

Features of the Technology of Application of Industrial Waste in the Construction of Constructive Layers of Roadwear

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Abstract – In this article, work was carried out to study the chemical, mineralogical composition and toxicological properties of waste (phosphogypsum, phosphorus slags, overburden) of the phosphorus industry, the optimal content of the grain composition of gravel-sand mixtures in the composition of road mixtures (crushed stone, sand-gravel, sand) and structures of the Zhambyl region of the Republic of Kazakhstan. The possibilities of using slag-mineral mixtures in the year - round construction of highways were studied on the basis of a comprehensive study of the physicochemical processes of hardening and the formation of the structure of slag-mineral materials at negative temperatures. Technological regimes for the construction of roads of various technical categories from slag binding materials, reformed after long-term freezing, have been established. New, unparalleled, binding road mixtures have been created to increase the utilization of waste from the phosphorus industry and expand the raw material base of road building materials. The main directions of application of road mixtures based on industrial waste for the purposes of road construction have been developed: construction of structural layers of road pavements; construction of road bed layers.

Keywords – Gravel-sand mixtures; granular phosphorus slag; road mixtures; slag mineral materials

1. INTRODUCTION

World experience shows that one of the economically and ecologically viable directions for the disposal of industrial waste is their use to obtain various road-building materials [1]–[5]. Road construction is one of the most material-intensive industries requiring an expansion of the range of binders and road mixtures used, the main components of which can be various industrial wastes. In domestic and foreign practice of road construction, foundations and coatings made of soils and stone materials, reinforced with various slag binders, are increasingly used. Their widespread use is explained by the possibility of obtaining a slab with high deformation properties, good manufacturability and high economic efficiency associated with the economy of scarce stone materials and cement.

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Phosphorus granular slags, which are a local material and have astringent properties under certain conditions [6], can serve to expand the use of fortified local stone materials in the construction of road pavements in Kazakhstan.

A promising direction for the use of man-made waste of phosphorus industries (phosphogypsum, electrothermophosphoric slag, internal overburden) is their use in the construction of highways. Dump slags and mineral powder from steel-making slags are successfully used in the preparation of asphalt concrete for the upper layers of road pavements. Asphalt concrete pavements with slag aggregate are characterized by high strength, abrasion resistance, high coefficient of adhesion, and absence of shear deformations [7].

In the study, it was found that electrothermophosphoric slag, dump phosphogypsum and overburden of coal mining can be used as components for box-type pavement [8].

In road construction, ash and slag mixtures are used in the construction of subgrade, for the construction of reinforced foundations, as a filler and mineral powder in asphalt concrete. High-quality mineral powder is obtained from steel-making slag, which is an important structure-forming filler for asphalt concrete [9].

Granulated slag in road construction can be used as:

- Sandy material in the preparation of asphalt and cement-concrete mixtures, as well as for underlying layers of bases (without processing and without adding additives);
- Monolithic base under an asphalt concrete pavement (with the addition of small doses of cement, clinker dust or alkaline additives);
- When reconstructing asphalt concrete pavements and crushed stone bases (with the addition of small doses of cement or clinker dust);
- Slag binder for obtaining monolithic concrete coatings and bases (after additional processing – fine grinding together with small doses of activators: cement, lime, clinker dust);
- Subgrade with the addition of a small amount of cement, clinker dust and phosphogypsum [10].

Granulated blast-furnace slags are mainly consumed in the production of ordinary slag cement, but they are also used to a significant extent as aggregate for concrete. When comparing two options for road pavements based on the use of metallurgical slag and sand-gravel mixture, it can be seen that the structure with the use of slag is not inferior to the sand-gravel surface in terms of strength characteristics, and from an economic point of view it is the most profitable and expedient, since the cost of slag is much less than the cost of gravel [11].

In work [12], many different types of raw materials were studied for the production of alkali-activated cements. However, considerable efforts have been focused on the disposal of crushed granular blast furnace slag (GBFS) from the iron and steel industry, as it is well known that alkali-activated cements obtained from this by-product can develop a microstructure comparable (in many respects) to that of a mixed portland cement.

