The study of deformation properties of a sand soil - expanded polystyrene granules mixture under cyclic loading conditions

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Abstract. The development of advanced materials for oil and oil products storage tank foundations under low temperatures and efficient technologies for their construction is an urgent task for oil and gas industry. It is proposed to use heat-insulating additives, for example, expanded polystyrene granules to reduce heat losses in foundation soils. The purpose of the research is to study the effect of artificial thermal insulation additives in sandy soils on the deformation properties of the resulting mixture. To achieve this goal, it is necessary to solve the following tasks: to prepare samples of the mixture "Sandy soil – expanded polystyrene granules", to carry out compression tests of the prepared samples and to process the results. Compression tests were carried out on samples of sandy soil – expanded polystyrene granules mixture with a 5% content of heat-insulating additives. Each test included five consecutive loading-unloading cycles. The maximum value of loading was 180 kPa. In the course of laboratory studies, data of a calculated value for a deformation modulus of investigated samples for the sandy soil – expanded polystyrene granules mixture were obtained. The calculated value of the mixture deformation modulus after the 4th loading cycle was 16.4 MPa, which was higher than minimum allowable (15 MPa) by 9%, and after the fifth cycle this value was 15% higher. The obtained results allow us to develop a tank foundation structure with improved heat-insulating properties and technology for its construction.

1. Introduction

The development of fuel and energy sector is impossible without a further search of efficient structures for soil foundations and beds, as well as technologies for their construction. One of promising directions for improving structures of foundations and beds is the use of innovation materials that provide a significant improvement in operational properties of the elevated structures. Thus, for example, the efficient moisture before a compaction of dispersed non-cohesive soils of oil and oil products storage tank foundations allows soils' bearing capacities to be doubled, thereby increasing the time of trouble-free operation of a technological infrastructure [1]. In its turn, application of progressive forms of cross-section piles will reduce material costs for the construction of foundations of oil and gas industry facilities up to 25% [2]. A "heat diode" application will increase the stability of buildings and structures built in permafrost soils [3]. The study of both the deformation properties of frozen soils [4] and their strength characteristics [5] also makes it possible to make full use of the available resources for the construction of buildings and structures in permafrost conditions. Modern technological equipment of the oil and gas industry is characterized by the cyclic nature of loading on bases and foundations. In addition, newly developed areas are characterized by increased seismic activity. Therefore, further study of the dynamic characteristics not only of rocks [6], [7], but also of various soils [8] [9] in terms of dynamic impact will intensify the search for rational design and technological solutions in the construction of oil and gas industry bases and foundations.

Obviously, the practical implementation of new construction solutions is impossible without the development of new energy and resource saving technologies. For example, the technology of piling foundations on a compacted bed allows material costs to be reduced up to 30% [10]. Important advantages of this technology are its virtually waste-free and ecological compatibility [11]. Further development of promising directions for a comprehensive solution to provide stability in a soil of buildings and structures foundations for a technological infrastructure of pipeline transportation of hydrocarbons is impossible without a wide range of theoretical [12] and experimental [13] studies. The soil foundation of tanks for oil and oil products is usually made of dispersed non-cohesive soils. The works aimed to refine a soil deformation model under a static [14] and a dynamic load [15], [16] can be examples of investigations to improve foundation structures and their construction technology. Results of experimental and laboratory studies, for instance, papers investigating the influence of a grain size distribution of non-cohesive soils on the value of a dynamic shear modulus [17] and the deformation modulus [18] are of special interest. The equipment, which can register studied processes by a remote and contact free method [19], as well as the software for correct processing of data obtained [20] are the necessary conditions to conduct experimental studies.

The analysis of existing structures of soil foundations and technologies for their construction showed that, in spite of a significant progress in these fields, the modernization potential of accepted engineering solutions is not fully exhausted. The development of the Far North regions makes actual the task to reduce heat losses in foundation soils during the transport and storage of liquid hydrocarbons. This involves both the change in rheological properties of the product (oil), and potentially dangerous thawing of foundation soils with a subsequent loss of soils' required bearing properties. At present this complex problem is being solved by means of energy- and resource-consuming methods, as, for example, the use of specialized refrigeration units for a foundation soil and oil heaters, seasonal cooling devices.

