Parameters of strength and deformability of ash and slag mixture of Ekibastuz coals

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Abstract. The article assesses the possibility of using ash and slag mixture for the construction of a road bed. To this end, the traditional and modern methods of calculation of road surfaces are analyzed, which allow establishing the parameters of strength and deformability that require experimental determination. Experimental determination of strength and deformability parameters is performed by laboratory tests. For the implementation of tests the authors make samples of ash and slag mixture of different density. During the experiments, the metal stamp is pressed into the model and the experimental dependences of the sediment on the pressure are determined. This makes it possible to calculate the California Bearing Ratio, the deformation modulus, and to establish the pressures at which the mixture of ash and slag operates under compaction or shear conditions. Mathematical models are developed to calculate the parameters of strength and deformability from the value of pressure.

1. Introduction
The territory of the Russian Federation is vast and distinguished by a variety of geotechnical, geophysical, cryogenic, etc. factors leading to the formation of rocky, dispersed and frozen soils. Therefore, in some regions of Russia local road-building materials are missing. Due to the lack of local rocky soil, crushed stone, gravel, and crushed stone-sand mixtures have to be transported long distances from the field and the source of production of granulated material to the construction site of the road bed and road pavement. Dispersed soils are the most common material used for filling of embankments and arrange layers of pavement from the soil reinforced with astringent materials. Despite the wide distribution of dispersed soils in order to reduce the cost of construction of embankments, it is possible to consider the use of technogenic soils and industrial wastes. Such waste includes ash and slag mixtures and fly ash stored in the ash dumps of thermal power plants. According to the work of [1], the reserves of ash and slag waste of thermal power plants in Russia are estimated at more than 1.3 billion tons. However, the authors of [2] report that only 4–5% of such waste is disposed of in Russia.

It is possible to increase the volumes of utilization of ash and slag waste by using them in the construction of the road bed. Moreover, at certain transportation distances, the construction of embankments from ash and slag mixtures will be economically justified compared to arrange embankments from local dispersed soils. However, this requires a large amount of experimental
research to determine the parameters of strength and deformability of ash and ash and slag mixtures. In this direction, it is necessary to establish the parameters of strength and deformability of ash and slag mixtures and fly ash, which need to be determined first. To solve this problem, we will perform an analysis of traditional and modern methods for calculating pavements, on the basis of which we will establish the strength and deformability parameters that need experimental determination.

The main calculation of pavement is to check the sufficiency of the thickness of its layers according to the allowed resilient deflection. The basis of this calculation is laid in the works of D.M. Burmister [3], they have improved over time [4-6]. In Russia, this calculation is performed in accordance with the provisions of the normative document ODN 218.046-01. To implement this calculation it is necessary to have data on the elastic moduli of materials of the structural layers of the pavement and the subgrade soil. As the modulus of elasticity of the soil of the roadbed use the stamp modulus of elasticity \( E_{el} \). Stamp tests are performed in full-scale conditions, but can be simulated and carried out in the laboratory by testing models of soil of subgrade. An example of such a simulation is the method of determining the California Bearing Ratio (CBR) [7], in which a plunger with a diameter of 5 cm is pressed into the soil model.

A modern version of this calculation is the determination of the elastoplastic sediment of the subgrade and layers of pavement from granular materials. When solving the axisymmetric problem, elastoplastic deformation determines by integrating the function of relative deformation over the depth of the soil half-space or layer of finite thickness [8-10]. In this case, the strain function relatively to stresses can be both linear and nonlinear. In the case of the application of small loads to the sample, as a result of which in the depth of the half-space appear low deviators of stresses \( \sigma_d = \sigma_1 - \sigma_3 \), the dependence of the deformation on the pressure is linear. This makes it possible for determine small elastic-plastic deformations apply the physical equations of the theory of elasticity, replacing the elastic modulus with the modulus of elastic-plastic deformation. Determination of the modulus of elastic-plastic deformation can be perform laboratory tests of models of ash and slag mixture. And this can be done simultaneously with the determination of the modulus of elasticity, performing the application of the load and its removal by steps. At high stress deviator, the connection of deformation with pressure is nonlinear and is described by various logarithmic [11,12], power-law [13,14], and exponential [15, 16] models. To perform mathematical modeling, three-axis soil tests are carried out. Given that for the soil of the roadbed is not allowed the occurrence of large values of residual deformation, we assume that the ratio of settlement and pressure should be linear. In this case, the elastic-plastic deformation modulus \( E_{elp} \) is to be determined.