Secondary catching cement dust – cement plant waste – has an activating ability. The rationality of using cement dust as an activator of phosphorus granular slags is determined not only by the fact that it contains various alkaline components, but also by the fact that, being an inadequate material, it is located in the area of the slag dumps.

The analysis of the raw materials used and the climatic characteristics of the study area (the fifth climatic zone) makes it possible to draw conclusions about the possibility of using waste from the phosphorus industry in road construction [13]–[16].

Of great practical importance for increasing the pace of road construction are not only issues related to the economic efficiency of the use of slag-mineral materials, but also issues related to the extension of the road construction season.

The purpose of the research robot is to involve waste from the phosphorus industry in the raw material base of road building materials.

The main task is to study the possibility of using slag-mineral mixtures in the year-round construction of highways.

2. METHODS AND METHODOLOGY

The suitability of man-made raw waste for use in road construction is established on the basis of a comprehensive study of their composition, physicochemical, mineralogical and toxicological properties. Waste sampled from dumps of enterprises was examined. The volumes of man-made waste in the dumps are: GPS – granular phosphorus slag NDFZ (Novodzhambul phosphoric plant) – 10–12 million tons; Phosphogypsum – stale, dumps of the MU (Mineral Fertilizers) plant – 8.5 million tons; Overburden ~20 million tons.

During the monitoring, the following was carried out:

1. Field work:
 - To map and clarify the boundaries of phosphogypsum dumps and granulated slag;
 - Sampling in this area;
2. Laboratory studies of the chemical and phase composition of waste, as well as some of its physical and mechanical properties.

Samples are taken in two ways from different points of the dump:

1. From the surface of the heaps;
2. From compacted soil.

When taking samples from the surface of the heaps, a special measuring device is used. When sampling from the compacted soil on the dump and along its slopes, a hand drill is used, the depth of penetration is from 1.0 m to 1.5 m. At the same time, an integral waste sample is also taken at each point.

The quantitative chemical analysis of granulated slag, phosphogypsum and overburden was carried out according to standard methods using gravimetric, spectrophotometric, potentiometric, complexometric, titrimetric methods of analysis.

The mineralogical composition of the waste was investigated according to the data of X-ray structural analysis performed on a computerized diffractometer of DRON class in Co-K α radiation.

For all considered wastes, a study of radioactivity was carried out according to the 'Methods for measuring the activity of radionuclides' using a scintillation gamma spectrometer 'Progress-BG'.

The study of the chemical composition of the granulated slag and the analysis of the results obtained showed that when sampling at different times of the year and at different points, the chemical composition of the granulated slag does not change, which confirms the homogeneity of the material. The content of basic oxides in the slag is within the following limits, wt. %: SiO₂ 39–43; CaO 45–51; Al₂O₃ 1–3; Fe₂O₃ 0.4–0.5; MgO 2–4; SO₃ 0.1–1; P₂O₅ 1–3; F 2–3.

The compositions of the studied samples of granulated slag comply with the requirements of the normative document ST RK 935-92 'Electrothermophosphoric granulated slags for the production of cements': SiO₂ content is not less than 38 wt. %, the sum of basic oxides CaO and MgO is not less than 43 wt. %, P₂O₅ not more than 2.5 wt. %.

The presence of oxides CaO (C), SiO₂ (S), Al₂O₃ (A) in a certain ratio determines the hydration properties of raw materials that can be used as cementitious road mixtures. The presence in slags of minerals with hydraulic activity (C₃S, C₂S, C₂F, etc.), and their hydrates predetermines the possibility of obtaining binders from them after preliminary drying, grinding and introduction of activators. In the study of the mineralogical properties of industrial waste, X-ray diffraction analysis of samples of the initial granulated slag showed that the materials of all samples are 98 % in a structural-amorphous state.

As the results of X-ray phase analysis of phosphogypsum samples, which were subjected to heat treatment in the temperature range from 170 °C to 240 °C and heating time from 2 to 4 hours, show, its dehydration and the transition of calcium sulfate dihydrate CaSO₄·2H₂O into hemihydrate CaSO₄·0,5H₂O, i.e. the mineral gypsum transforms into the mineral bassanite.