The problem of costs' reduction on the stage of transport and storage of liquid hydrocarbons under low temperatures and in permafrost soil conditions can be solved with the help of new, promising building materials with improved heat-insulating properties for the construction of soil foundations, including oil storage tanks. An important condition for application of such materials is a provision (along with the improved heat-insulating properties) of the required deformation properties according to the current regulations.

A composite material i. e. a mixture of sandy soil (SS) and a heat-insulating additive, for example, expanded polystyrene granules (EPSG) is proposed to use as this promising material. Obvious advantages of the proposed additive are high heat-insulating properties, low cost, durability, but at the same time, its significant disadvantage is unsatisfactory deformation properties.

As a rule, dispersed non-cohesive soils used for the construction of soil foundations of oil and oil products storage tanks have deformation characteristics that exceed minimum allowable values. According to current regulations, modulus of soil deformation E_k is one of the main soil deformation characteristics [21]. Therefore, it was decided to study the effect of EPSG additives in SS on the deformation modulus E_k of the obtained mixture under cyclic loading conditions that meets the conditions of both: the technology of a tank foundation construction and its further maintenance.

2. Problem statement

We propose to conduct a series of laboratory studies to specify the influence of EPSG additives on deformation modulus E_k for the SS-EPSG mixture under a cyclic loading.

3. Methods and materials

Laboratory studies are planned to conduct in three stages. At the first stage of preparation it is necessary to determine the type of SS according to its grain size distribution [22]. Since the maximum density of the studied SS-EPSG mixture is achieved with its moistening to optimum values w_{opt} [1], the required water amount Δm_w, taking into account initial hygroscopic moisture w_g of the used SS is calculated according to the formula:

$$\Delta m_w = m \cdot \frac{w_{opt} - w_g}{1 + w_g} \quad (1)$$

where m is the SS sample weight of the initial moisture; w_{opt} is the required optimum moisture of SS; w_g is the initial, hygroscopic moisture of SS sample, which is determined according to the current regulations [23].

For the mixture preparation, a part of SS is replaced by an equal amount of EPSG:

$$\Delta V_{\mathrm{EPSG}} = \Delta V_{SS}, \quad (2)$$

where ΔV_{EPSG} is the volume of EPS granules added into SS sample; ΔV_{SS} is a replaceable SS volume.

During the second stage, the stage of laboratory studies - a series of compression tests of prepared samples for the SS-EPSG mixture is planned. The existing regulations determine the procedure [24] and the necessary equipment to conduct compression tests [25]. The compression test program provides for five loading - unloading cycles (Fig. 1).

