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# The results of experimental studies of the soil cement deformation capacity under the "loading-unloading" cycle conditions

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**Abstract.** The application of soil-cement elements for strengthening weak and subsiding foundations has become increasingly widespread in recent years. At the same time, the requirement for the technology of soil-cement production, which is a mixture of soil and cement mortar, is increasing. The quality control of the soil-cement production is in searching its properties, in particular deformation properties, which are decisive for strengthening the soil base. The paper describes the methodology for preparing soil-cement samples and the main analytical formulas for determining absolute and relative deformations. The results of experimental research on the deformed state of the samples, which were tested under the conditions of seven "loading-unloading" cycles, are given. Deformation graphs are constructed, and deformation values are analyzed, which indicate that in the stress range from 0.05 to 1.2 MPa, elastic deformations are already observed during the first cycle and the main compaction stage occurs. It is proved that the value of elastic deformation in seven cycles ranges from 0.14 mm to 0.18 mm and practically does not change after the third load cycle. The obtained results prove that they can be the basis of numerical analysis and that the elastic approach during mathematical modeling is correct.

## 1. Introduction

To date, several organizations are engaged in the installation of soil-cement elements to strengthen soil foundations in Ukraine. During their work, it is important that the creation of geocomposite material, i.e. soil-cement, is carried out with high quality, i.e. ensuring strength and especially deformation parameters [1-3].

A soil-cement element can be in the form of a pile or a micropile and is an artificial structure produced at a construction site. The soil-cement element must meet the requirements outlined in the project documentation and current regulatory documents, since it is part of the sub-foundation base and thus ensures the reliability of the super-foundation structure [4, 5]. One of the main parameters of soil cement is the modulus of deformation $E$ (MPa), which is a calculated index, the value of which ensures the normal deformed state of the massif, fixed by piles or micropiles. Therefore, in

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construction practice, it is important to determine the main factors that increase the deformation modulus of weak soils. The main factor is the technology of the soil-cement element production [6, 7].

As is known, soil cement is a mixture of natural soil and a cement-based fixing solution [7, 8]. Depending on the composition of the soils and their physical and mechanical characteristics, the solution may also include other components (slag, discrete filler, various plasticizers, etc.). If we draw an analogy with concrete, then soil-cement should be divided into at least two types: soil-cement itself – a material obtained in loamy, including subsiding soils, except for peat, an analog of cement (cement-sand) solution, and soil-concrete – a material obtained in medium- and coarse-grained sands and large-debris soils, an analog of ordinary and fine-grained concrete.

The process of soil-cement element production is a process of loosening the natural soil to the design depth with the simultaneous application of a fixing solution [8, 9]. For this, drilling rigs are used, which can implement soil loosening, which is carried out by a special tool, the function of which includes the supply of fixing solution. High-quality loosening requires considerable energy to rotate the tool, as well as synchronization of the rotation velocity, the depth of the tool, and the supply of the fixing mixture. For different types of soil, these parameters have significant differences.

In some cases, the combination of these parameters cannot be achieved for technical reasons. The quality of soil cement as a material decreases, and then emergencies arise with already-built objects. An auger with a drill bit is often used as a loosening tool, but it cannot physically ensure the quality of the soil-cement element, because the bit removes thick chips and cannot loosen them, so the soil-cement is segregated. The auger is a tool that transports the destroyed rock to the surface, so there are quite large pieces of soil in the cement mortar. And since it is impossible to predict their sizes and order of placement, it is also impossible to calculate the load-bearing capacity and deformed state of the massif.

From the practice of performing work, the rotation velocity of the tool for high-quality soil crushing cannot be less than 150 rpm [8]. The velocity of deepening the tool depends on the type of soil in the engineering-geological section. If there are sandy-clay or loess-subsiding soils [8, 10], crushing occurs at a higher velocity of immersion than in clay soils. However, for high-quality mixing, it is necessary to go through each interval several times. This dependence is valid for almost all types of soils, except for large-debris (gravel-pebble) and coarse-grained sands, since in them, in addition to the cement content, the initial aggregates (solid particles) also have a significant impact on the strength and deformation capacity of the soil cement.

The strength of soil cement directly depends on the cement content in the volume of processed soil, respectively, the deformation modulus depends on the quantity and quality of cement [5, 8]. Therefore, an important stage is the correct calculation of the amount of cement for the work and the method of its preparation and injection. Pumps capable of cooling the loosening tool, as it heats up during operation, should be used to supply the solution, and the solution should be dosed into the well. Loose and solution-soaked soil has a high viscosity, so the initial pressure required for pumping must be sufficient, which means greater than the natural pressure at the corresponding depth.

