Justification of Requirements for Crushed Rock for Open-pit Automobile Road Topping

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***Abstract* - The rational size distribution of the granular materials is proved in this paper on the basis of the theoretical studies of their optimal structure based on the particle-particle packing probability theory, the laboratory studies in the dependencies of bulk density and static modulus of elasticity of the content of particles of various sizes as well as the calculation of the ultimate crushed rock shearing resistance. The suggestions on the recommended brands according to their frost hardiness, shatter, abrasion and water resistance of the crushed rock used for the open-pit automobile road toppings and bases, based on the analysis of the impact of climatic conditions and loads from the impact of technological vehicles on operational performance of pavement layer, are also given.**

***Keywords* - Open-pit; open-cut mine; rock; road; topping; property; elasticity; shear; composition; resistance.**

I. Introduction

Topping is one of the most important elements of the pavement layer of open-pit automobile roads, on the condition of which the average speed of open-pit automobile traffic and, accordingly, its performance depend to a large extent [1]. Given that transport costs account for between 40 to 70% of the total costs [2], improving the quality of topping is one of the main ways to reduce the cost of production of minerals by open-pit mining method [3].

II. Subject of research

The review of the literature [4-8] and the experience of opencast coal mines of Kuzbass have shown that the construction of asphalt concrete and cement concrete pavements is not economically justified, when we are talking about the roads located in a dynamically developing open-pit space where the temporary roads are up to 80% of their entire length. The experience has shown that the crushed rocks are the most suitable for the pavement construction of both permanent and temporary technological roads.

Despite the fact that, according to [9], which is referred to the normative document [10], only the dense rubble-gravel-sand mixtures (crushed rocks of predetermined particle size distribution) can be used as the crushed rock for road paving, in practice the design organizations continue to apply both the one-stone grading gravel and the choke crushed stone, as the topping material. This fact can be explained by the reference to the standard operating procedures [11], but this leads to the rapid destruction of such pavement layers and, consequently, to low efficiency of operation of open-pit motor vehicles, which requires deeper study of the issue on the effective use of crushed rock for open-pit road topping. One of the main unsolved issues of their effective use is the desired particle size distribution.

The analysis of the results of research carried out earlier showed that the crushed rock of optimum particle size distribution should consist of different size particles, taken in the certain proportion, providing the increased internal friction and the adhesion between particles, the high bulk density and the low grain grinding intensity [12-15]. These conditions can be achieved with the maximum possible amount of coarse particles and the minimum necessary amount to produce the high bulk density and to ensure the cohesiveness of coarse particles in the content of fine and dust particles.

III. Results and discussions

These findings based on the basic theoretical propositions of A.V. Biryukova, B.S. Radovsky and I.I. Kandaurova [16-18] are the basis of the theoretical model of the optimum packaging of different size particles. In this theoretical model, the following assumptions and suggestions have been introduced:

1. All the crushed rock is composed of *N*-components; the certain fraction, characterized by the average diameter being taken as a component. It is inconvenient to use the absolute values of the average particle diameter, so the mean particle diameters of certain fractions were replaced in the theoretical model with the relative dimensions such as Dmax, Dmax/2, Dmax/4 and so on.

2. The particles of the largest component are distributed uniformly throughout the volume, which allows considering not the totality of the particles (macroobject), but only one of them (binary object).

3. All particles have a spherical shape. If we take the particles form as a cube, theoretically the minimum voidage of the crushed rock layer will tend to the porosity of the rock itself since the individual particles can tightly contact with each other on all the sides. Tetrahedron-like shape is difficult to consider using a random packing of particles since the grains may occupy one position, but always have the different orientations in space. But the shape of the particles in the form

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of a ball fulfils both the conditions: between the particles there is always the space (void) that cannot be filled completely; regardless of the location of an individual particle, its orientation in space does not affect the packing.