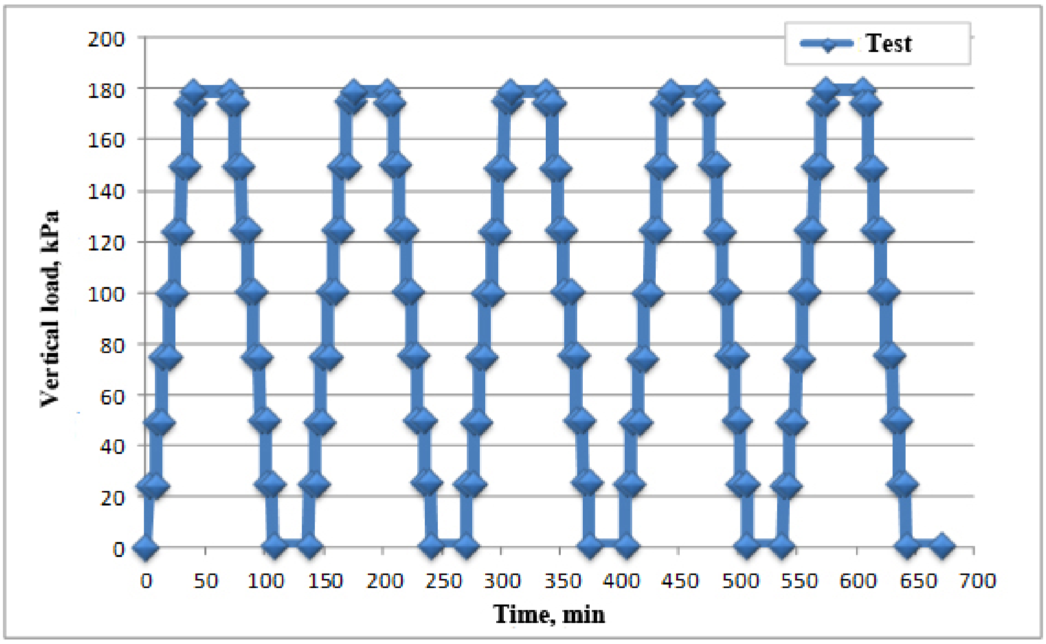

Figure 1. The program of cyclic compression tests for SS-EPSG mixture samples

The maximum loading value is 180 kPa that corresponds to the pressure on foundation soils under the bottom of a vertical steel tank for oil and oil products with 50000 m^3 volume during hydraulic tests. Although the current regulations, the state standard [26] and the set of rules [21] establish minimum six definitions of soil characteristics, taking into account possible rough deviations in the definitions, it is planned to conduct 21 compression tests to define the deformation modulus E_k for SS-EPSG mixture. The reason for this is that the methods of statistical processing of laboratory studies applied in the state standard use a normal probability distribution [26]. The selected number of parallel definitions for deformation modulus E_k takes into account the need to determine preliminarily a distribution pattern of the examined characteristic.

At the final stage, the processing phase of data obtained, it is planned to perform mathematical [25] and statistical [27] processing of laboratory study results according to the current regulations. From the results of compression tests, the deformation modulus E_k is determined by the formula [25]:

$$E_k = \frac{\Delta p}{\Delta \varepsilon} \cdot \beta \quad (3)$$

where Δp is an interval of pressures applied to the sample; Δε is a change of a relative compression corresponding to Δp; β is a coefficient taking into account the lack of a soil lateral expansion in a compression device.

To establish the distribution law pattern of the examined characteristic - the deformation modulus E_k it is proposed to use a composite criterion and a technique of its definition given in [27].

To verify the composite criterion, at first we need to calculate arithmetic mean value $\bar{E}$ of measurement results by the formula:

$$\bar{E} = \frac{1}{n}\sum_{i=1}^{n} E_i \quad (4)$$

where E_i is the i-th measurement result; n is the number of corrected measurement results.

Rough errors can occur in defining the deformation modulus E_k in the course of laboratory studies. Preliminary accepting a hypothesis of the normal distribution for the group of results, from the assumption that the largest E_{max} or the smallest E_{min} measurement result is caused by rough errors, Grubbs' tests are used to avoid them:

$$\begin{cases} G_1 = \dfrac{\left|E_{\max} - \bar{E}\right|}{S} \\ G_2 = \dfrac{\left|\bar{E} - E_{\min}\right|}{S} \end{cases} \quad (5)$$

where S is the standard deviation calculated by the formula:

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(E_i - \bar{E}\right)^2}{n-1}} \quad (6)$$

Comparing G_1 and G_2 with theoretical value G_T of Grubbs' test in the chosen significance level q (is 5%), one makes a conclusion about the presence or absence of rough errors in the group of results. If $G_1 > G_T$, then E_{max} is excluded as an unlikely value. If $G_2 > G_T$, then E_{min} is excluded as the unlikely value. After eliminating rough errors, it is necessary to repeat calculations of arithmetic mean value $\bar{E}$ by the formula (4) and Grubbs' tests G_1 and G_2 by the formula (5).

To examine whether the measurement results belong to the normal distribution, it is proposed to use a composite criterion consisting of Criterion 1 and Criterion 2. According to Criterion 1, measurement results in the series are considered normally distributed under condition:

$$d_{1-q/2} < \tilde{d} \le d_{q/2} \quad (7)$$

where $d_{1-q/2}$ and $d_{q/2}$ are fractiles of probability distribution, which tabular values are presented in [27].