Thus, the research of already prepared soil cement, considering the technology, is related to the search for the deformation capacity of this material. The purpose of the presented scientific article is to determine the deformation properties of soil-cement, which characterize elastic and plastic properties, which can be found only during a special cycle of "loading-unloading".

## 2. Methods

Determining the deformation properties of the soil-cement element should be performed at all stages of its creation. First, the soil-cement mass is selected during production. Then, to control homogeneity, the produced soil cement elements are drilled along their entire length with a coring tool. At the same time, the structure of the soil-cement material and the presence of inclusions that reduce its strength are revealed. Accordingly, prepared samples are tested for uniaxial compression, and the quality of the work performed is evaluated based on these results.

While drilling, a sample of cylindrical shape is obtained. It must have parallel lower and upper

IOP Conf. Series: Earth and Environmental Science **1491** (2025) 012005 doi:10.1088/1755-1315/1491/1/012005

faces to test its deformation properties. A special machine was made to ensure such conditions (figure 1).

**Figure 1.** A machine for preparing samples for testing.

Its main important detail is the diamond discs placed at a given distance. This ensures the sample size. The quality of sample cleaning is also important, which is ensured by selecting the rotation velocity of the diamond cutting discs. Figure 2 shows a sample prepared for testing.

**Figure 2.** The view of the soil-cement sample after its processing.

According to normative documents, it is customary to test samples for uniaxial compression and to determine the modulus of deformation $E$ based on the strength of the sample at failure. However, in the design practice, there is a need to determine absolute and relative deformations to determine the elastic and plastic properties of the material. Meanwhile, there is no method of obtaining them in the regulatory documentation. Therefore, in a series of experimental studies, the goal was set to obtain, through laboratory tests, the appropriate parameters characterizing the deformation capacity of soil-cement.

In the work, the authors experimentally obtained the values of various types of deformations on soil-cement samples under specific loads and their multiple repetition (the so-called "loading-unloading" cycles). It is known that the relative deformation $\varepsilon$ (it has no dimension), which consists of elastic and residual, manifests itself during loading. Elastic deformation is uniquely associated with the level of applied stresses, usually, it is a small part of the total amount of deformation. Accordingly, if the applied stress is removed, the sample will return to its previous size. The residual deformation component characterizes changes in plastic or brittle bonds in the soil that are irreversible.

For experimental research, samples were taken at the construction site from the soil-cement mass obtained during the formation of the body of the soil-cement element during its production. The mass was taken during the production of soil cement from brown, yellow-brown, lightly dusty, hard, loess, and subsiding loam with carbonate inclusions. The density of the loam skeleton is $\rho$ = 1.53 g/sm$^3$, soil consistency $I_L$ = 0.37, and deformation modulus $E$ = 13.6 MPa.

From the analysis of the engineering and geological situation, the presence of soils with special properties in the sphere of interaction between buildings and structures with the geological environment, namely loess subsiding soils, is noted at the construction site. They lie to a depth of 8...12 m (taking into account the overlap from the surface with a bulk and plant layer). The initial subsidence pressure of loess semi-hard and hard loams is $p_{SL}$=120…280 kPa.

The soil-cement mixture was collected in polyethylene cylindrical forms. The forms were stored in a container with wet borings for 28 days, and then the samples were stored and tested in a room with an air-dry environment.

## 3. Results and discussion

In the course of experimental studies of soil cement, a series of tests on six samples was performed. Samples with a diameter of 91 mm, a height of 79 mm with a specific gravity $\gamma$ = 1.75 g/sm$^{3,}$ and an initial porosity factor $e_0$ = 0.819 were tested. The compression test was carried out by step loading. Each subsequent stage was conducted after the stabilization of the previous one. The samples during loading had the possibility of lateral expansion, which was not measured in the experiments. The results in the "loading - unloading" cycles are shown in figures 3-5.

As can be seen, the branches of the "loading-unloading" cycles have characteristic differences. Thus, on the first branch, the greatest compaction of the sample is noted (figure 3). In the stress range from 0.05 MPa to 1.2 MPa, the value of absolute compression deformation is 0.64 mm, during unloading – 0.48 mm. Thus, the residual deformation along the first branch of the load is 0.48 mm, and the elastic deformation is 0.16 mm.

The second loading cycle was performed after unloading to 0.05 MPa, while the sample was already compacted. The start readout to determine the amount of absolute compression deformation along the second branch is counted from 0.46 mm. At a stress of 1.2 MPa, the total compression was 0.66 mm, the elastic component was 0.15 mm, the difference in compression on the first branch and the second one was 0.02 mm. The difference in the values of the unloading branches is 0.05 mm. This is the value of the residual deformation of the sample.

