Optimization of granulometric composition of railway routes ballast layer

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Abstract. The paper demonstrates the contribution of the type and particle size distribution of ballast materials to the result of obtaining the required performance indicators of the ballast layer of the railway embankment. The criteria influencing the quality of crushed stone and its functional affiliation are investigated. The necessary and sufficient criteria for the formation of the optimal granulometric composition of functionally selected ballast materials are established, which make it possible to obtain embankments with specified parameters of structure and properties. The proposed methods were tested in the development of a practical technology for obtaining embankments with specified operational properties based on the optimal granulometric composition of various fractions of polymineral waste after glass chemical polishing.

1 Introduction

The modernization of traditional technologies and the improvement of new ones based on the use of significant loads, as well as the intensive use of aggressive chemicals, makes it necessary to create and improve effective and durable building materials and composites that guarantee environmental safety and production efficiency. The most important at present is the environmental safety of various mineral dumps along transport routes, obtaining high-quality embankments from various ballast materials, localization of accidents, docking and encapsulation of hazardous waste, protection of equipment and personnel from the adverse effects of the environment. The solution of these problems is associated with the creation and improvement of effective building composites with strictly specified properties and structure parameters.

Such a task is impossible without taking into account many environmental criteria, material characteristics, structure and properties parameters, technology and formulation features, that is, the embankment material must be considered systematically, as a complex technical system that has controllable parameters and experiences various extreme impacts. The following are used as ballast materials: crushed stone, gravel, sand, a mixture of materials, slag, shell rock, etc., and crushed stone is obtained from natural hard rock (granite, basalt) by fragmentation. Depending on the size, it is divided into fractions: 5-25 mm, 25-50 mm, 25-60 mm. Therefore, optimization of the granulometric composition of

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the ballast layer of the railroad track embankment is one of the main ways to control the operational properties of the ballast layer of the embankment. In addition, the construction of high-quality embankments for transport routes is an urgent task and an effective measure to reduce the cost and accident rate of transport routes, considering the very large volumes, the high cost of earthworks and the long period of operation of embankments

2 Research methods and materials

Optical glass production waste (OGPW) with its medium density ρo = 5100 kg/m3 and a mixture of various metal production slags were taken as the main ballast material for transport routes embankments. Parameters of the granulometric composition of the mixture of OGPW and slag: fraction 5,0-2,5 mm – 1 m2/kg; fraction 2,5-1,25 mm – 3 m2/kg; fraction 1,25-0,63 mm – 5 m2/kg; fraction 0,63-0,315 mm – 14 m2/kg; fraction 0,315-0,14 – 42 m2/kg; fraction 0,14-bottom – 100 m2/kg.

As crushed stone for control compositions, building limestone crushed stone with density 1300 kg/m3, specific surface 1,5 m2/kg and its and fineness modulus 1,4 according to GOST 8267-93 was used with density 1300 kg/m3, specific surface 1,5 м2/kg and fineness modulus 1,4 [in accordance with GOST 8267-93. Crushed stone and gravel from dense rocks for construction work. Specifications. – M.: "Standartinform", 2018].

When researching the operational, physical and mechanical properties of the embankment, modern research methods were used, which are based on the achievements of physical chemistry, physics and current regulatory and technical documents. The specific surface area was determined on a PSKh-10M instrument according to the procedure described in [GOST 21043-87 (ST SEV 5499-86). Iron ores and concentrates. – M.: Publishing house of standards, 1987].

Density was determined using the method of hydrostatic weighing according to [GOST 15139-69 (ST SEV 891-78). Methods for determining density (bulk mass). – M .: Publishing house of standards, 1981].

The bulk density of minerals was determined by pouring them through a funnel of a special design and then weighing a certain volume of material [in accordance with GOST 11035.1-93. Determination of the bulk density of the molding material, which wakes up through a special funnel. – M.: IPK Standards Publishing House, 1995].