The results of the study of the radioactivity of waste showed that the effective specific activity of all samples (209; 100; 37; 39; 60.7; 45; 80 Bq/kg) does not exceed the level of 300 Bq/kg established by the Sanitary Regulations ‘Sanitary and Epidemiological Requirements for Ensuring Radiation Safety’, approved by the Resolution of the Government of the Republic of Kazakhstan No. 202 dated 03.02.2012. On this basis, no restrictions are imposed on the use of the considered waste in economic activities, including in the production of building materials and mixtures.

3. RESULTS AND DISCUSSION

3.1. Study of the Optimal Content of the Grain Composition of Gravel-Sand Mixtures of the Zhambyl Region in the Composition of Road Mixtures (Crushed Stone, Sand-Gravel, Sand) and Structures

In recent years, in a number of industrialized countries, the possibilities of using a variety of industrial waste, including slag, for the construction of road surfaces and foundations have been increasingly being studied. As a result of the research and experimental work, two main directions have been identified:

- Strengthening of waste with binders;
- The use of the binding properties of industrial waste.

In Kazakhstan, about 90 % of motor roads with asphalt-concrete pavements have non-rigid bases made of crushed stone, gravel-crushed stone and gravel-sand mixtures of optimal composition. The use of such bases, especially on roads with heavy and heavy traffic, leads to a loss of evenness of the surface, and, consequently, to a decrease in its transport and operational performance.

When an unreinforced base is used in a non-rigid road pavement, under the action of heavy dynamic loads from passing vehicles, large stresses arise in the contact zone of individual crushed stones, which often exceed the ultimate strength of the material and cause destruction of crushed stone grains. Such a foundation cannot be stable for a long time.

Naturally, the stability of the base will increase significantly if individual gravels are tied together, exclude the possibility of their relative movement, and turn the base into a solid slab with good bearing and distribution capacity.

For the study, gravel-sand mixtures of typical compositions for deposits in Kazakhstan, located in the V climatic zone, were subjected to.

The results of a survey of open pits, with the identification of the characteristics of the grain composition of gravel-sand mixtures of the Zhambyl region showed:

- The volumetric bulk weight of the studied gravel-sand materials varies from 1.50 to 1.84 t/m³;
- Specific gravity – from 2.65 to 2.84 g/cm.

In terms of strength (wear in a shelf drum), samples of gravel-sand materials belong to I and II grades. In terms of frost resistance, the studied mixtures have losses within 3–4 %. The content of poorly soluble salts in the dusty fraction does not exceed 0.2 %.

3.2. Research of the Technology of Road Construction from Slag-Mineral Materials in Winter

Freezing of slag mineral material at an early age negatively affects its structure due to the passage of destructive processes, which reduces the strength of the material during its further hardening under normal conditions. Large structural disturbances occur at low negative temperatures up to –5 °C due to more favourable conditions for moisture migration during slow freezing of the slag-mineral material, as well as at temperatures below –15 °C, due to the rapid freezing of the bulk of moisture in the entire volume of the material. Freezing of slag mineral material with a small amount of binder (10–15 %) in the composition leads to large losses of strength (25–40 %). With an increase in the amount of binder over 15 %, the negative effect of early freezing on the strength of slag-mineral materials containing more than 35 % of particles larger than 5 mm dies out. Consequently, such compositions of slag-mineral materials can be used in winter conditions of construction with freezing immediately after laying.

When arranging layers of road pavements in winter conditions, it is possible to change the temperature regime of the hardening of the layer with the transition through 0 °C immediately after its compaction, especially characteristic of the climatic conditions of the V road zone. When studying the effect of alternating changes in the hardening temperature of the slag binder, it was found that such conditions intensify the process of strength gain. Therefore, it could be assumed that alternating freezing and thawing will also accelerate the hardening process of slag-mineral materials.