The relationship $\tilde{d}$ is calculated by the formula:

$$\tilde{d} = \frac{\sum_{i=1}^{n}\left|E_i - \bar{E}\right|}{nS^*} \quad (8)$$

where S * is a shifted standard deviation calculated by the formula:

$$S^* = \sqrt{\frac{\sum_{i=1}^{n}\left(E_i - \bar{E}\right)^2}{n}} \quad (9)$$

According to Criterion 2, measurement results are considered normally distributed, if no more than m differences (E_i - $\overline{E}$) exceeded $z_{p/2} \cdot S$ value. Here, $z_{p/2}$ is an upper fractile of a probability distribution for a normalized Laplace's function, which tabular values are given in [27], and S is the standard deviation calculated by formula 6.

Thus, both criterions - Criterion 1 and Criterion 2 must be met for belonging of measurements results of the group to the normal distribution.

In case the normal distribution of obtained values for deformation modulus E_k is confirmed according to [26], it is necessary to determine its calculated value E by the formula:

$$E = \frac{E_n}{\gamma_g}, \tag{10}$$

where E_n is a standard value of the deformation modulus E_k, obtained as a result of compression tests; γ_g is a soil reliability factor.

The standard value of deformation modulus E_n is assumed to be equal to arithmetic mean value $\overline{E}$ for the results of laboratory definitions and is calculated by formula 4. The soil reliability factor γ_g is calculated using the formula:

$$\gamma_g = \frac{1}{1-\rho_\alpha}, \tag{11}$$

where ρ_α is an accuracy (error) figure of the average value for deformation modulus $\overline{E}$, calculated by the formula:

$$\rho_\alpha = \frac{t_\alpha \cdot V}{\sqrt{n}}, \tag{12}$$

where t_α is a tabular coefficient, which values are given in [26], V is a coefficient of variation for the deformation modulus calculated by the formula:

$$V = \frac{S}{E_n}. \tag{13}$$

We expect that the calculated value of deformation modulus E will help to estimate the prospects of use for EPSG additives in SS foundations of vertical steel tanks for oil and oil products storage under low temperatures and in permafrost soil conditions.

4. Laboratory Studies

An air-dry sandy soil of average size (see table 1) was used for the preparation of examined composite mixture.

Table 1. The grain size distribution of a sandy soil

	Particle size, mm							
	more than 10	5-10	2-5	1-2	0.5-1	0.25-0.5	0.1-0.25	less than 0.1
Fraction's mass content, %	2.8	1.5	3.8	8.0	14.5	27.6	35.7	6.1

The initial hygroscopic moisture w_g of SS samples was 0.15%. According to the previous studies, the value w_{opt}=7 % was chosen as an optimum moisture content of SS samples used [1]. The required water amount Δm_w was calculated by formula 1. Since in modern technical and special literature there were no data about the effect of EPSG additives in foundation soils on the obtained mixture properties, it was decided to limit the EPSG amount to 5% from the obtained mixture of SS-EPSG. The required volume of EPSG is defined according to equation 2. The examined sample has a cylindrical shape, its height is 25 mm, the diameter is 87 mm (Fig. 2, A). For conducting compression tests, the SS-EPSG mixture sample was installed in the odometer in a specialized loading device (Fig. 2, B). The compression test program is shown in Fig. 1.