The granulometric composition was determined by sieve analysis [in accordance with GOST 2093-82. Sieve method for determining particle size distribution. – M .: IPK Publishing house of standards, 2001]. This method consists in dividing a certain sample of material into fractions by sifting through a set of standard sieves and determining the residue on each of them, expressed as a percentage. Cell size, mm: 5; 2,5; 1,25; 0,63; 0,315; 0,14.

When selecting the optimal particle size distribution, a six-point simplex-lattice plan of the second order was used. The result of the analysis of the experiment, carried out according to such a plan, is the construction of the Gibbs-Rosenbom concentration triangle, which makes it possible to establish a correlation between the composition and properties of the mixture of fillers and aggregates. The regression analysis of such models begins with testing hypotheses about the equality of individual coefficients to zero. This check is performed according to Student's criterion. This allows you to exclude insignificant coefficients from the model, which are due to experimental errors. This simplifies the model and reduces "information noise". By comparing the absolute value of the coefficient with the confidence interval, it is possible to determine significant coefficients, obtaining a refined regression equation with this significant coefficients [1].

Next, the adequacy of the model to the experimental data on which it was built is checked. This check is performed according to the Fisher criterion. The verification of adequacy is reduced to checking the null hypothesis about the equality of the true variance, due to the inadequacy of the model, and the true variance, corresponding to the set of experimental values at any point [1, 2].

3 The main results

In the theory of composite materials, it has been proven [3, 4, 5] that the most important indicators that affect the properties of dispersed mixtures are the type, dispersion and volume fraction of the filler of certain fractions. Moreover, the dependence of the indicators of the structure of the mixture (composite) on these factors has an extreme character (the alignment law). For example, to obtain materials that are resistant to highly aggressive environments or under the action of ionizing radiation, it is necessary to take into account the resistance of the composite components to the action of an aggressive environment. Also, the filler of the ballast material, and the design of the upper part of the embankment, and the joints that are formed at the interface between the phases of various materials and structures during their interaction should also have resistance [6].

Some researchers [7, 8, 9] suggest using a continuous fractional composition of fillers or reinforcing (reinforcing) elements. Such a campaign has a number of technical and economic advantages, however, when filling voids with a finer fraction formed by a larger fraction, larger grains will inevitably move apart, which will affect the increase in porosity and the amount of binder. When creating high-density embankments for extreme strength, this approach is not effective.

It was proved in paper [10] that discontinuous particle size distribution is more effective than continuous particle size distribution.

To date, there are many theories and methods for selecting the granulometric composition of mixtures and embankments, which indicates the lack of a unified view of researchers on this problem.

In this paper, the author summarizes the experimental and practical experience in creating high-density embankments of transport routes. The methodology for obtaining a mixture of embankment fillers with the lowest porosity and the highest bulk density is based on the idea of discontinuous granulometry. The optimization of the composition was carried out by the methods of planning the experiment. When choosing the factors of the mathematical plan and their variation limits, the following hypothesis was used – to arrange multi-fraction mixtures so that the ratio of grain diameters of adjacent fractions was within 1:4 ÷ 1:5. With this ratio of fractions, the maximum possible volume of voids formed by a larger fraction is filled with a finer fraction with little or no subsequent separation of the grains. Therefore, the following fractions were chosen as factors of the mathematical plan: X1 = < 0,14 mm; X2 = 0,315-0,63 mm; X3 = 1,25-2,5 mm, which have the ratio of the diameters d3 : d2 : d1 = 4.

When choosing the intervals of variation of the factors X1, X2, X3 it was taken into account that in the natural state in soils or other bulk materials, the amount of medium fractions is 1.5–2 times greater than the number of coarse and fine fractions. The same quantitative ratio was adopted between fractions X1, X2, X3.

With continuous filling of the volume, when individual grains of aggregates touch each other, a further decrease in voidness is possible only by placing smaller grains in the voids of the previous fraction. Such a compaction of the structure is accompanied by a noticeable strengthening of the macrostructure of the embankment as a result of an increase in the number of contacts of individual grains in the bulk of the backfill. Based on this assumption, it is sufficient to optimize the particle size distribution by bulk density.

