

The object of this study is the process of constructing a waterproof underground barrier from local soil using loess loam and medium-sized sand as an example. The values of waterproofing of soil cements on different types of soil and the norms of net labor consumption corresponding to them were obtained. The research solves the task of protecting agricultural lands in the areas of geological burials of low-level radioactive waste.

Configuration of a mechanized drilling mixing assembly for installing a waterproof barrier in the field has been proposed. Waterproofness of soil cement on clay and sandy soils was determined experimentally. The corresponding norms of the net consumption of time for manufacturing the barrier in these soils have been determined.

Units of the mechanized assembly are repairable, utilize widely available materials, parts, and mechanisms. As a result of studies on the labor intensity of the installation of soil cement, a net labor rate was established, which varies from 35 to 52 min/m³ depending on the type of soil. The corresponding values of waterproofness, which ranged from W6 to W14, were determined, which substantiates the possibility of effective functioning of soil-cement underground barriers. Options for the structural solution for impenetrable barriers have been offered. The values of the obtained net time rates are explained by the high degree of mechanization of the technological process and the use of local materials.

A distinctive feature of the results is the emphasis on the data collection on the time consumption of machines and mechanisms, the characteristics of local soils under production conditions, and the use of local materials. The assembly implies using affordable and repairable units that can be serviced right in the field. Given this, the manufacturability of the proposed process was defined, confirmed by time-keeping studies.

The realm of practical application of the reported results are sites within flat areas with sandy or loess bases. Barrier solutions are designed exclusively for geological waste storage facilities under the conditions of a high level of groundwater and the presence of a waterproof layer at the base

Keywords: low-level radioactive waste, soil-cement, mechanized assembly, waterproof engineering barriers, immobilization

A MECHANIZED ASSEMBLY FOR ERECTING SOIL-CEMENT BARRIERS TO PROTECT AGRICULTURAL LANDS FROM LOW-ACTIVE WASTE DURING FLOOD

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Received date 16.07.2024

How to Cite: Petrash, O., Zotsenko, V., Petrash, R., Popovych, N., Rozhko, I., Danova, K., Malysheva, V., Nikitchenko, O., Moroz, M.,

Accepted date 24.09.2024

Bogatov, O. (2024). A mechanized assembly for erecting soil-cement barriers to protect agricultural lands from low-active waste during

Published date 25.10.2024

flood. *Eastern-European Journal of Enterprise Technologies*, 5 (10 (131)), 29–36. <https://doi.org/10.15587/1729-4061.2024.313044>

1. Introduction

The current trend to the transition of energy economies of states to renewable and decentralized sources involves the

gradual decommissioning of nuclear power plant reactors. Today, there are about 400 active nuclear reactors in the world, about 100 of which are located in Europe. Decommissioning control requires the disposal of tens of thousands m³

of low-activity waste. Such waste contains some residual radioactivity, including naturally occurring radionuclides. According to the classification of the International Atomic Energy Agency, low-level waste does not require a high level of isolation. Therefore, near-surface landfills with limited regulatory control are suitable for their disposal.

The current legislation in the EU, Ukraine, and the USA defines the concept of a near-surface (geological) repository for the disposal of low-level radioactive waste, which is an object located either on the surface or in the upper layers of the soil cover (usually at a depth of several tens of meters). It includes a system of engineering barriers aimed at protecting and isolating radioactive waste from the surrounding biosphere.

This disposal technique really saves resources for the proper management of more active waste and is quite practical under stable environmental conditions. However, data collection and visualization by the US Environmental Protection Agency predicts rising sea levels. According to the National Oceanic and Atmospheric Administration (USA), the water level is rising due to climatic factors that lead to the melting of glaciers and thermal expansion of water. In 2023, global mean sea level was 10 cm above 1993 levels, making this the highest annual mean level in at least 30 years.

Environmental organizations are recommending that hazardous waste disposal facilities upgrade engineering controls and protective barriers, specifically with the risk of flooding in mind. In this context, an actual applied task of geotechnics and mechanical engineering is the development of the technology for the construction of the required additional engineering barriers. Taking into account the potential volume of construction, the proposed technology should be normalized for the possibility of applying the pricing procedures of different countries to its composition of works.