The third branch of the "loading-unloading" cycle is formed by analogy with the previous two. At stress of 1.2 MPa, the total compression of the sample is 0.66 mm, as in the second branch, and at unloading – 0.54 mm, and the elastic component is 0.13 mm. As we can see from the graph (figure 3), compaction at the third branch of the load increased the residual deformation by 0.03 mm.

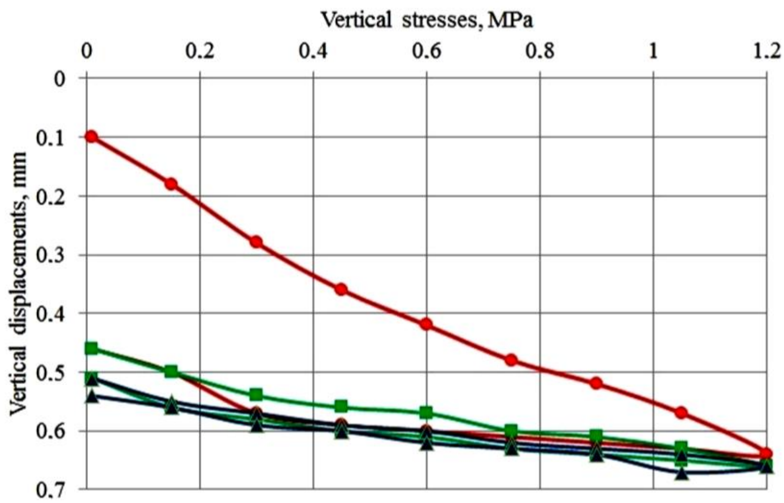


**Figure 3.** The first (red color), second (green color) and third (blue color) branches of the "loading-unloading" cycle.

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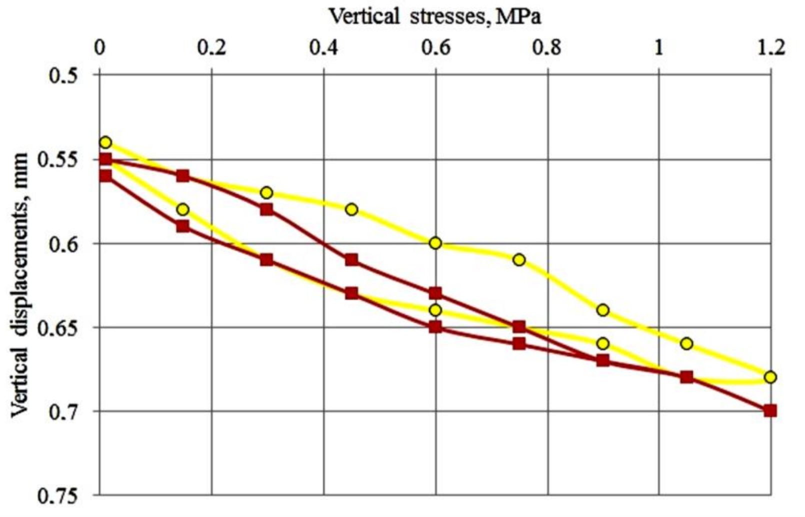


**Figure 4.** The fourth (yellow color) and fifth (red color) branches of the "loading-unloading" cycle.

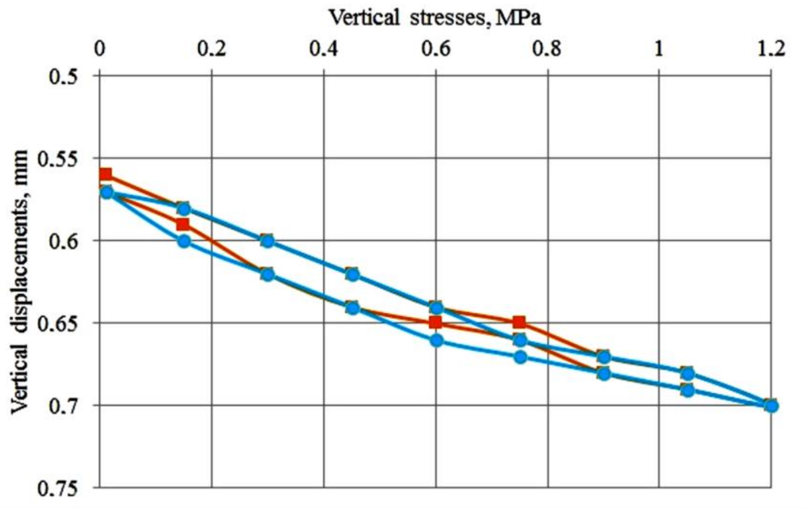


**Figure 5.** The sixth (orange color) and seventh (turquoise color) branches of the "loading-unloading" cycle.

The start readout of the load on the fourth branch of the "loading-unloading" cycle is counted from 0.54 mm at a stress of 1.2 MPa (figure 4). This value on the fourth branch caused a total settlement of 0.68 mm, and 0.55 mm was obtained during unloading. Therefore, the absolute residual compression deformation is 0.01 mm, and the elastic component is 0.14 mm. On the fifth branch at a stress of 1.2 MPa, the absolute compression deformation is 0.70 mm, the residual strain is 0.01 mm, and the elastic strain is 0.14 mm.