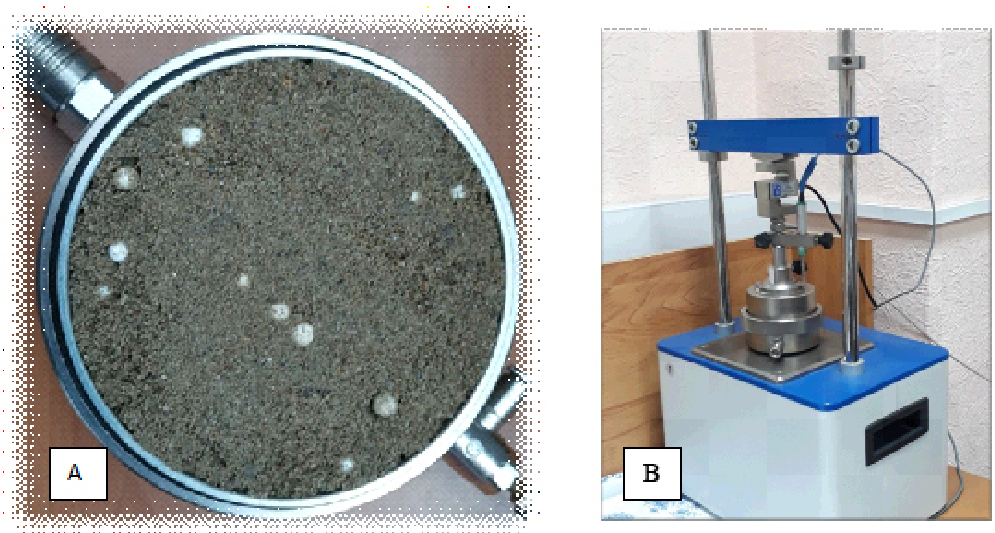

Figure 2. An SS-EPSG mixture sample in the odometer (A); Test unit for samples of mixture under compression conditions (B)

Data on changes in relative deformation ε of SS-EPSG mixture samples depending on the applied pressure p were obtained after compression tests. The example of representation for the results obtained during compression tests is shown in Fig. 3.

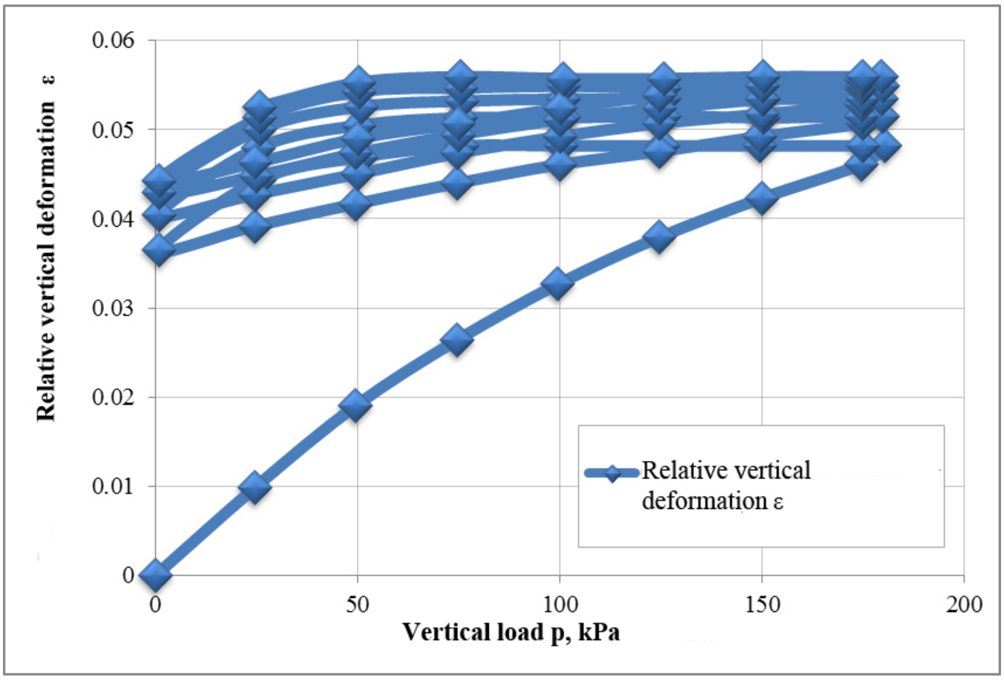

Figure 3. The change in a relative deformation of SS-EPSG mixture sample in the course of laboratory studies

The analysis of obtained laboratory data is expected to estimate the effect of both EPSG additives and cyclic loading on the deformation modulus E in the course of compression tests.

5. Results of Laboratory Studies

It was established that the calculated value of the deformation modulus E for five loading cycles of SS-EPSG mixture exceeds the minimum allowable value E_{min} equal to 15 MPa. 21 compression tests to determine the deformation modulus E_k of SS-EPSG mixture samples were carried out in the course of laboratory studies. The average values of $\overline{E}$ for the deformation modulus calculated by formulas (3) and (4) are shown in Fig. 4. The diagram also shows the minimum and maximum values of deformation modulus E_k, as well as values $\overline{E}$ + S and $\overline{E}$-S, calculated using equation (6), Fig. 4.

