visible surface changes.

The test of cuts from section No. 2 showed that replacing the traditional limestone mineral powder with a mineral powder from phosphorus granular slag did not change the asphalt concrete coating during the initial period (3 years) of its operation. The results of the tests of the cuts taken after 10 days from the surface on section No. 3 showed intensive formation of the coating, which was due to the high structural action of phosphorus slag on the bitumen.

The elastic modulus test was conducted at an air temperature +20–25°C. Thus, the average elastic modulus of the test section (E = 569.6 Mpa) and the control (E = 551.7 Mpa) was established. The determination of the asphalt concrete surface elasticity module was made at an air temperature of +35°C and a coating of +40°C, with Q = 5600 kg; P = 0.45 MPa; D = 37.9 cm; B/D = 0.24; E = 905 MPa at the test site and E = 820 Mpa at the control site.

The results obtained show that the substitution of natural mineral materials with slag in road construction does not reduce the overall road module. Moreover, the elasticity modulus of the asphalt concrete coating at the high summer temperatures is higher on the test site than on the control site and higher than the value of the design characteristics

Table 11. Results of determination of road structural elasticity modules in test and control areas

Area	Km+	L, mm	Q, kg	RO, mPa	D, cm	λ	E, mPa
Test	499+800	0.24				0.00062	800
	499+900	0.38				0.00099	500
	500+100	0.34				0.00088	563
	500+300	0.35				0.00091	544
	500+500	0.41				0.00107	463
	500+700	0.35	5850	0.45	38.6	0.00091	544
	500+900	0.25				0.00065	760
	501+100	0.37				0.00096	516
	501+300	0.37				0.00096	516
	501+500	0.39				0.00101	490
Control	501+700	0.63				0.00163	304
	501+803	0.38				0.00099	500
	501+900	0.34	5850	0.45	38.6	0.00088	563
	502+003	0.23				0.00059	840

Q – wheel loading, compression in tyres; D – diameter of the circle; L – deflection; E – elasticity modulus on the road surface.

of the asphalt concrete plate at the high design temperature. Thus, studies established that hot asphalt concrete using cast slag meet the requirements for shear resistance in summer temperature calculated coating temperatures.

Higher elasticity modulus values on the test site are due to the best adhesive bonds at the edge of bitumen-slag as compared to bitumen-crushed gravel [41]. The adhesion coefficient to the vehicle wheel was measured with the PCRS-2Y wet driving dynamometer at a speed of 60 km/h, in the test section and two control sites. From the average values of adhesion coefficients for the defined service life of the road pavement, it can be noted that the adhesion coefficient of the vehicle at the test area is bigger than the adhesion at the control areas. The same pattern of changing the curves over time indicates identical performance of mineral material from cast slag and traditional mineral material (crushed gravel) under all other equal conditions.

However, the slip resistance at the test site remained higher than at the control site for three years of service, with the wet adhesion coefficient at 60 km/h above 0.45 with a slight change over the width of the carriageway. However, at the control section, the adhesion coefficient decreased to 0.40 over this period. This suggests that the mineral material from the cast slag under the wheel of the car works differently than the mineral material from the ground gravel.

Due to its rough surface, slag gravel gives the surface higher roughness in the initial operation period. Moreover, the porosity of slag gravel plays a positive role because it contributes to the renewal of the surface of individual gravel, which breaks down under the wheels of the cars [42]. This maintains roughness of the road surface during operation, while the rubble stone from traditional materials is only polished. In this way, the use of cast phosphorus slag contributes to extending the life of asphalt concrete pavements.

5. Conclusions

The feasibility of adding phosphorus slag in asphalt concrete mixtures when constructing pavements has been theoretically proved and experimentally established. The technology of asphalt concrete mixtures' preparation and compaction was developed, which ensures high operational properties of road surfaces.

A petrochemical recalculation method was used, which allowed us to establish the number of electro-positive ions in a phosphorus slag cell. It was proven that the intensity of interaction with bitumen is similar to that of limestone. The effects of phosphorus slag on bitumen ageing are similar to

those of natural minerals. The utilisation of phosphorus slag (both in cast and granulated forms) as a substitute for gravel, mineral powder, and sand was found to yield a uniformly blended asphalt concrete, being a property that is exceedingly challenging to achieve with conventional mineral materials from natural deposits like limestone.

According to the result of the analysis, the following recommendations about the material obtained can be formulated:

1. The feasibility of adding phosphorus slag into asphalt concrete mixtures when constructing pavements was theoretically and experimentally proven. The procedure for asphalt concrete mixture preparation and compaction was developed, which ensured high operational properties of road surfaces.
2. The study revealed distinct characteristics of the asphalt concrete structure when prepared using phosphorus slag. It was observed that the significant porosity of phosphorus slag has a direct impact on the bitumen content and the structure of asphalt concrete by improving its final properties. Incorporating activated mineral powder derived from finely ground slag causes a reduction in bitumen consumption. The establishment of a well-defined network of structuring centres in the asphalt concrete mixture lead to improved density during the construction phase. As a result, this enhances asphalt concrete strength and waterproofness.
3. It was proved that the intensity of interaction with bitumen was similar to that of limestone. Effects of phosphorus slag on bitumen ageing were similar to those of natural minerals.
4. Hot asphalt concrete mixtures with a mineral component (gravel, necok, and mineral powder) is completely composed of phosphorus slag and have an increased value for certain indicators.
5. The coarse texture of slag gravel and sand enhances the internal friction angle, diminishes adhesion indicators, and plays an important role in the stability and mobility of asphalt concrete when exposed to elevated summer temperatures.
6. The utilisation of phosphorus slag, both in cast and granulated forms, as substitutes for gravel, sand, and mineral powder demonstrated the feasibility of creating uniform asphalt concrete. This was challenging to attain when relying on conventional natural mineral materials like limestone.

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