Experimental technique of defining the elastic modulus of bulk materials in laboratory conditions

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Abstract. Defining the elastic modulus of bulk materials is an important issue in quality assurance of design and construction of motorway bases. The analysis of current regulatory framework shows that there are no applicable methods for defining the elastic modulus of loose (bulk) materials in laboratory conditions. Moreover, if new or underinvestigated materials are used for motorway bases, it is necessary either to abandon their use or define their compliance with the regulations after motorway base construction. In view of the latter, an experimental technique and a device for defining the elastic modulus of bulk materials in laboratory conditions are developed. Following this technique, the elastic modulus of 5 mm – 20 mm, 20 mm – 40 mm crushed dump blast furnace and steelmaking slags was defined. Comparison of the obtained results with the recommended design values of the elastic modulus of similar materials shows good convergence (the difference is within 8%). There is no connection between the diameter of a stamp transmitting load to a sample and the specified value of the elastic modulus. Deviations do not exceed 10% for Ø50 mm, Ø120 mm, Ø150 mm stamps.

1. Introduction

1.1. Background

Road construction is one of the most material-intensive industries. Creation of a durable and qualitative road design involves reliable base construction providing an even underlay for the road surface and transmitting the road surface load onto a sub-grade. Motorway bases are made of bulk materials – crushed stone, gravel, crushed stone and sand mixtures. To ensure high road performance, base material must have sufficient strength and rigidity (elastic modulus). Strength and reliability of a base is achieved by its layer-by-layer compaction for the material to create elastic strength through loaded road surfacing, and using the material the strength of which is not lower than regulated. A quality indicator of base compaction is its elastic modulus. Internationally, load-bearing capacity of road surfacing as a whole is evaluated in terms of base elastic modulus.

1.2. Analysis of current regulatory framework for defining the elastic modulus of bulk materials

Current regulatory requirements and recommendations provide for defining the elastic modulus of loose bulk materials (road construction materials) by static methods using a rigid stamp or dynamic methods [1] - [4]. It is decisive that all these methods and the described techniques relate to field tests of materials, namely areas with a compacted material, the elastic modulus of which is to be defined. Although this approach accurately reflects real stress-strain properties of road structure layers, it does not allow defining them for new or underinvestigated materials.

According to the regulations [4] on testing samples of loose (crushed stone, gravel, sand) materials, a stamp of 25 cm – 35 cm in diameter is to be applied.

Another regulation (see Annex B, [3]) describes a method of making samples of loose materials to define the elastic modulus in both field and laboratory conditions. The schematic diagram of sampling to define the elastic modulus in laboratory conditions is shown in figure 1.
According to the given scheme, for the most widespread crushed stone grade of 20 mm – 40 mm a stamp size should be \( D_m \geq d \cdot 4 \cdot D = 4 \cdot 40 = 160 \) mm. Respectively, a mould diameter cannot be less than \( 7 \cdot D_m \), i.e. \( D = 7 \cdot 160 = 1120 \) mm. The thickness of a compacted layer must be no less than the width of a mould, so the height of the mould must be no less than 1120 mm. Thus, the regulations recommend making a cylindrical mould higher and wider than one meter. If we take into account the requirement contained in [4] that a stamp diameter is to be within 25 cm – 35 cm, the size of a mould is to be doubled.

Therefore, the drafters believe that a 2100 mm high and 2100 mm wide mould (designed for a 300 mm stamp diameter) is to be produced in a base of road surfacing and afterwards filled with crushed stone to accurately simulate crushed stone behaviour (20 mm – 40 mm grade) in laboratory conditions. If taken literally, the mould size exceeds the size of many bathrooms of residential buildings of the 1960s. The thickness of the material layer to be created is also unreasonable. Its estimated value is 2100 mm. In Ukraine, there is hardly any road (except for artificial embankments) where the thickness of a base layer is 2 metres. According to Annex F [5], the minimum possible thickness of a slag crushed stone base varies within 12 cm – 15 cm. For the crushed stone graded 40 mm – 60 mm, the mould dimensions will change proportionally, up to 3 m in diameter and in height. Thus, in real life there are no such roads and operating conditions of their bases to be reproduced in laboratory conditions.