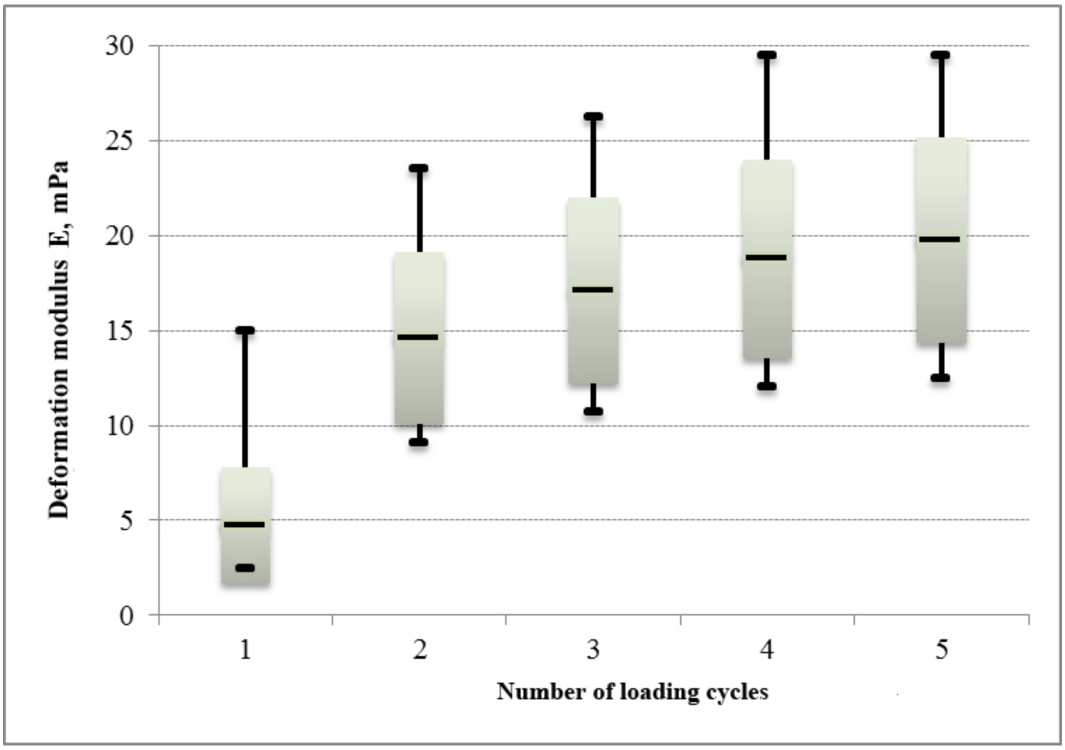

Figure 4. The influence of loading cycles number on results of laboratory studies

The analysis of values for deformation modulus E_k for rough errors using Grubbs' test was performed for the data obtained at the fifth, final loading stage. The analysis results are given in table. 2

Table 2. Analysis of laboratory data for rough deviations

Characteristic	Parameter			Conclusion
	G_T (n=21, q=0.05)	G_1	G_2	
Deformation modulus E_k	2.733	1.786	1.352	No rough errors

The verification of measurement results belonging to the normal distribution according to the composite criterion was also performed for the data obtained at the fifth, final loading stage. The results of verification that measurement results belong to the normal distribution according to Criterion 1 are given in table 3.

Table 3. Verification of distribution pattern for laboratory data (Criterion 1)

Characteristic	Parameter			Conclusion
	$d_{1-q/2}$ (n=21, (1-q_1/2) =95%)	$d_{q/2}$ (n=21, q_1/2=5%)	$\tilde{d}$	
Deformation modulus E	0.7304	0.8768	0.8598	Measurement results belong to normal distribution

The results of verification that measurement results belong to the normal distribution according to Criterion 2 are shown in table 4.

Table 4. Verification of distribution pattern for laboratory data (Criterion 2)

Characteristic	Parameter			Conclusion
	$z_{p/2}$•S (n=21, q_2 =5%, P=0.96)	m	m_{act}	
Deformation modulus E	0.7304	0.8768	0.8598	Measurement results belong to normal distribution

Since both criterions - Criterion1 and Criterion1 2 are met, it is considered that the distribution of measurement results of data groups for deformation modulus E for the final loading stage corresponds to the normal distribution. Thus the normal nature of distribution allows us to determine the calculated value of the deformation modulus by formulas (10) - (13) for various loading stages, see table 5.