The study of the effect of alternating freezing and thawing on the strength properties of the slag-mineral material was carried out taking into account the preservation of the optimal moisture content in the samples, at which they were pressed. This condition was adopted because the optimum moisture and density are the most favourable for hardening hardened soils. Samples – cylinders with a diameter and height of 100 mm were formed from slag-mineral materials of various compositions. In this case, gravel-sand mixtures of three grain compositions were used with a content of particles larger than 5 mm in the amount of 30, 50 and 70 %. The amount of binder in the mixture was varied from 10 to 30 % with an interval of 5 %. To eliminate moisture loss during the first period of freezing and thawing, the samples were wrapped in a polyethylene film. Freezing was carried out at a temperature of –5 °C, which is most typical for transition periods (autumn-winter, winter-spring). Thawing was carried out in baths with a hydraulic seal for at least 4 hours. The freshly formed samples were immediately placed in a refrigerator, and then defrosted during the day and frozen again at night, considering the approach to the real temperature regime of the pavement.

For the V road-climatic zone, the number of air temperature transitions through 0 °C does not exceed 80–90, therefore, the number of freezing-thawing cycles was taken to a maximum of 90, considering the holding of samples for 90 days (one cycle per day). Testing of one part of the samples was carried out after 90 freeze-thaw cycles, and the other after additional incubation for 90 days under normal conditions.

Thus, the above results showed that with alternating freezing-thawing of slag-mineral materials immediately after their compaction, their strength properties decrease due to destruction when the material contains 10 % binder and when using fine-grained compositions (particles larger than 5 mm = 30 %) ... With an increase in the amount of binder to 15–30 % and when the content of particles larger than 5 mm in the composition of the slag-mineral material is more than 50 %, the strength of the material relative to the strength of samples of normal hardening increases by 5–30 %.

3.3. Technological Features of the Preparation of Road Mixtures

The technology of road construction, in particular of road structures, consists of the construction of the roadbed and then road pavements. Due to the long-term hardening of slow-hardening cements (90 days), maintenance work, ensuring the hardening of slag-mineral materials, is replaced by the device of the upper layers of pavements. Phosphogypsum was used as a regulator and acceleration of hardening in the composition of slag-mineral mixtures, therefore its use is not considered separately. When using slow-hardening slag-mineral binders, they may have some peculiarities in technological modes associated with the setting and hardening times of the binders used. Technologies for arranging the working layer of the subgrade and layers of road pavements using slow-hardening slag cements consist of the following main technological operations:

- preparation of concrete and soil-concrete rigid road mixes in modern mechanized mixers;
- laying of rigid road mixtures by mobile pavers of monolithic layers of road pavements and the working layer of the subgrade and compaction of the layers by compaction by pneumatic rollers to the required density;
- Carrying out work on the maintenance of the hardening of layers, due to the long hardening of slow-hardening cements (90 days), is replaced by the device of the upper layers of road pavements.

The grain size composition of the materials used (stone materials or soils) also affects the technological regimes. For the construction of road pavements, stone materials are used, and for the construction of the roadbed, various finely dispersed soils. When binders are used, the top of the subgrade is usually strengthened, called the working subgrade. At present, various mechanized stationary and mobile mixers are used to prepare road mixtures for the construction of pavement and the working layer of the subgrade. The quality of road mixes depends, first of all, on the uniformity of cement distribution and the homogeneity of the components in road mixes. To study the dependence of the quality of the final product on the type of mixing of road mixtures, in the preparation of various mixtures, forced mixing mixers were used, as the most common in the road industry of Kazakhstan.

The optimality of the selected technological parameters for the preparation of the processed materials was evaluated by the physical and mechanical parameters of the obtained material. Research on the development of the technology for the preparation of hard road mixtures was carried out by their preparation in laboratory mixers for forced mixing with the addition of surfactants. Sulfite yeast mash (SYM) was used as a surfactant.

To reduce the volume of experiments and obtain more reliable information, the studies were carried out using the method of mathematical planning of the experiment [17]–[20] as the most effective for solving recipe-technological problems.