In addition, to fill a cylindrical 2100 mm high and 2100 mm wide mould, 7.27 m³ of uncompacted crushed stone or, provided the bulk density \( \rho = 1200 \) kg / m³, crushed stone weighing 8.7 t will be required. Annex B [3] states that crushed stone should be placed in layers with subsequent compaction of each individual layer. According to the same annex, which is mandatory, the following load levels must be applied to each layer:
- 5 MPa – 15 MPa for soils and soil mixtures;
- 15 MPa – 25 MPa for sands, sandy and fine-grained mixtures;
- 20 MPa – 40 MPa for medium- and coarse-grained.

Due to compaction, the volume of the analytical sample should be increased by 30% - 40%. That is, the volume of the sample material will increase to 12 t.

Another question is what means can create pressure inside the mould of specified dimensions to compact the material layers? Let us consider the above-mentioned crushed stone 20 mm – 40 mm grade. Its compaction requires a pressure of 20 MPa as it is a medium-sized material.

\[
A = \pi \cdot D^2 / 4 = 3.14 \cdot 2.1^2 / 4 = 3.46 \text{ m}^2 \quad \text{– compaction area.}
\]

\[
F = \sigma \cdot A = 20 \cdot 10^6 \cdot 3.46 = 69.2 \cdot 10^6 \text{ H} = 7.054 \cdot 10^8 \text{ kg} = 7054 \text{ t.}
\]

Thus, the drafters make it incumbent to create a load of more than 7 kt in order to create a sample to define the elastic modulus of 20 mm – 40 mm crushed stone in laboratory conditions. How to create this load? What stamp is needed to transmit it by weight and size? How to put crushed stone into the

![Figure 1. The dimensions chart of a mould and sequence of compacting road construction materials when defining the elastic modulus [3]: I, II, III – layers of loose materials; d – a diameter of a maximum grade; h – a thickness of a compacted layer; Dш – a stamp diameter; D – a mould diameter; H – a total compaction thickness.](image-url)
mould? How to remove it after the experiment? Where to store such an amount of crushed stone? In this case, these questions are rhetorical.

Current regulations contain [1] - [4] different information on the methods of field tests aimed at defining the elastic modulus of a road structure or base layers by static load using a rigid stamp. So, in [1] the road structure elastic modulus is defined. To do this, the design static load is applied through a rigid stamp to road structures. Then, the deflection value is specified. Afterwards, the stamp is unloaded and the reverse deformation value is specified. The latter value is the basis for calculating the elastic modulus of road structures. It should be noted that the regulation in question does not indicate the amount of load to be applied for testing. There is only a rather generalized expression – a design load. The annexes of this regulation comprise the recommended specification of stamping equipment. They state that the capacity of load generating facilities is to be 60 kN. This is the only way to find out what is meant by the term design load. These assumptions are confirmed by the information given in table B [5], where the design load imposed on a first category road is equal to 65 kN. Equivalent to a stamp size of 30 cm, this load creates a pressure of 0.9 MPa on the surface. For a fourth category road this value is 0.5 MPa.

In another regulation [2] the load value is given indirectly. It is said that the pressure gauge value should be (160 ± 5) kgf/cm² or 15.7 MPa. This load value created by the hydraulic cylinder through a rigid stamp is to be applied to the pavement or the surface. Next, elastic deformation and then the elastic modulus are defined by the difference of the indicators when load is applied and then released.

According to [6] when defining the elastic modulus of pavement, load is applied gradually through a rigid stamp, namely: Q1 = 0.25Qmax; Q2 = 0.5Qmax; Q3 = 0.75Qmax; Q4 = Qmax. At each load level, the elastic deformation value is determined and a chart of the elastic deflection value caused by the load is plotted. After drawing a tangent to this chart, the elastic modulus value is determined. It is suggested to define Qmax value following the instructions given in [7]. According to the latter, Qmax value = 0.5 MPa for base surfaces and Qmax = 0.2 MPa for a sub-grade. This document provides a clear answer to the question of the load levels to be applied to different layers of a road structure, but it was abolished in 2019. The alternative regulation does not contain this information.

The regulation [3] contains the same algorithm for determining the elastic modulus as the previous one [6], referring to the repealed regulation [7] and plotting. It should be noted that the determination of any characteristics via plotting leads to a significant error of the obtained values.

The greatest clarity regarding load intensity and its application method was presented in [7] (abolished in 2019). Thus, the design load on a base is 0.5 MPa, which is to be applied gradually (3 levels – 5 levels), with exposure at each level and unloading. The elastic deformation rate is defined for each level. The obtained values provide for plotting, but the value of the elastic modulus is defined analytically by calculating the elastic deformation rate obtained for the highest load level.

