The elastic modulus for ash and slag mixtures reinforced with inorganic binders

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Abstract. The article analyses applications of waste produced by thermal power plants and used by the road construction industry. One of the promising areas for the use of ash and slag materials is their reinforcement with inorganic binders and using for the construction of pavement. The Russian regulatory documents governing the use of ash and slag materials have several drawbacks, including the lack of recommendations for determining the elastic modulus for bases and coatings made from ash and slag mixtures reinforced with an inorganic binder in laboratory conditions. The lack of these recommendations does not allow the selection of the mixture with specified design values of the elasticity modulus. It makes it difficult to ensure required values of the modulus of elasticity in the construction of road pavement. The authors developed a method for determining the elasticity modulus in laboratory conditions in order to produce materials with specified values of the elasticity modulus and improve quality of design and construction of road pavement from ash and slag mixtures reinforced with inorganic binders.

1. Introduction
The road industry needs cheap and effective building materials which can improve quality of pavement, increase its turnaround time and reduce the cost of road maintenance. The use of waste produced by thermal power plants for producing road-building materials can help reduce their cost and preserve natural resources [10, 16, 23]. Over 80 million tons of ash and slag materials have been accumulated in Irkutsk region, and their volume is increasing.

One of the promising areas for the use of ash and slag materials in the road industry is their reinforcement with inorganic binders for the construction of base layers of pavements [1-33].

The reinforcement of ash and slag materials with inorganic binders is regulated by the following documents:

- GOST 23558-94 “Mixtures of crushed stone-gravel-sand and soils reinforced with inorganic binders for road and airfield construction. Specifications (as Amended by N 1, 2)”;
- ODM 218.2.031-2013 “Guidelines for the use of fly ash and ash and slag mixtures from coal combustion at thermal power plants in road construction”.

These documents have a number of drawbacks, the most important of which is the lack of recommendations for determining the elasticity modulus for ash and slag mixtures reinforced with inorganic binders in laboratory conditions. The lack of these recommendations does not allow the
selection of the composition of mixtures with specified design values of the elasticity modulus. It makes it difficult to ensure required values of the modulus of elasticity in the construction of road pavement.

The article aims to develop a method for determining the elasticity modulus for ash and slag materials reinforced with inorganic binders in laboratory conditions.

2. Materials and methods
To determine the elasticity modulus for ash and slag mixtures reinforced with inorganic binders, the following method has been proposed.

1. Production of laboratory samples of reinforced soil with specified values of maximum density and optimal humidity.

Samples are made using a hydraulic press.

To produce samples of reinforced soil, it is recommended to use mold cylinders, the requirements for which can be found in GOST 12801-98 “Materials based on organic binders for road and airfield construction. Test methods” (Table 1).

| The largest size of soil grains, mm |   |   |   |   |
|-----------------------------------|---|---|---|---|
|                                   | Diameter d | Height H | Top liner height h1 | Lower liner height h2 | Area, cm² |
| 5                                 | 50,5        | 130       | 80               | 50               | 20       |
| 10, 15, 20                        | 71,4        | 160       | 100              | 60               | 40       |
| 40                                 | 101         | 180       | 110              | 70               | 80       |

The mass of soil required for producing one sample is 600 - 2200 g. Depending on the size of the molds, sample cylinders have a height of 50.5; 71.4; 101.0 mm. If the sample cylinders have a height different from these dimensions, the mass of the mixture has to be adjusted.

\[ g = g_0 \frac{h}{h_0}, \]

where \( g_0 \) - mass of the test sample, g;
\( h \) – required height of the sample, mm;
\( h_0 \) – height of the sample, mm.

The required amount of the mixture is determined by formula

\[ P_{cm} = \rho_s \cdot V \cdot n = \rho_{sc}(1 + 0.01W_o)Vn, \]

where \( P_{cm} \) – mass of the mixture, g (kg);
\( \rho_s, \rho_{sc} \) - density of the wet mixture and the skeleton of the mixture, g / cm³;
\( V \) – volume of the sample, cm³;
\( n \) – the number of samples required to determine physical and mechanical properties of the mixture;
\( W_o \) – optimal humidity of the mixture, %.

Water content is determined in accordance with optimal humidity values determined according to PNST 324-2019 “General automobile roads. Soils. Determination of optimal humidity and maximum density by the Proctor method” and GOST 22733-2016 “Soils. Laboratory method for determining maximum density (as amended).”