In a two-factor experiment (mixing time of the mixture – X_1 and the amount of SYM – X_2), it is necessary to obtain the value Y – a response that depends on two variable factors X_1 and X_2 , i.e. $Y = f(X_1, X_2)$. Using the method of the full factorial experiment, we obtain the total number of points $N = 13$; $N = 2k + 2K + n_0$, where $2k$ is the number of star points in the full

factorial experiment ($2k = 4$), $2K$ is the number of star points ($2K = 4$), n_0 is the number of central points ($n_0 = 5$), and the magnitude of the stellar arm $L = 1.414$.

The planning matrix was drawn up in accordance with the recommendations [21]. Since at all points of the planning matrix the same number of parallel experiments was accepted (3), the Cochran test was applied to check the homogeneity of the variance.

Checking the significance of the coefficient of the regression equation:

$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_{1,2} X_1 X_2 + B_{1,2} X_{12} + B_{2,2} X_{22}, \tag{1}$$

performed according to the Student's criterion (t) [22], [23]. The correspondence of the obtained model to the studied phenomenon for adequacy was checked by the Fisher criterion (F) [17]–[20].

The factors and values of the experimental levels as for the preparation of mixtures in a forced mixing mixer are shown in Table 1.

The experiment planning matrix, test results and calculations are shown in Table 2 for forced mixing.

After testing the hypothesis about the adequacy of the mathematical model using Fisher's F-test, at the 5 % significance level and justifying the zero hypothesis of the significance of the regression coefficients using the Student's t-test, the mathematical model has the form:

– With forced stirring:

$$Y = 265.8 + 15.1X_1 - 36.8X_2 + 2.75X_1X_2 - 6.2X_{12} - 25.2X_{22}, \tag{2}$$

and in natural values:

$$R_{nv} = 205.6 - 1.19V + 163D - 0.005V_2 - 572.7D_2 \tag{3}$$

TABLE 1. FACTORS AND THEIR LEVELS OF VALUE

Index factor	Name factors	Conditional designation	Variation step	Variation levels				
				-1.414	-1	0	+1	+1.414
X_1	Mixing time, in s	<i>B</i>	35	25.51	40	75	110	124.49
X_2	Amount of SYM %, of the binder weight	<i>D</i>	0.21	0	0.09	0.03	0.51	0.595

The calculation results are shown in Table 2.

Thus, the technologies for arranging the working layer of the subgrade and layers of road pavements using slow-hardening cements based on industrial waste from the phosphorus industry consist of the following technological operations:

- Technologies for the preparation of hard water with a limited amount of water for moistening road soil-concrete and concrete mixtures in stationary or mobile installations. To increase the mobility of rigid road mixtures and further increase the strength of the monolithic working layer of the subgrade and road pavements, plasticizing additives (surfactants) are introduced;
- Technologies for laying and compaction of road concrete and soil-concrete mixtures, by pressing, in particular, rolling by rollers on pneumatic running to the required density, since inactive rigid road mixtures are used;
- The technology of performing work on the care of the hardening of layers, used when using fast-hardening traditional cements, is also not used, due to the slow and long hardening of slag-mineral materials, it is replaced by the device of the upper layers of the pavement.

TABLE 2. MATRIX FOR PLANNING EXPERIMENTS, RESULTS OF TESTS AND CALCULATIONS WITH FORCED MIXING OF ROAD MIXTURES

№	Plan				$Y = R_{nv}$ actual kgf/cm ²	Calculated matrix							$Y = R_{nv}$ calculated kgf/cm ²
	coded		natural			X_0Y	X_1Y	X_2Y	$X_1 X_2Y$	$X_{12}Y$	$X_{22}Y$	Y_2	
	X_1	X_2	Time mixing, s	quantity SYM, %									
1	-1	-1	40	0.09	256	+256	-256	-256	+256	+256	+256	65 536	241
2	+1	-1	110	0.09	279	+279	+279	-279	-279	+279	+279	77 841	287
3	-1	+1	40	0.51	176	+176	-176	+176	-176	176	176	30 970	180
4	+1	+1	110	0.51	210	+210	+21	+210	+210	+210	+210	44 100	211
5	-1	0	25.51	0.3	235	+235	-332.3	0	0	470	0	55 225	231
6	-1.414	0	124.49	0.3	280	+280	+395.9	0	0	560	0	78 400	275
7	+1.414	-1.414	75	0	271	+271	0	-383.2	0	0	542	73 441	268
8	0	+1.414	75	0.596	168	+167	0	+237.6	0	0	336	28 224	159
9	0	0	75	0.3	266	+266	0	0	0	0	0	70 756	265
10	0	0	75	0.3	251	+251	0	0	0	0	0	63 001	265
11	0	0	75	0.3	258	+258	0	0	0	0	0	66 564	265
12	0	0	75	0.3	270	+270	0	0	0	0	0	72 900	265
13	0	0	75	0.3	284	+284	0	0	0	0	0	807 620	265
						(OY)	(1Y)	(2Y)	(1.2Y)	(1.1Y)	(2.2Y)	(YY)	
						3204	120.6	-249.6	11	1961	1799	807 620	