A review of the available regulations on defining the elastic modulus of loose road construction materials in laboratory conditions indicates a lack of a single approach to this issue. The regulations contain mutually contradictory instructions; load levels can differ significantly.

2. Research methods
As there is no real mechanism of estimating the elastic modulus of loose and bulk materials, it is advisable to start developing real methods for defining this parameter in laboratory conditions. The following method of defining the elastic modulus is the engineering one. It requires further research, comparison of research findings with the results of field tests and the formation of an appropriate calculation mechanism. The current regulatory requirements [1] - [4] to a sample creation and altered test methods enabling its conduct in laboratory conditions are taken as a basis. Apart from that, a device for making a sample and defining the elastic modulus was developed.

The schematic diagram of a stand for defining the elastic modulus of loose materials is shown in figure 2.
**Figure 2.** The schematic diagram of a stand for defining the elastic modulus of loose materials: 1 – a layered compacted sample of material; 2 – a cylindrical mould; 3 – a support for a dial test indicator extension; 4 – an extension of a dial test indicator; 5 – a stamp; 6 – a bracket for dial test indicator fixing; 7 – a dial test indicator (division value – 0.01 mm); 8 – a dynamometer; 9 – a load generating device (hydraulic jack); 10 – a fixed rest

In accordance with the requirements [8], a cylinder with a plunger and a bottom with the same dimensions as in crushing tests (Ø150 mm) was used for the tests. Additionally, clip brackets were made and put on the cylinder to support the indicator extension. A similar holder was made for the plunger to attach the indicators. During the tests, 4 dial test indicators (0.01 mm division value) were used. They were placed on four sides of the plunger in orthogonally related directions. The number and location of the indicators should ensure greater accuracy of the tests and avoid off-center application of load. Pressure was produced by a hydraulic jack, while its rate was controlled by a ДОСМ-3-1 dynamometer.

The tests were done for crushed dump blast furnace and steelmaking slags graded 5 mm – 20 mm, 20 mm – 40 mm. Size grading was carried out in accordance with the requirements [8]. Two analytical samples weighing 4 kg each were taken from each grade. Analytical samples for dry basis tests were dried to a constant weight. An overall view of the analytical samples by grades is shown in figure 3 and figure 4.

**Figure 3.** The analytical sample of crushed dump blast furnace slag.

**Figure 4.** The analytical sample of crushed steelmaking slag.

A test sample was prepared taking into account the requirements of Annex B [3]. The cylinder (inner diameter – 150 mm) was conditionally divided into three parts throughout its height and filled with crushed stone layer-by-layer. When the layer was formed, it was compacted on a hydraulic press П-125 with the load meeting the requirements of Annex B [3]. Then, the next layer was produced and the procedures above were repeated. 5 mm – 20 mm crushed stone was compacted with the load of 20 MPa, and 20 mm – 40 mm grade with the load of 30 MPa. After compaction, the outer surface of the sample was covered with a layer of screened sand (up to 3 mm thick) to level off the surface and avoid possible off-center application of load. The overall process of making the test sample is shown in figure 5.
The sample created in this way was tested for compaction sufficiency in accordance with the requirements [1]. To do this, the load from 0 MPa to 0.5 MPa was applied recording the sensors readings in 0.1 MPa after attenuation of deformations (no more than 0.01 mm within 20 s to 30 s) at each load value. The total modulus of deformation was determined by data processing. Having repeated the same procedures for the second time, a new value of the total modulus of deformation was defined. The mixture is considered to be sufficiently compacted if the ratios of the first and second modulus of deformation do not exceed 2 [1].

The elastic modulus was determined using the methods described in [7] and in [1]. The load level of 0.5 MPa was chosen as the design load to be imposed on the surface of the road structure base through a rigid stamp. This load level is mentioned in the regulations [3], [6] and partly in [1]. In addition, this load level is specified in regulations of neighbouring countries (Belarus, Russia).

In accordance with the requirements [7], the load was applied level-by-level, with a level value of 0.1 MPa. Load application time – 30 s, pauses after unloading – 30 s, time spent on loading and unloading – 10 – 20 s. The indicators readings were taken after maintaining the specified load level, as well as after the pause following unloading. Discrepancy of the readings was used to determine elastic deformation of the structure. Due to the fact that the regulations [3] require applying a load through a stamp with the diameter being three or more times smaller than the mould diameter, the load was applied three times through stamps of different diameters, namely: Ø50 mm, Ø120 mm, 150 mm. With a mould (cylinder) diameter of 150 mm, the first stamp (Ø50 mm) met the regulatory requirements. Two other stamp diameters were adopted to compare the test results with a stamp diameter meeting the requirements with the results to be obtained when testing with stamps of other diameters. An overall view of a stand defining the elastic modulus of slag crushed stone with stamps of different diameters is shown in figure 6.