The essence of the theoretical model is that the largest component and the space adjacent to it, we consider as an elementary area (the bounded discrete structure), a set of which constitute the macrostructure. The space consisting of empty cells having a size sufficient for the discretization of the finest of components that make up the crushed rock is formed within the discrete structure. We insert the largest component into central part of the region and further by repeated random selection of the component gravity centre locations having the average particle diameter *D*max/2 we try to insert the component till the largest possible filling of discrete structure. In the course of the discrete structure filling with the smaller components we put a condition that if at least one of the cells, which must be filled with the smaller components, falls on any cell already filled with the larger component, we randomly choose a new gravity centre locations of this component and the process repeats. Thus, first we insert the component having an average particle diameter *D*max into the discrete structure, and then try to fill all the space remaining free with the component having an average particle size *D*max/2, further we conduct the similar operations with the component having an average particle diameter *D*max/4, and so further.

To test the adequacy of the theoretical model, we conducted the laboratory studies of the dependencies of the bulk density and the static modulus of elasticity of crushed rocks of different particle size distribution. In addition, the ultimate crushed rock shearing resistance has been defined by means of calculation. The laboratory tests were carried out in the following sequence:

1. We moved the crushed rock sample from the exsiccator to a metal or plastic plate and mixed thoroughly.

2. We loaded the crushed rock in the complete mould: the mould was filled with the crushed rock in three equal layers, each layer being rodded by the 12 mm diameter steel rod with the rounded end; the number of rod pushes was taken equal to 25; rodding was performed uniformly in a spiral shape from the edges to the middle.

3. The mould was placed on the press plate, the hard punch was adjusted to the surface of the crushed rock layer, and dial gauges were also fixed.

4. The readings were read within the accuracy of 0.001 mm.

5. We vented the hydraulic pressing of 2.5 MPa passed, which was maintained for 2 minutes to compact the crushed rock layer.

6. We removed the load and again took the readings; if the difference in the readings of dial gauges before and after loading exceeded 0.002 mm, it was believed that the crushed rock was contracted, and the repeated loading was made.

7. To measure the elastic deformation the pressure 0.5 MPa was applied to the layer under the test and maintained for 2 minutes; after a specified time the three dial readings were taken, the load was removed, and re-readings were taken with an accuracy of 0.001 mm; the magnitude of the elastic deformation of the crushed rock l_y, mm, was determined by the formula:

$$l_y = \frac{\sum_{i=1}^{3}(L_i - l_i)}{3} \quad (1)$$

In the type: L_i – i–dial reading after the load application, mm; l_i — dial reading under the load, mm.

8. As a result of the four measurements in different quarters of the mould, determined by the calipers the average height from the upper edge of the mould to the crushed rock layer with an accuracy of up to 0.1 mm;

9. On balance with an accuracy of 1 g we weighed the mould with the crushed rock and calculated its bulk density (ρ_w), taking into account the presence of water with an accuracy of up to 0.01 g / cm^3:

$$\rho_w = \frac{m_1 - m_2}{V_m} \quad (2)$$

In the type: m_1 – the mass of the mould with the crushed rock, g; m_2 – the mass of the mould without the crushed rock, g; V_m – the actual volume of the crushed rock in the mould, cm^3, calculated with an accuracy of up to 1 см^3 by the formula:

$$V_m = \frac{\pi \cdot D^2}{4} \cdot (H - h) \quad (3)$$

In the type: π – the coefficient, equal to 3.14; D – the mould diameter, см; H – the mould height, см; h – the average height from the upper edge of the mould to the crushed rock layer, см.

10. We calculated the bulk density of the crushed rock ρ, without accounting for the presence of water with an accuracy of up to 0.01 g/cm^3:

$$\rho = \frac{\rho_w}{1 + 0.01 \cdot W} \quad (4)$$

In the type: W – the current crushed rock humidity, %.