3.4. Influence of Long-Term Technological Ruptures Caused by Transportation or Other Reasons on the Strength of Road Cinder Concretes and Slag Soils for the Construction of Subgrade on Slow-Hardening Cements

The above test results indicate the high manufacturability of road mixtures from slag-mineral materials. Considering that in production conditions, emergency cases are possible with a delay in the laying of ready-made road mixtures for a long time. Research has been carried out on the influence of the duration of the technological cycle from the preparation of slag concrete and slag-ground mixtures to their laying and compaction on the strength of concrete.

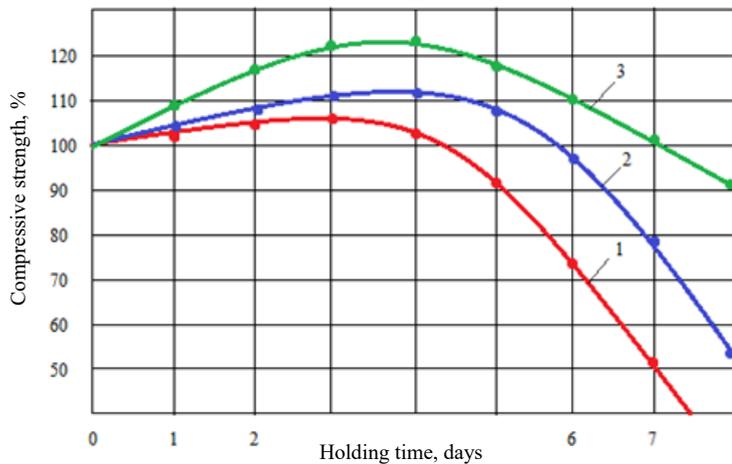
From the moment of preparation to laying and compaction, slag concrete mixtures undergo changes associated with the continuously flowing hydration and hydrolysis of the binder, as well as the physicochemical processes occurring between the aggregate (sand + crushed stone, ASG) and the products of the binder hydrolysis. To check the reliability of the results of theoretical assumptions about the possibility of a longer technological gap between the preparation of the mixture and its compaction for road concretes based on slow-hardening cements from industrial wastes of the phosphorus industry (granular slag, phosphogypsum), the following studies were performed.

To study the effect of the duration of the technological process from the preparation of the mixture to the compaction on the physicomechanical parameters of cinder concretes and slag soils, rigid mixtures were prepared with mixing them with an optimal amount of water.

The mixtures were kept under natural conditions in air at a temperature of 20–30 °C for a specified time. Then, every day (up to 8 days), one part was taken from the aged mixtures, moistened to the optimum moisture content, thoroughly mixed, and then cylinder samples with a diameter and height of 100 mm were prepared on a press under a load of 20 MPa, followed by their testing at the age of 90 days. The test results are shown in Fig. 1.

As can be seen from Fig. 1, preliminary curing of the mixture before laying and rolling (molding) leads to an increase in the strength indicators of soil slag concrete and slag concrete. The strength of the materials increased from 105 % to 121 % over the reference strength. The strength of samples made from mixtures of optimum moisture content within 1–2 hours after mixing with water was taken as the reference strength.