On the sixth and seventh branches of the cycle "loading-unloading" (figure 5), as on the previous ones, a decrease in the residual compression deformation is observed, which indicates that during the loading of the first three branches, significant compaction of the sample has practically taken place, and elastic deformations occur during subsequent cycles. The sixth and seventh branches of the "loading-unloading" cycles repeat themselves, forming a hysteresis loop, which is characteristic of loamy soil.

Based on the results of laboratory experiments, according to which the graphs (figures 3-5) were constructed, the relative deformations of the sample ε (table 1) were calculated for each branch according to the formula (1):

$$\varepsilon = \Delta h/h, \quad (1)$$

where $\Delta h$ is the absolute deformation of the sample, mm; $h$ is the height of the sample, mm.

**Table 1**. Deformation values for seven "loading-unloading" cycles.

| Cycle No. | Absolute deformation $\Delta h$ under stress (mm) | | Relative deformation ε under stress | |
|---|---|---|---|---|
| | Up to 0.05 MPa | Up to 1.2 MPa | Up to до 0.05 MPa | Up to 1.2 MPa |
| 1 | 0.18 | 0.64 | 0.0023 | 0.0081 |
| 2 | 0.05 | 0.20 | 0.0006 | 0.0025 |
| 3 | 0.03 | 0.15 | 0.0004 | 0.0019 |
| 4 | 0.03 | 0.14 | 0.0004 | 0.0018 |
| 5 | 0.01 | 0.15 | 0.0001 | 0.0019 |
| 6 | 0.01 | 0.14 | 0.0001 | 0.0018 |
| 7 | 0.00 | 0.13 | 0.0000 | 0.0016 |

Table 2 presents the determination of the porosity factor performed according to formula 2 and for seven branches of the "loading-unloading" cycle.

$$e = e_0 - \varepsilon \cdot (1 + e_0), \quad (2)$$

where $e_0$ is the initial value of the porosity factor of soil-cement, which practically corresponds to the porosity of the soil from which it is made.

**Table 2**. Porosity factor for each branch of the load.

| Load branch No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Porosity factor ($e$) at a load of 1.2 MPa | 0.804 | 0.799 | 0.701 | 0.797 | 0.793 | 0.789 | 0.787 |

An important calculation parameter of the deformation capacity is the compaction factor $a$ ($MPa^{-1}$), which is determined by the formula:

$$a = (e_1 - e_2)/(P_2 - P_1), \quad (3)$$

where $e_1$, $e_2$ – respectively, are the values of the initial and final porosity factors, which correspond to the pressure values respectively $P_1$ (0.05 MPa) and $P_2$ (1.2 MPa).

The compaction factor on the first branch is equal to 0.0123 $MPa^{-1}$, on the seventh branch – 0.003 $MPa^{-1}$, which proves that the deformation capacity is already almost exhausted in this "loading-unloading" cycle.

## 4. Conclusions

As a result of tests of soil-cement samples, it was determined that in the range of stresses from 0.05 to 1.2 MPa on the first "loading-unloading" cycle, elastic deformations are observed and the main stage of compaction, characterized by irreversible settlement, takes place. The average value of the first cycle settlement is 0.47 mm and after the seventh – 0.56 mm. As can be seen from the research results, after the first load cycle, the next six cycles increased the irreversible settlement by 0.09 mm. The value of elastic deformation in seven "loading-unloading" cycles ranges from 0.14 mm to 0.18 mm and practically does not change after the third cycle.

Thus, during the research of soil-cement samples, it was proven that its almost complete compaction occurs already in the first "loading-unloading" cycle. After the sixth cycle, it was recorded that the compaction of the sample is practically absent, and it works in the mode of an elastic body. In addition, the elastic component of the absolute deformation from the first to the seventh cycle remains practically constant. The obtained data are the basis for the numerical analysis of weak or subsiding foundations reinforced with soil-cement elements. The results of the conducted experimental studies prove that, based on them, the elastic approach during mathematical modeling is correct.

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