11. We calculated the static modulus of elasticity of the crushed rock, E (MPa), by the formula:

$$E = \frac{(1 - 2 \cdot \mu) \cdot P \cdot l}{(1 - \mu) \cdot l_y} \quad (5)$$

In the type: μ – Poisson ratio, taken equal to 0.30; P –the pressure on the crushed rock layer applied in the deformation measurement, MPa; l – the height of the sample in the mould, mm, defined according to the dependence:

$$l = H - h \quad (6)$$

In the type: H – the mould height, mm; h – the average height from the upper edge of the mould to the crushed rock layer, мм; l_y – the magnitude of the elastic deformation, mm.

All the laboratory tests were carried out using the samples of crushed rocks of different particle size distribution shown in Table I.

TABLE I. Selected size distributions of crushed rocks

# of the mixture	Total residue, %, on sieve of size, mm:					
	10	5	2.5	0.63	0.16	0.05
# 1	9.70	24.09	33.08	48.91	56.64	71.83
# 2	12.93	28.91	46.90	55.70	66.86	77.47
# 3	33.95	48.33	61.82	61.82	81.14	85.48
# 4	48.50	58.09	62.58	66.54	69.63	80.92
# 5	29.10	43.48	61.47	69.39	77.11	83.63
# 6	19.40	38.58	52.07	67.90	79.49	83.83
# 7	38.80	57.98	66.97	66.97	86.29	88.46
# 8	58.19	72.58	81.57	89.49	93.35	93.35
# 9	48.50	58.09	67.08	75.00	78.86	85.37
# 10	58.19	67.79	76.78	80.74	83.06	88.26

The proposed theoretical model was implemented by computer simulation method. The results of the simulation are presented in Table II.

TABLE II. The optimum particle size distribution of the crushed rock as a result of theoretical research

Component diameter, мм	Dmax	Dmax/2	Dmax/4	Dmax/8	Dmax/16	Dmax/32	Dmax/64	Dmax/128	Dmax/256	Dmax/512	Dmax/1024	Dmax/2048	Dmax/4096	Dmax/8192
Total volume content of the components (total residue), %	52.4	58.95	64.68	71.12	74.97	77.71	80.66	83.43	85.76	87.87	89.61	91.03	92.31	93.07

The results obtained allowed the theoretical dependence to be determined characterizing the optimal particle size distribution of the crushed rock:

$$V_D = 52.4 + \int_{D}^{0.5D\max} \left(\frac{\frac{30}{(D\max+25)^{0.5}} + 1.84}{D^{0.8}} \right) dD \quad (7)$$

In the type: V_D – the summed volume content of i-component and all the previous larger components, %; D – the average diameter of *i*-component particles, mm; $D\max$ – the average diameter of the largest component particles, mm.

The results of laboratory tests are shown in Figures 1 and 2 in relation to the crushed coarse-grained sandstone rocks with a maximum grain size $D\max = 20$ mm.

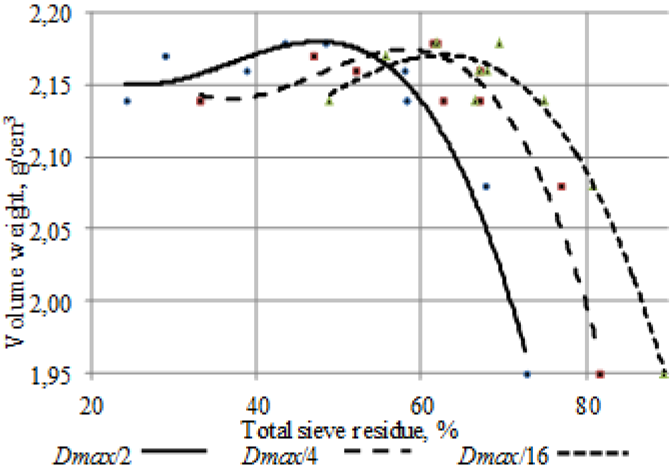

Fig.1. Dependence of the bulk density on the total residue on the sieve of a given size