The test results showed that for fine-grained slag concrete, the time of preliminary holding of the mixture for 4 days in air-dry conditions does not have a negative effect on its final strength, but, on the contrary, contributes to its increase. For medium-grained slag concretes and coarse-grained slag concretes, the optimal (permissible) holding time of the mixture is 6 and 7 days, respectively. With further aging of the mixtures, respectively, for more than 4, 6 and 7 days, there is a decrease in the strength of cinder concretes and slag soils.



1 – fine-grained slag concrete (soil slag concrete); 2 – medium-grained slag concrete; 3 – coarse slag concrete

Fig. 1. Kinetics of the influence of the holding time of various road slag-mineral mixtures before compaction on the strength of concrete in compression.

The increase in the strength of cinder concretes and cinder soils from pre-seasoned road mixtures in natural conditions, apparently, can be explained with subsequent physicochemical processes occurring in a dispersed medium. From the moment the mixture is mixed, a thixotropic coagulation structure is first formed, followed by the creation of a denser structure on its basis. An increase in the time from mixing the mixture to mechanical action creates the conditions for even greater growth of hydrosilicate shells around the mineral shells of the binder. Mechanical action (repeated mixing and pressing) on the mixture during this period leads to rupture of the shells, with exposure of new surfaces and, accordingly, a large formation of a gel of hydrosilicate composition, which causes the observed increase in strength.

3.5. Technology of Compaction of Road Pavements and Working Layers of Subgrade from Slag-Minerals Based on Slow-Hardening Cements

The ready-made slag-mineral mixtures for the arrangement of layers of road pavements or the working layer of the subgrade are transported to the construction site of the highway and unloaded with a road mixture spreader. Compaction is one of the main technological operations that determines the quality of the layer and during which the mixture is deformed in a complex way, acquiring a certain density. An increase in intergranular porosity can lead to a sharp drop in the strength of concrete, much more than that which can be caused by an increase in the porosity of the cement stone due to an increase in the water-cement ratio. In addition to decreasing strength, increasing porosity worsens frost resistance, water resistance, and hence its durability.

For clarity, Fig. 2 shows the experimental results as a relationship between the relative strength of concrete, expressed as a percentage (the strength of concrete at full compaction is taken as 100 %) and the compaction coefficient. The figure clearly shows that under-compaction of the mixture by 10 % can more than halve the strength of slow-hardening road cinder concretes. Considering the great difficulty of compaction of a rigid mixture with compaction coefficients (C_c) in the range of 0.98–1.0, the lowest compaction coefficient value of 0.98 can be assumed.

During compaction, the total porosity of slow-hardening cinder concretes decreases, which leads to a decrease in its water saturation and a decrease in the volume of water, the freezing of which causes tensile stresses inside the material. An increase in concrete density increases its frost resistance. Fig. 3 shows the dependence of the frost resistance of slow-hardening slag concrete on the degree of its compaction.

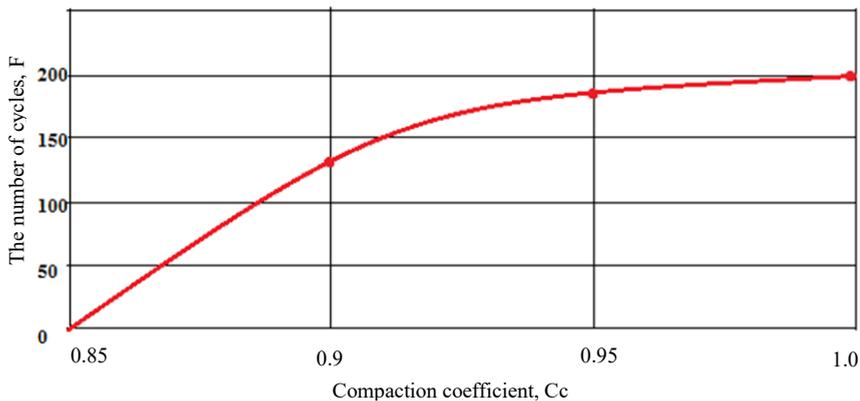


Fig. 2. Dependence of concrete strength on the degree of its compaction.