Table 5. Calculated deformation modulus E (according to loading stages)

Loading stage	Coefficient of variation, V	Accuracy (error) figure ρα	Soil reliability factor γ_g	Calculated value of deformation modulus E, MPa
1	0.65	0.29	1.42	3.3
2	0.31	0.14	1.16	12.5
3	0.29	0.13	1.15	14.9
4	0.28	0.13	1.15	16.4
5	0.27	0.12	1.14	17.3

The data about the influence of both EPSG additives in sandy soils and the number of loading stages on a calculated value of deformation modulus E obtained during laboratory studies will estimate the possibility to use the proposed mixture for the construction of foundations for vertical steel tanks at low temperatures.

6. Results and Discussion

The tank foundation for the storage of oil and oil products with 50000 m^3 volume is considered as a target structure of the performed laboratory study. According to the current regulations “Soil beddings must be made of a soil packed in layers with optimal moisture, the soil deformation modulus after compaction must be at least 15 MPa” [28]. Therefore of interest is to compare the obtained values of calculated deformation modulus E and its minimum allowable value E_{min} (Fig. 5).

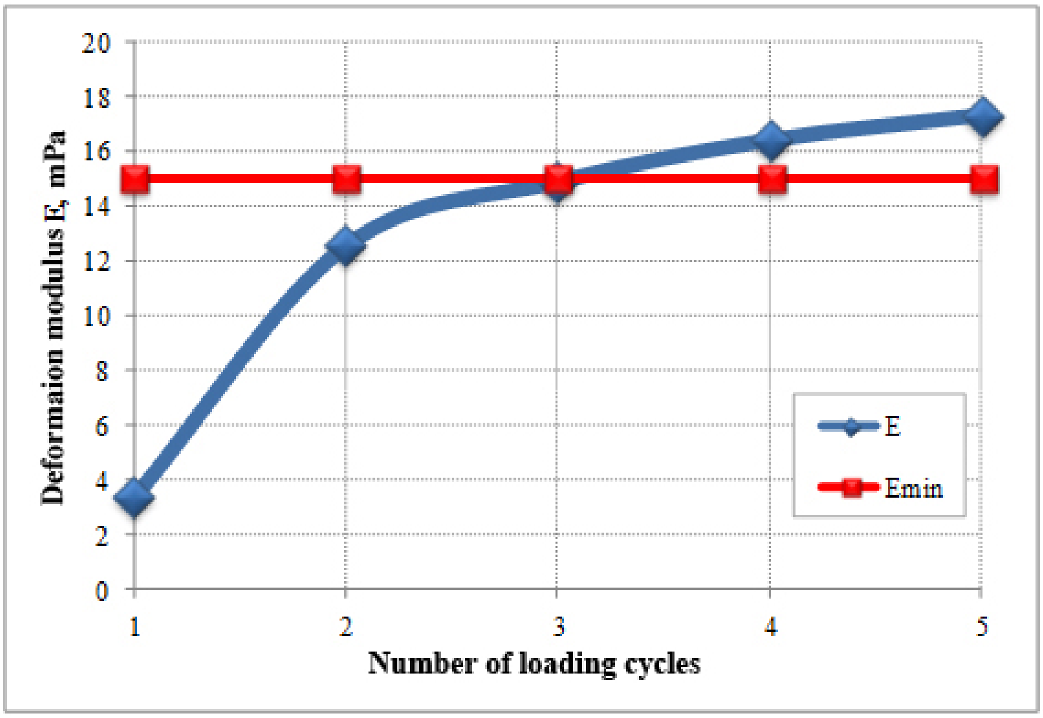

Figure 5. Influence of number of loading cycles on a calculated value of deformation modulus E

In Fig. 5 a horizontal line shows a minimum allowable value of deformation modulus E_{min}. As seen from graphical data after the third stage of loading, the calculated value of the deformation modulus is almost equal to the minimum acceptable value. After the fourth stage of loading, the calculated value of modulus exceeds the minimum allowable one by 9%, and after the fifth – by 15%.