Another type of mechanical-empirical methods is the determination of the rut depth [20-22]. If the actual depth of the rut is compared with the limit value calculated by a special method [23], such calculation can be carried out by a separate criterion. The essence of the calculation to design the construction of the pavement, which during the service life does not accumulate the rut, the depth of which exceeds the limit values. In such methods, the depth of the rut is connected either with deformation of asphalt concrete or with deformation of granular material or soil. The connection of strain with stress can be established from the data of three-axis tests, and in the case of linear dependence of the settlement on the pressure, it can be calculated through the elastic-plastic deformation module. Thus, the determination of the elastic-plastic deformation modulus will allow to calculate the depth of the rut, but with the limitation of pressures relatively small values.
One of the main traditional calculations of road pavement is to check the soil of the roadbed for shear resistance. In this case, the calculation is based on the application of the Mohr–Coulomb criterion. The parameters of material in this criterion are the cohesion and the angle of internal friction. Such parameters of ash and slag mixture were determined in [24]. In modern methods for calculation of the soil bases of the criterion of Coulomb–Mohr is recorded in the effective stresses [25-28]. The modified equations of limit state are known, which contain as cohesion and angle of internal friction, and the third parameter of the material [29, 30]. In addition, the conditions of plasticity are known, in which the material parameters are calculated through the cohesion and the angle of internal friction [31-34]. To apply such criteria, it is also necessary to determine the parameters of the Mora–Coulomb criterion. To calculate the components of the stress tensor arising in the ash and slag mixture array, one can use the formulas of work [35].

Given the analysis performed, we note that:

- the results of the work [24,35] allow to perform check the roadbed from ash and slag mixture. Therefore, there is no special need in determining the cohesion and the angle of internal friction of the ash and slag mixture from Ekibastuz coals.
- first of all, it is advisable to determine the California Bearing Ratio of the soil and the elastic-plastic deformation modulus of the ash and slag mixture.

2. Materials and Methods

Production of model of a roadbed from ash and slag mixture is executed in a metal form in diameter of 150 mm. To compaction was used a rammer of Russian standard compaction measuring device, meeting the requirements of standard GOST 22733-2016. The authors of paper [1, 24] report that the mechanical properties of fly ash and ash and slug mixtures depend on the degree of compaction, which is characterized by the value of the compaction coefficient. The compaction ratio is the ratio of the density of dry soil in soil construction (in our case in cylindrical form) to the maximum standard density of the same dry soil. In order to further calculate the compaction coefficient, we have determined the maximum standard density of the ash and slag mixture and its optimal humidity. These tests are carried out in a standard compaction measuring device that meets the requirements of GOST 22733-2016. In accordance with the requirements of this standard, the soil is placed in a cylindrical cage with a diameter of 10 cm and compact by three layers of 40 impacts of rammer on each layer. The diameter of the rammer is equal to the inner diameter of the cylindrical shape and is 10 cm.

For testing, three groups of models are used, in each of which the ash and slag mixture was compacted with a different number of strokes. In model № 1, the seal is made in three layers of 30 impacts on each layer. In the model № 2 made 50 impacts on each of the three layers, and in the model № 3 on each of the three layers produced 70 impacts. Table 1 shows the number of ramming impacts on each of the three compacted layers and the corresponding compaction coefficients of the ash and slag mixture.

| № of model | 1    | 2    | 3    |
|-----------|------|------|------|
| Number of impacts on each of the three sealing layers | 30   | 50   | 70   |
| The coefficient of compaction of ash and slag mixture | 0.9  | 1.0  | 1.05 |

From the analysis of table 1 follows that at the different diameters of the metal clip 150 mm and rammer 100 mm, for compaction of ash and slag mixture to a value of compaction factor of 1.0 requires 50 impacts on each layer, not 40 impacts, as it is obtained by application of standard sealing according GOST 22733-2016. An illustration of the compaction of the ash and slag mixture is shown in fig 1, a. The model with a cylindrical form mounted in a tensile testing machine. At the same time,
the coincide of the model axes and the loading mechanism was controlled. An example of model installation is shown in fig 1, b. After installation of the model, a plunger with a diameter of 5 cm was pressed into the ash and slag mixture. An illustration of the pressing is shown in fig 1, c. Indentation of a metal plunger in ash and slag mixture was performed until the mixture came out from the mold. The model after the test is shown in fig 1, d.