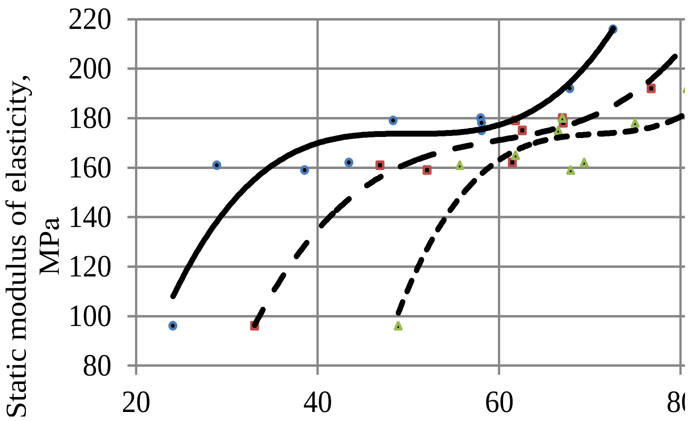

Fig.2. Dependence of static modulus of elasticity on the total residue on the sieve of a given size

The response bulk density function (ρ) and the static modulus of elasticity (E) of the crushed rocks from the total residue on the sieve of a given size are the following (the values of the Beta coefficients are shown in Table III):

$$\rho(V_D) = 0{,}79 \cdot \rho_0 \cdot \left[\cos\left(\frac{V_D^2 - k_1}{k_2} \right) \right]^2 \quad (8)$$

$$E(V_D) = \int_0^{V_D} k_3 \cdot V_D^{k_4} \cdot [1 - \cos(k_5 \cdot V_D)]^{k_6} \, dV_D + 40 \quad (9)$$

In the type: V_D – the share of the particles of size not more than D mm in the crushed rock, %; ρ_0 – the input rock density, g/cm³; $k_1, k_2, k_3, k_4, k_5, k_6$ – the beta coefficients.

TABLE III. Beta coefficients

Average diameter	Beta coefficient magnitude					
	k_1	**k_2**	**k_3**	**k_4**	**k_5**	**k_6**
*D*max/2	800	9000	13.5	–0.537	0.091	0.721
*D*max/4	1800	10000	0.838	0.223	0.075	0.822
*D*max/8	2800	13000	0.032	1.06	0.070	0.700
*D*max/16	3200	14000	0.0028	1.60	0.060	0.600

The developed method of estimation of the strength characteristics (ultimate shear strength) for coarse soils, which are not much different from the crushed rocks, are presented in the source [19]. It is based on dependence of the internal friction angle and the specific crushed rock cohesion on the particle content (debris) having a size of more than 2 mm. Then the ultimate shear resistance calculation is carried out according to Coulomb's law. A graphical representation of the calculation results is shown in Figure 3.

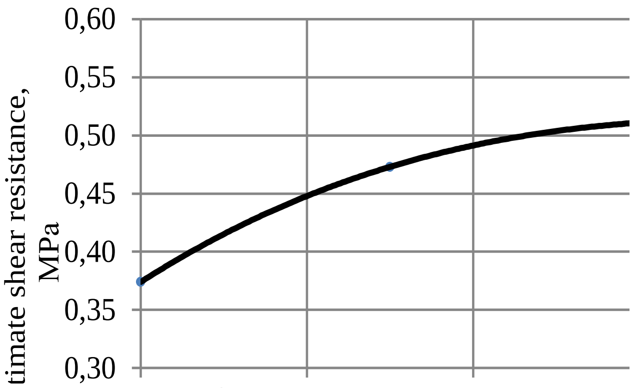

Fig.3. Dependence of the ultimate resistance crushed rock shear on the share of particles having a size of more than 2 mm

The resulting dependences of bulk density, static modulus of elasticity and ultimate crushed rock shear strength on their particle size distribution allow performing its optimization. All three characteristics are taken as the optimization parameters.