For the experiment, a simplex-lattice design of the second order was chosen, which makes it possible to construct a complete quadratic regression equation of the following form:

$$Y = A_1 \cdot X_1 + A_2 \cdot X_2 + A_3 \cdot X_3 + A_{12} \cdot X_1 \cdot X_2 + A_{13} \cdot X_1 \cdot X_3 + A_{23} \cdot X_2 \cdot X_3 \qquad (1)$$

there A1, A2, A3, A12, A13, A23 – statistical values determined from experimental data;

$X_1 = \begin{cases} 0,5 = 15V \\ 1 = 30V \end{cases}$ – fraction < 0,14 as a factor of mathematical plan;

$X_1 = \begin{cases} 0,5 = 28V \\ 1 = 36V \end{cases}$ – fraction 0,315 – 0,63 as a factor of mathematical plan;

$X_1 = \begin{cases} 0,5 = 10V \\ 1 = 20V \end{cases}$ – fraction 1,25 – 2,5 as a factor of mathematical plan.

Calculations of the coefficients of the regression equation (1), the prediction dispersion function and the verification of the adequacy of the equation were performed according to the standard method [6].

The final regression equation is:

$$\rho(X_1 X_2 X_3) = 7{,}87 \cdot X_1 + 7{,}89 \cdot X_2 + 7{,}9 \cdot X_3 + 0{,}2 \cdot X_1 \cdot X_2 + 0{,}5 \cdot X_1 \cdot X_3 + 0{,}02 \cdot X_2 \cdot X_3 \qquad (2)$$

According to equation (2), the Rosenbom concentration triangle was constructed (Fig. 1). As can be seen from fig. 1, the optimal ratio of filler fractions of the embankment of transport routes is X1:X3 = 2:3 by volume. In this case, fraction <0.14 mm acts as a filler, and fraction 1.25-2.5 mm acts as a filler. The absence of the expected middle fraction can be explained by the fact that during free laying, the grains of the middle fraction, located between the grains of the large fraction, somewhat push them apart, increasing the voidness of the mixture. In an idealized mixture consisting of spherical particles of the same size, the volume of voids, as is known, does not depend on the size of the particles and varies from 47.6 to 25.9%, depending on the relative position of the particles. When analyzing Figure 1, it was found that the voidness of real polyfractional mixtures depends on the ratio of the sizes of the previous and subsequent fractions, as well as on the number of fractions. The smallest voidness of mixtures is realized with two fractions with a ratio of diameters of 1:16 and does not exceed 16% (ratio X1:X3 = 1:16).

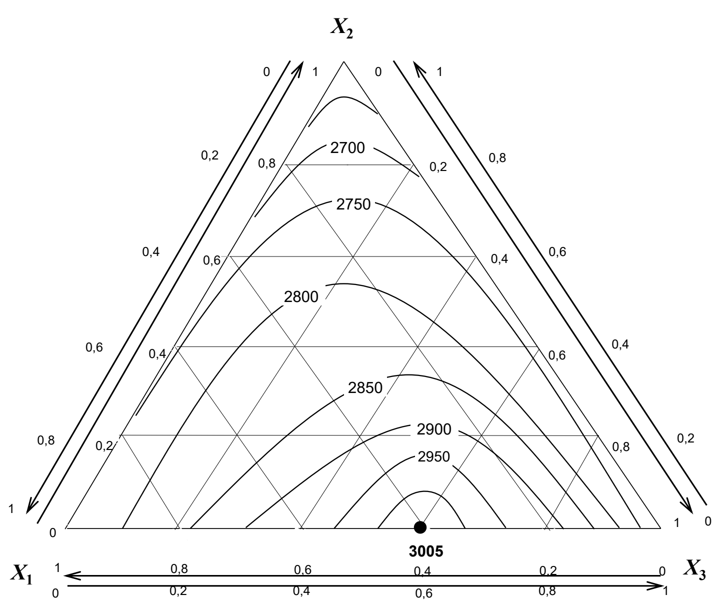

Fig. 1. The dependence of bulk density on granulometric size distribution

The theoretical maximum bulk density calculated from equation (2) is 3005 kg/m3, with a voidage of 15,85%, and the practical maximum bulk density obtained during the experiment is 2995 kg/m3 with a voidage of 16%. As can be seen from the data presented, the experimental error is 0,33%.