Figure 1. Test illustration: a – soil compaction in the manufacture of the model; b – installation of model in a tensile testing machine; c – indentation of a metal plunger; d – completion of the test when ash and slag mixture came out from metal form.

3. Results

The CBR value is expressed in %, determined according to the standard (7) and calculated by the formula:

$$CBR = 100 \cdot \frac{p_{soil}}{p_{crushed\ stone}}, \quad (1)$$

where $p_{soil}$ and $p_{crushed\ stone}$ – pressures, which must be applied to the soil and standard crashed stone to deform them to the same value, MPa.

The CBR value depends on the required depth of the plunger settlement and is regulated by the standard [7]. The required depth of settlement of the plunger is taken 0.1 inch or 0.2 inch, which corresponds to 2.54 mm and 5.08 mm. When processing the experimental data, the deformation value is 2.54 mm. The amount of pressure that must be applied to the crashed stone to deform it to the specified value is standard and is 6.9 MPa. The pressure $p_{soil}$ is determined from the data of the experiment by the graphoanalytic method, the implementation of which is obtained by the adjusted value of $p_{soil}$. In fig. 2 shows the determination of the corrected values $p_{soil}$ for soil models with a compaction coefficient $k_c=1$, and the results of calculations CBR.
Figure 2. The results of determination of corrected values $p_{soil}$ and $CBR$.

The elastic-plastic deformation modulus was determined by the formula:

$$E_{elp} = \frac{p_{soil} \cdot D \cdot (1 - \mu^2)}{S},$$ (2)

where $D$ – diameter of the stamp, mm; $\mu$ – Poisson ratio; $S$ – required value of settlement ($S=2.54$ mm).

Table 2 shows the results of determining the adjusted value on ground pressure, calculating the CBR and elastic-plastic deformation modulus for models with different compaction coefficients.

| № of model | 1  | 2  | 3  |
|------------|----|----|----|
| The compaction coefficient of ash and slag mixture | 0.9 | 1.0 | 1.05 |
| Adjusted pressure value, MPa | 0.68 | 0.89 | 1.04 |
| $CBR$, % | 9.9 | 12.3 | 15.1 |
| Module of elastic-plastic deformation, MPa | 12.4 | 16.2 | 18.9 |

4. Discussion

According to the test results, it can be argued that:

- The values of the California Bearing Ratio and elastic-plastic deformation modulus increase with the value of compaction of the ash and slag mixture.

- Regression analysis showed that the parameters CBR and $E_{elp}$ are correlated with the value of the compaction coefficient of ash and slag mixture. Mathematical models are shown in table 3.

- As the humidity of the ash and slag mixture increases, the strength and deformability parameters decrease. Therefore, the ash and slag mixture in the upper part of the embankments should be protected from moisture. To do this, it is advisable to put the ash and slag mixture in a clip made of waterproof and vapor-proof material. Such an event will allow to maintain high mechanical properties of ash and slag material during the entire service life.

The new criterion makes it possible to use reliable databases on the amount of cohesion and the value of the internal friction angle for various soils and materials.
Table 3. Empirical formulas for CBR and Eelp determination of ash and slag mixture.

| Indicator | Type of model | Formula | $R^2$ |
|-----------|---------------|---------|-------|
| CBR       | Linear        | $CBR = 13.14 \cdot k_c - 20.15$ | 0.946 |
|           | Logarithmic   | $CBR = 31.98 \cdot \ln k_c + 13.03$ | 0.937 |
|           | Power-law     | $CBR = 12.87 \cdot k_c^{2.63}$ | 0.963 |
|           | Exponential   | $CBR = 0.842 - \exp(2.722 \cdot k_c)$ | 0.97  |
| Eelp      | Linear        | $E = 1.241 \cdot CBR + 0.389$ | 0.98  |
|           | Logarithmic   | $E = 15.41 - \ln CBR - 22.79$ | 0.993 |
|           | Power-law     | $E = 1.271 \cdot CBR^{1.0003}$ | 0.981 |
|           | Exponential   | $E = 5.746 \cdot \exp(0.08 \cdot CBR)$ | 0.961 |

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