Since according to the experimental design theory [20] the optimization parameter should be one, in order to perform the three criteria optimization, it was decided to use not the absolute values of the optimization parameters, and their relative values, defined by relationships:

$$K_\rho = \frac{\rho_i}{\rho_{\max}},\ K_E = \frac{E_i}{E_{\max}},\ K_\tau = \frac{\tau_i}{\tau_{\max}} \qquad (10)$$

In the type: ρ_i, E_i, τ_i – *I* values of respectively bulk density, static modulus of elasticity and the ultimate crushed rock shear strength of the specified particle size distribution; $\rho_{\max}, E_{\max}, \tau_{\max}$ – the maximum values of respectively bulk density, static modulus of elasticity and the ultimate crushed rock shear strength observed in their research and analysis.

This made it possible to transform the three optimization parameters in the determined sum:

$$K_\Sigma = K_\rho + K_E + K_\tau \qquad (11)$$

To find the optimal size distribution the dependences of K_ρ, K_E, K_τ и K_Σ on the share of the particles of size larger than the predetermined one in the composition of crushed rock were determined (Figures 4, 5). In Figure 5, a line with an arrow also shows the theoretically optimum content of particles with a defined particle size obtained by the results of theoretical research.

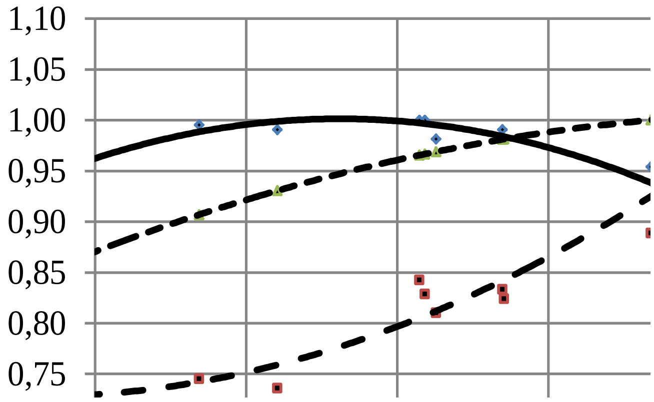

Fig.4. Dependence of optimization parameters K_ρ, K_E, K_τ on the total residue on the 2.5 mm sieve

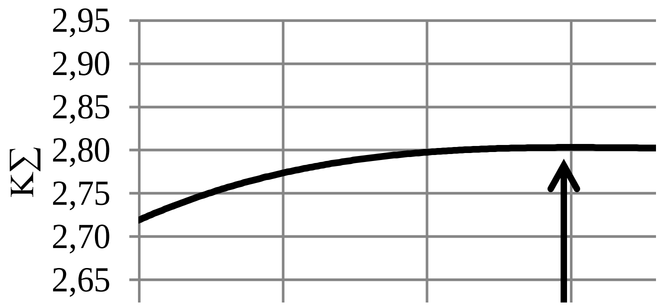

Fig.5. Dependence of optimization parameters K_Σ on the total residue on the 2.5 mm sieve

The comparison of empirical data (Figure 5) with the results of theoretical studies shows that they are almost identical. The difference is that according to the results of experimental data, the optimal size distribution constitutes an area, and for theoretical studies - a single value in this optimum region. Consequently, the dependence that characterizes the optimal particle size distribution of crushed rock, can be written as:

$$V_D = (40...55) + \int_D^{0.5D\max} \left(\frac{\frac{30}{(D\max + 25)^{0.5}} + 1.84}{D^{0.8}} \right) dD \qquad (12)$$

Other physical and mechanical characteristics, the main of which are crushability, abrasion, water resistance and frost resistance should be taken into account, in addition to particle size distribution, to the crushed rock to ensure the efficiency of open-pit road pavement within the specified service life [21].