**Figure 5.** Making the test sample for elastic modulus defining.

**Figure 6.** A stand for defining the elastic modulus of slag crushed stone.
3. Results and discussion

Based on the obtained values of elastic deformation of the samples, the elastic moduli of the considered grades of slag, steelmaking crushed stone and three values of stamp diameters were calculated by formula 7.1 [4]:

\[
E_s = \frac{\pi \cdot \rho \cdot D \cdot \left(1 - \mu^2\right)}{4 \cdot f},
\]

where \(\mu\) – Poisson ratio (\(\mu = 0.25\)); \(\rho\) – surface design pressure (\(\rho = 0.5\) MPa); \(D\) – stamp diameter, m; \(f\) – elastic deflection (elastic deformation), m.

Using this formula (1) and the research results, the elastic modulus was calculated (see Table 1)

| Crushed stone grade, mm | Ø stamp – 150 mm | Ø stamp – 120 mm | Ø stamp – 50 mm | Theoretical value of elastic modulus [7], MPa |
|------------------------|------------------|------------------|-----------------|------------------------------------------|
|                        |                  |                  |                 |                                          |
| crushed dump blast furnace slag |
| 5 – 20                 | 470              | 449              | 433             | 350 – 450                                 |
| 20 – 40                | 487              | 441              | 466             | 350 – 450                                 |
|                        |                  |                  |                 |                                          |
| crushed steelmaking slag |
| 5 – 20                 | 398              | 392              | 357             | 350 – 450                                 |
| 20 – 40                | 469              | 436              | 427             | 350 – 450                                 |

Table 1 shows not only the results of calculations of the experimental elastic modulus of crushed stone of different grades but also the theoretical value of this parameter. Comparison of theoretical and experimental values indicates their good convergence. Experimental data either fall within the range of theoretical values or slightly (up to 8%) exceed the upper limit of values. The latter can be explained by the fact that design (theoretical) values are usually smaller than experimental ones because they assume variability and heterogeneity of studied materials by underestimating their real physical and mechanical parameters.

Comparison of the obtained experimental values of the elastic modulus defined by using stamps of different diameters indicates that the elastic modulus values are not impacted by a stamp diameter significantly. The difference in values does not exceed 10%. Given the convenience of the experiment and stability and predictability of the indicators, it is more appropriate to conduct an experiment with a larger stamp diameter.

It should be noted that this technique is experimental. It is worth mentioning that crushed stone in the middle of the cylindrical mould, provided that the stamp diameter is equal to the inner diameter of the cylindrical mould, is in a three-axis stress state, which may differ from operating conditions of a road structure. It should be borne in mind that during real operation a road structure base takes a load of vehicles through a surface layer (asphalt or cement concrete) of 150 mm – 300 mm thick. A surface will also constrain base distortion not only under a car wheel, along with the base material located on the sides and a sub-grade material.

To determine the degree of reliability of the results obtained, additional research is needed. The latter should consist in conducting field tests to determine the elastic modulus of base layers of a real road structure made of similar crushed stone. In order to compare, base layers must be compacted to the same state as the material of the laboratory sample. This can be controlled by determining the modulus of base deformation of a road structure. The last requirement is caused by the fact that crushed stone with different degrees of compaction will predictably have different elastic moduli.

If elastic modulus values defined through laboratory and field tests vary significantly (more than 15%), the calculation formula is to be amended. At present, the suggested method allows for
experimental tests to determine the elastic modulus of loose and bulk materials, while regulations make such operations physically impossible.

4. Conclusions
The analysis of current regulatory requirements and guidelines for defining the elastic modulus of loose and bulk materials indicates that it is physically impossible to carry out such operations in laboratory conditions. The developed engineering technique and device for defining the elastic modulus in laboratory conditions show a good convergence with the recommended calculated values of the elastic modulus of similar materials. The performed tests of slag crushed stone allowed obtaining the elastic modulus for differently graded crushed stone. The results either fall into the range recommended by the regulations, or slightly exceed the limit value (deviation of up to 8%). It is proved that different stamp diameters do not impact test results. The deviation of the elastic modulus values for stamps of Ø50 mm, Ø120 mm, Ø150 mm do not exceed 10%.

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