2. Literature review and problem statement

The authors of works [1, 2] provided a practical classification of radioactive waste, in the context of which the rational use of the presented research solutions is limited to waste from very low to low levels. Such waste has a reserve of concentration of activity in which shielding and reliable isolation are necessary for a period of up to several hundred years. The category of geological waste disposal methods is clearly defined as an underground location out of human reach and sufficiently isolated from water to prevent seepage of waste beyond the disposal area. Leak prevention technologies were not covered in the publication.

In [3], a review of research on the use of cement materials for radioactive waste management systems was carried out. Most of the technologies under consideration are designed for the conditioning of a large amount of technological radioactive waste from the operation of nuclear power plants and other nuclear fuel cycle facilities. Research highlights the specificity of the interaction between waste and cementing materials and provides for the placement of radioactive materials in the cement matrix. Considering the general focus of the study, it does not provide enough options for waste immobilization in the subsurface soil layer without interfering with the structure of the contaminated mass.

Studies [2, 4] highlight a comprehensive analysis of more than 275 publications on the topic of liquid radioactive waste management. They draw conclusions about the dominance in society of the social aspect of understanding waste man-

agement and the inadequacy of the technical aspect. The criteria for the requested interdisciplinary approach to solving the problem are not given.

In paper [5], the authors substantiate the use of geological repositories for radioactive waste. The study emphasizes the need for careful data collection for effective waste accounting and transparent communication with the public on the issue of civil safety. The given rational options for near-surface storages, however, do not take into account the danger of rising groundwater levels and the risk of waste being washed away and spread by them.

Study [6] also concerns geological methods of waste disposal. It examines the benefits of using local soil to make impermeable underground containers for radioactive waste. The proposed method applies to waste from low to medium levels, which partially corresponds to [2]. The scope of application of the solutions proposed in [6] is limited to areas of loess soils, which is similar to the conditions of the flat part of the Ukrainian territory. The authors conducted a study of the strength and waterproofing of soil-cement samples made according to 2 formulations and drew conclusions about the prospects of this material. The technological aspects of the mechanized production of soil cement, such as the availability and productivity of the drill-mixing plant and the influence of the type of soil on the waterproofing of the soil-cement barrier, were not covered in the study.

In works [7, 8], the authors studied the technology of making soil-cement underground structures under the conditions of the Poltava loess plateau. The field of application of soil cement was mainly limited to the foundations of buildings and structures, where the focus of attention was on the mechanical strength of the material. The use of soil cement for the construction of engineering barriers was not considered.

In study [9], the authors used the timekeeping method to obtain the rate of time consumption per unit volume of a soil-cement structure. The results and methodology are presented on the example of foundation preparation for a civil facility and are valuable for this work but require additional analysis and adjustments in view of the location of soil-cement elements. In [9], a distance (step) is provided between the elements, and when making an underground engineering barrier, the elements will be arranged in a continuous row. Therefore, the data must be adjusted in at least 3 elements of the mechanized process, which relate to the removal of supports, moving to the parking lot, and bringing the drill to the design position.

The authors of work [10] investigated the possibilities of protecting the surrounding soil environment from toxic well drilling waste, where they showed the comparative effectiveness of soil-cement impermeable curtains due to the concept of waterproofing.

Papers [11–13] report data from studies on the microstructure of soil cement with various additives and substantiate the expediency of its use in hydraulic structures.

Thus, the reviewed sources provide logical prerequisites for the use of soil-cement elements as an engineering barrier around the geological repository of liquid toxic waste. At the same time, the problems related to the criterion of effectiveness of this material for the specified purpose remain unresolved. Productivity, and therefore the effectiveness of barrier construction, has no quantitative measure. The unsolved issue is the technology for the production of soil cement in the field, logistically advantageous for the conditions of the war/post-war state.

3. The aim and objectives of the study

The purpose of our study is to determine the possibilities of using a mechanized drilling and mixing technological assembly to protect the natural environment in the case of flooding of low-level radioactive waste landfills. This study solves the practical problem related to the technology of erecting a waterproof engineering barrier around a geological repository of low-level radioactive waste under current conditions of shortage of working time, complicated logistics, and the danger of flooding due to an emergency or climate change.