Cylinder crushing value is the main strength characteristic of the crushed rock that characterizes the intensity of the grain refinement during the open-pit road operation. According to the public road service experience the normative document [9] defines the minimum acceptable rock crushability grades, which are not less than the M600 for the toppings and M400 for the bases. Since the methodologies for determining the ultimate uniaxial compression strength and propagation velocity of elastic longitudinal and transverse waves [22-24] are applicable to rock massifs rather than the crushed rocks, their application for evaluation of crushability grade is not correct. Therefore, we need a method to quickly and reliably determine the suitability of the rock for the open-pit pavement layers.

One of the methods meeting the conditions imposed, is the method of measuring the time and the propagation velocity of the ultrasonic pulse from the transmitter to the receiver. For its practical application it is necessary to know the relationship between the ultimate rock compression strength in the water-saturated state and the propagation rate of longitudinal ultrasonic waves in it.

Panachev I.A., Ryzhkov Y.A., Shalamanov V.A., Stumpf G.G. conducted numerous studies of physical and technical characteristics of the rocks and coals of Kuznetsk coal basin [25, 26], the statistical and mathematical processing of which allowed to establish the relationship between the rock crushability value in the water-saturated state and the of propagation velocity of longitudinal ultrasonic waves in the water-saturated rocks (Figure 6):

$$M = 9.81 \cdot (a + b \cdot V_{prograp} + c \cdot V_{prograp}^2) \quad (13)$$

In the type: M – the rock crushability value in the water-saturated state; a, b, c – non-dimensional coefficients of response function, depending on the rock type (Table IV); $V_{prograp}$ – propagation speed of longitudinal ultrasonic wave, m/s.

Table IV. Non-dimensional coefficients of response function

Brief description of the rock	a	b	c
medium granular sandstone	48.08	–0.0376	0.00000987
coarsely granular sandstone	–13.71	0.00214	0.0000052
fine granular siltites	106.81	–0.072	0.000015

The analysis of the relationships shows that the coarsely granular sandstone can be used for the road bases without any restrictions, and for the toppings - with the propagation velocity of longitudinal ultrasonic waves of more than 3600 m/s. The medium granular sandstone and the fine-grained siltstone are practically not suitable for the toppings and can only be used for road bases at the propagation speed of longitudinal ultrasonic-waves of more than 3500 m/s.

The abrasion value is the additional characteristic of crushed rocks, characterizing their amortization (abrasion) under the loads of open-pit motor transport. The importance of this indicator is determined by the decrease of the bearing capacity of the structural layer with increasing share of fine dust particles (Figures 2, 3), and the increase in dusty air of the working area. The normative reference [9] establishes the requirements for the minimum abrasion grade of crushed rocks, which is not less than A3 for the toppings and A4 for the bases.

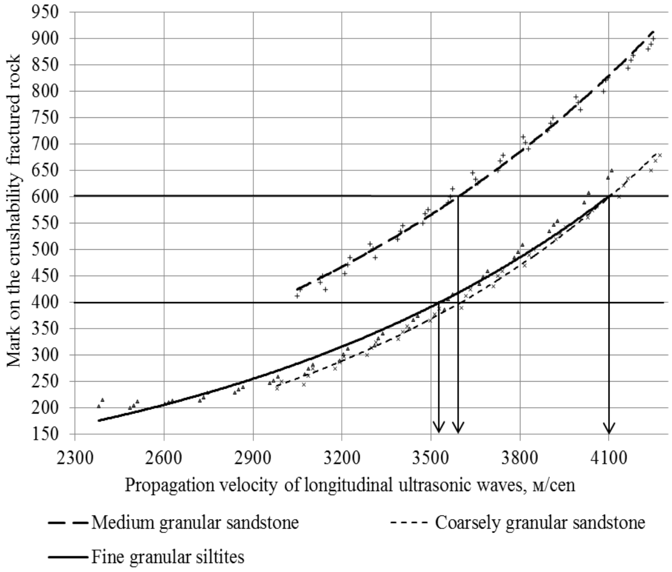

Fig.6. Graph of dependency of rock crushability grade in the water-saturated state on propagation velocity of longitudinal ultrasonic wave

One of the standardized physical characteristics is the frost resistance grade, which characterizes the number of cycles of alternate freezing and thawing, which the crushed rock mass can withstand at no more than 5 (10)% mass loss. The importance of this indicator is determined by the need to limit the formation of rock stuff over the pavement life, affecting, as noted above, the reduction of the bearing capacity of the structural layer.