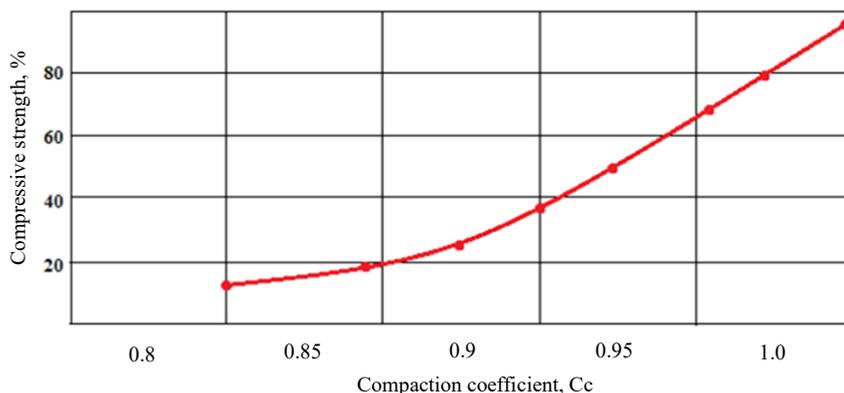


Fig. 3. Influence of the degree of compaction (Cc) of concrete on its frost resistance (F).

It has been established that the quality of the mixture compaction is of decisive importance to increase the frost resistance of slow-hardening concrete.

4. CONCLUSION

Based on the above results of studies of the features of the structure of the subgrade and road pavements using industrial waste (phosphorus granular slag, phosphogypsum), the following generalizing conclusions can be drawn:

1. The results of the studies carried out to study the chemical, mineralogical composition and toxicological properties of industrial waste in the Zhambyl region were the main ones for identifying the features of the technology for the construction of structural layers of road pavements using slag-mineral materials on roads of various technical categories;
2. The study of the optimal content of the grain composition of gravel-sand mixtures of the Zhambyl region in the composition of road mixtures (crushed stone, sand-gravel, sand) and structures showed that the obtained indicators of the studied gravel-sand mixtures meet the regulatory requirements. Their use in their natural form for the construction of bases or coatings is possible when strengthened with binders;
3. Studies have shown that gravel-sand mixtures, fortified with a slag binder during alternate freezing-thawing at an early age for 3 months, do not lose their properties for further hardening, since the main part of the binder is involved in this process after thawing of the material during positive temperatures. At the same time, freezing has a beneficial effect on the processes of binder hydration, which ultimately leads to the healing of the resulting partial loosening in the material and, with a sufficient amount of binder (more than 15 %), to gain strength without a decrease.
4. The best local gravel-sand materials for strengthening them with slag binder are mixtures with particles larger than 5 mm from 35 to 50 %, and with an increase in the amount of binder over 15 %, also mixtures with a content of such particles up to 20 % and finer particles 0.05 mm – less than 30 %.
5. Research into the technology of road construction from slag-mineral materials in the winter period showed that with alternating freezing-thawing of slag-mineral materials immediately after their compaction, their strength properties decrease due to destruction when the material contains 10 % binder and when using fine-grained

- compositions (particles larger than 5 mm = 30 %). With an increase in the amount of binder to 15–30 % and when the content of particles larger than 5 mm in the composition of the slag-mineral material is more than 50 %, the strength of the material relative to the strength of samples of normal hardening increases by 5–30 %.
6. With the elimination of partial loosening in slag-mineral materials with small additions of binder (10–15 %), during their thawing, apparently, it is also possible to achieve the strength of normal hardening. This once again confirms the possibility and expediency of using slag-mineral materials in winter construction conditions.
 7. Research has established that slag-mineral materials have a sufficiently high frost resistance, which makes it possible to use this material in layers of pavements on roads of any technical category. The frost resistance of the material obtained at the age of 90 days after 15 freeze-thaw cycles is more than one, which meets the requirements of CH 25–74 for soils strengthened with slow-hardening binders.

The use of large-tonnage man-made waste from the phosphorus industry during road construction will contribute to their widespread utilization and, as a result, reduce the cost of road construction and increase the efficiency of environmental protection, which corresponds to the priorities of the Green Economy.

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