The analysis of obtained data also allows us to establish the influence nature of the number of laboratory experiments on the resultant of the calculated value for deformation modulus E. According to formulas (10) - (13) for data obtained at the fifth final loading stage, necessary calculations were performed for 6, 10 and 15 consecutive tests (Fig. 6).

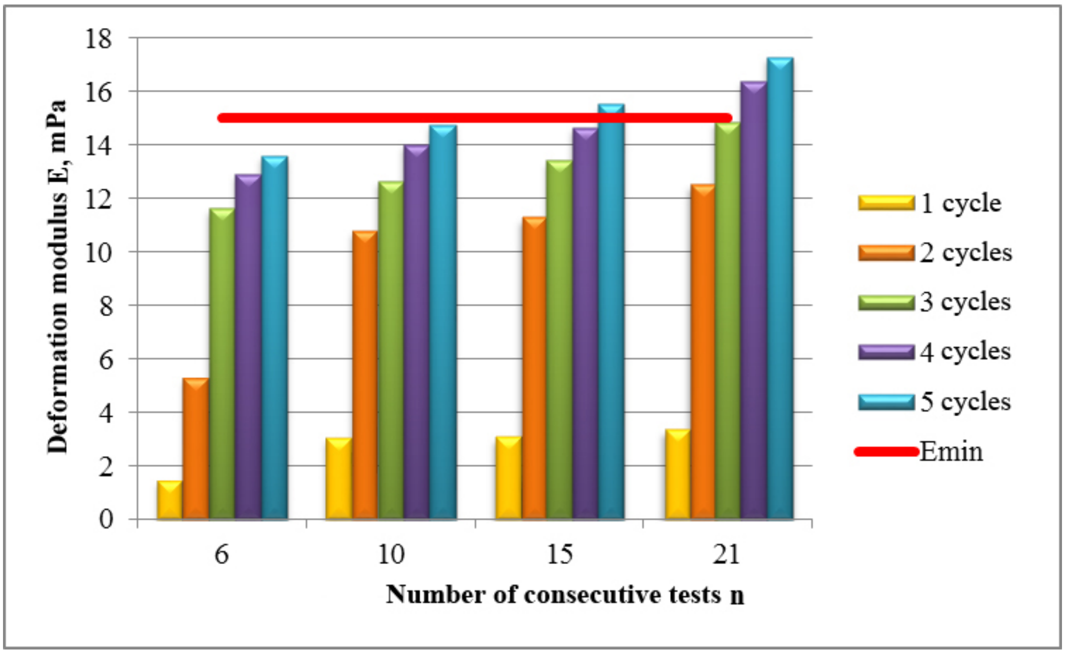

Figure 6. Influence of number of consecutive laboratory tests of calculated value for deformation modulus E on its value for various number of loading cycles

As can be seen from provided data, if the minimum acceptable number of consecutive experiments was accepted, according to the state standard [26] and the set of rules [21], than the calculated value of deformation modulus E of the mixture would not exceed minimum allowable value E_{min} even after five loading cycles. Exceeding of the minimum allowable value takes place after 15 consecutive tests and only for 5 loading cycles.

7. Conclusions

In the course of conducted studies it was established that the obtained results for defining of deformation modulus E_k for SS-EPSG mixture with optimum moisture w_{opt} with a 5% content of heat-insulating additive belong to the normal distribution. This allows the existing method to be used to define deformation properties of the proposed mixture. To specify construction parameters of a vertical steel tanks' foundation with a volume up to 50000 m^3 and technological modes of its construction, it is proposed to include in the laboratory test program at least five loading - unloading cycles. It was established that the calculated value of the deformation modulus E after the five loading cycles of SS-EPSG mixture exceeds the minimum allowable one E_{min} (15 MPa) by 2.3 MPa. This allows the proposed mixture to be used as a base with improved heat-insulating properties for vertical steel tanks up to 50,000 m^3 for oil and oil products storage under low temperatures. The obtained laboratory data also confirm the prospects of further study of EPSG effect on the deformation properties SS-EPSG mixture by the increase of EPSG volume fraction in the mixture.

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