The requirements for this indicator should be determined primarily on the basis of the analysis of climatic conditions of the construction area. Thus, according to statistical observations of weather stations in the Kemerovo region [27] it was established the cumulative number of cycles of alternate freezing and thawing of the upper layers of soil to a depth of 10 cm during 16 years of observation (Figure 7), which revealed the dependence of the desired crushed rock frost resistance value on the service life of the open-pit roads:

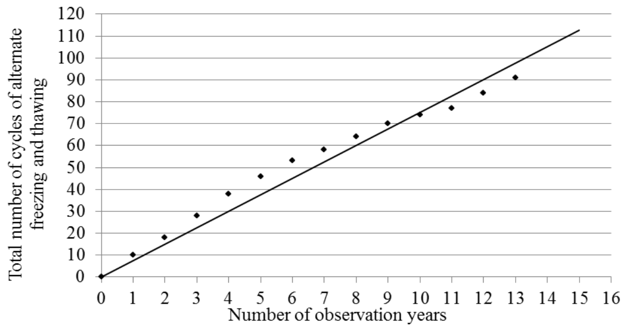

Fig.7. Graph of dependency of the aggregate number of cycles of alternate freezing and thawing on the number of observation years

$$F_{req} = f_{year} \cdot T_{empl} \quad (14)$$

In the type: F_{req} – the required frost resistance value; f_{year} – coefficient of linear regression equation, numerically equal to the average arithmetic of cycles of alternate freezing and thawing of the toppings over the year, obtained as a result of observations for 10-15 years (for the Kemerovo region f_{year} = 7); T_{empl} – technological road service life, years.

The resulting dependence allows to assign reasonably the required frost resistance grades of crushed rock used for open-pit road pavement layer (Table V).

Table V. The required frost resistance grades depending on the service life of the road in the climatic conditions of Kemerovo region

The target road service life, years	The required frost resistance grades
till 2	F15
from 2 to 3	F25
from 3 to 7	F50
More than 7	F100

Another important indicator is the required water resistance grade characterizing the crushed rock weight loss under the influence of water [28]. This figure, as well as the frost resistance grade, limits the possible stone chipping, reducing the bearing capacity of the structural pavement layers. According to the experience of public roads service, the required water resistance grades are regulated [9], which should be no lower than B1 for crushed rock used for the topping, and B2 - for the road base.

IV. Conclusion

1. The optimum particle size distribution of the crushed rock, providing simultaneously the high bulk density values, the static modulus of elasticity and the ultimate shear strength is reached when the share of particles larger than half of the maximum amounts from 40 to 55% and integrally increases with the average particle diameter decrease.

2. The crushability grade of crushed rock in water-saturated state increases nonlinearly with the increasing propagation velocity of longitudinal ultrasonic waves. The coarse-grained sandstone can be used for the construction of open-pit automobile road base without restrictions, and for the topping - with propagation velocity of longitudinal ultrasonic waves of at least 3600 m/s. The medium-grained sands and fine-grained siltstone can be used for the construction of the technological road base, if the propagation velocity of longitudinal ultrasonic waves is not less than 3500 m/s.

3. The required frost resistance grade of crushed rock increases linearly with the increasing service life of technological roads and makes in Kuzbass conditions F15 for the service life of up to 2 years old, F25 – from 2 to 3 years, F50 - from 3 to 7 years and F100 - more than 7 years.

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