Based on the foregoing, it can be concluded that the most suitable for obtaining especially dense embankments of transport routes under the action of chemically aggressive media is a two-fraction mixture of minerals with a ratio of fractions: < 0,14:1,25÷2,5 = 2:3.

4 Discussion

It should be noted that the chemical composition of minerals for embankments of transport routes, resistant to the action of especially aggressive environments, is not the only condition for high operational properties and durability of embankments. In addition to the above, ballast materials must: be well wetted with water and pass (filter) water through them; be inert to water or form compounds that are more stable in aggressive environments than the original components; have a temperature coefficient of linear expansion close in value (when using a mixture of minerals); have an elastic modulus characteristic of solids with ductile fracture; have sufficient resistance to loads and operational impacts.

However, the ballast filler, which possesses the entire set of these properties at the same time, most likely does not exist. Ballast materials used in the practice of transport construction have only a part of these properties. In this regard, complex ballast materials or mixtures of ballast materials can be used, where each component of such mixtures allows you to control either a separate process of structure formation or the formation of certain operational properties of the embankment. As an example of such complex ballast materials, one can cite: mineral mixtures that optimally combine chemical elements of large and small atomic mass (a mixture of barite and carbon black, a mixture of barite and magnetite, a mixture of heavy flint waste, a mixture of optical glass production waste, etc.) [11, 12, 13].

To a large extent, this contradiction can be resolved by a systematic approach to the selection of ballast materials and their particle size distribution. Namely, it is necessary to select the type and granulometric composition of the embankment material from specially selected groups of minerals that meet the specified functional requirements. As selection criteria, it is necessary to use significant recipe-technological factors that affect the main structurally sensitive properties of embankments of transport routes.

The main parameters of the structure and properties of embankments for transport routes depend on a large number of recipe-technological parameters. In paper [14], using the example of mineral mixtures of fillers for radiation-protective composites, the classification and decomposition of factors were carried out, a hierarchical structure of criteria was constructed, and the possibility of taking them into account in the synthesis of materials with specified parameters was shown. The practical use of the necessary regularities is based on the Pareto principle: approximately 20% of the recipe and technological parameters determine approximately 80% of the quality of the structure and properties of the ballast materials of embankments [15]. This approach makes it possible to identify groups of significant formulation and technological parameters that have a decisive influence on the structure and properties of embankment ballast materials.

In this regard, for an effective practical technology for obtaining ballast materials of embankments with specified operational properties, it is necessary and sufficient for these recipe-technological factors to establish the dependences of their joint influence on the parameters of the structure and properties of the embankment for transport routes (for example, density, strength, etc.).

5 Conclusion

The conducted studies allow us to draw a number of conclusions. The nature of ballast materials has a decisive influence on the formation of the structure and operational properties of embankments for transport routes. The whole variety of minerals and potential fillers must be divided into functional groups based on their suitability for performing specified functions. To select the optimal granulometric composition, it is sufficient to use the most significant criteria, which are determined as a result of decomposition and analysis of the hierarchical structure of recipe and technological parameters that have a decisive influence on the quality parameters of the embankment structure or their performance (strength, impact resistance, abrasion, frost resistance, etc.). For embankments resistant to aggressive media, such criteria are the specific gravity of crushed stone, the specific surface of the ballast material, the ratio of the diameters of the ballast material fractions and their ratio to each other. Accounting for these criteria will allow obtaining optimal granulometric compositions from the functional groups of minerals, which, in turn, is a necessary condition for obtaining effective embankments for transport routes.

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