1. Holding samples of reinforced soil under normal hardening conditions until they reach a design age

Samples are tested at the design age, depending on the type of binder:
- 28 days - Portland cement, slag Portland cement;
- 90 days – slowly hardening binders (fly ash, lime-ash, lime-slag, lime, cement-ash, etc.).

The samples should be stored and hardened at 20 ± 2 °C and a relative humidity of 95 ± 5%. They are placed in
- a chamber with normal hardening conditions;
- a bath with a hydraulic shutter;
- a desiccator, etc.

Samples are placed on liners so that the distance between the samples, as well as the samples and the walls of the chamber is at least 5 mm. The contact area of the sample with pads on which it is installed should be no more than 30% of the area of the reference face of the sample. The samples should not be moistened. They should be stored under wet sand, sawdust or other moistened hygroscopic materials.

**Water saturation of samples**

Compressive strength is determined on samples subjected to complete or capillary water saturation in accordance with PNST 322-2019 “Automobile roads of general use. Soils stabilized and fortified with inorganic binders. Specifications” and GOST 23558-94 “Mixtures of crushed stone-gravel-sand and soils reinforced with inorganic binders for road and airfield construction. Specifications (as Amended by N 1, 2) “.

**Compression of samples**

The samples are compressed using a press under the static load. When the load reaches a value of 50% of the breaking load, the sample is unloaded and reloaded (cycling).

**Data processing**

The elasticity modulus is calculated by formula

\[
E = \frac{\sigma}{\epsilon},
\]

where \(E\) – elasticity modulus, Pa;
\(\sigma\) – stress caused by the acting force, Pa

\[
\sigma = \frac{F}{A},
\]

where \(F\) – acting force, N;
\(A\) – force application area, m²;
\(\epsilon\) - elastic relative deformation of the material caused by stress

\[
\epsilon = \frac{l_1 - l_0}{l_0} \times 100\%,
\]

where \(l_1\) – size after deformation;
\(l_0\) – initial size.

The elasticity modulus is determined by testing a series of laboratory samples. The number of samples should be 6.

To conduct an experiment according to the proposed method, an ash and slag mixture produced by Ust-Ilim TPP was used. Ash-cement binder based on Portland cement and an ash-slag mixture of Novo-Irkutsk TPP were used as binders.

The results of determination of the elasticity modulus are presented in Table 2 and Figure 1.

**Table 2.** The results of determination of the elasticity modulus for ash-slag mixture reinforced with inorganic binders

| Binder          | Binder content, % | Age, days | Elasticity modulus E, MPa | Compression strength, MPa | Values of the elasticity modulus E according to ODM 218.2.031-2013 |
|-----------------|-------------------|-----------|---------------------------|--------------------------|---------------------------------------------------------------|
| Ash-cement      | 8                 | 28        | 1250                      | 3.7                      | no                                                             |
| Ash-cement      | 8                 | 90        | 1500                      | 6.6                      | no                                                             |
| Hydrated Air Lime | 7                 | 90        | 1200                      | 4.39                     | 350-250                                                        |
Fig. 1. Determination of the elasticity modulus for ash and slag mixture reinforced with ash-cement binder in the amount of 8%:

- 0-1 - loading;
- 1-2 - unloading;
- 2-3 - loading

The elasticity moduli of layers of monolithic materials can decrease as a result of cracking and water-frost effects and increase as a result of long-term physical and chemical processes. For materials and soils reinforced with inorganic binders located in the structural layers of pavement, cracking and spatial heterogeneity is characteristic. Therefore, the calculated value of the elasticity modulus is

$$E_p = K_k \cdot E,$$

where $K_k$ is the coefficient taking into account the change in the modulus of elasticity of the material in the structural layer.

The estimated value of the coefficient $K_k$ is 0.4.

3. Conclusion

Determination of the elastic modulus for ash and slag mixtures reinforced with inorganic binders is very important since it allows the construction of pavement with specified elasticity modulus values.

The following conclusions can be drawn:

1. The current regulatory and technical documents governing the design and construction of pavement have several drawbacks, including the lack of recommendations for determining the elasticity modulus for ash and slag mixtures reinforced with inorganic binders in laboratory conditions.

2. The method proposed by the authors makes it possible to produce materials with specified elastic modulus values and improve quality of road pavement made from soils reinforced with inorganic binders.

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