To achieve the goal, the following research tasks were defined:

- to offer the toolset for a mechanized assembly for the production of a soil-cement engineering barrier using drilling technology;
- to experimentally determine the waterproofness of the manufactured soil cement on sandy and clay soils;
- to determine in the field the appropriate labor costs for the production of soil-cement barrier elements for sandy and clay soils.

4. The study materials and methods

The focus of our research is the process of making soil cement using drilling mixing technology and its physical and mechanical characteristics, which are decisive for the functioning of the material as part of a waterproof engineering barrier (WEB). The object of research is the process of building a waterproof underground barrier. The main hypothesis of the study assumes that in order to prevent the spread of radionuclides from the geological repository through groundwater, it is necessary to prevent the movement of groundwater by installing a closed, continuous, and impermeable engineering barrier around the repository. Based on the analysis of literary sources, waterproofness is accepted as a quantitative characteristic of the barrier's ability to not pass water under pressure.

This hypothesis is supported by the proven practice of installing "clay locks" around underground structures, which must not wet. This also includes the manufacture of "wall-in-the-soil" structures capable of restricting the movement of groundwater. The results of research on the waterproofness of common building materials also strengthen the accepted hypothesis.

Based on this, an engineering solution was made for a barrier around the radioactive waste repository of a geological type in the form of a row (several rows) of vertical soil-cement elements (SCEs) arranged in a checkerboard sequence to ensure the integrity of the structure (Fig. 1).

Drilling mixing technology (DMT) involves installing a drilling mixer at the location of SCEs and preparing the soil-cement mixture along their entire length (Fig. 2). After that, the drilling mixer is pulled out and rearranged, the injection device is washed after cementing, and the injection line is moved.

Considering the specificity of the structure's operation, we consider waterproofness to be a criterion for effective performance since the lack of movement of water through the barrier makes it impossible for it to scatter radionuclides.

Waterproofness, as the ability of a material not to pass moisture through under pressure, is characterized by the ultimate water pressure at which no seepage through the ma-

terial under study occurs. Groups of cylindrical fragments of an engineering barrier manufactured in the field were selected to study the waterproofing of soil cement. One group was made in clay soils, and the second – in sandy soils. These samples were subsequently tested under laboratory conditions. The amount of Portland cement M 400 in both cases was 20 % of the weight of the soil skeleton. The selected formulation is based on preliminary studies of engineering and geological conditions of a specific site and production experience. Previous studies have established that the use of more cement does not lead to a significant increase in strength [14, 15].

The water-cement ratio of the soil-cement solution on sandy soil was equal to 1, and on clay soil – 2.7. No chemical additives were used. The amount of moisture was chosen experimentally, based on the need for efficient pumping of the suspension with a pump and mixing of the solution with a drill. According to granulometric data, the sand is medium-sized, homogeneous; clay soil – loess loam, light brown, fluid-plastic, carbonate with a plasticity number of 0.12.

The waterproofness of the samples was measured by the express method of assessing air permeability with the VV-2 device (Fig. 3).

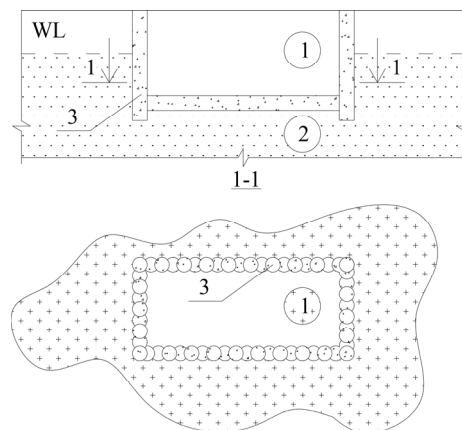


Fig. 1. The structural solution of a waterproof engineering barrier made of soil-cement elements: 1 – internal space inside a solid barrier; 2 – surrounding soil; 3 – barrier made of soil-cement elements; WL – ground water level

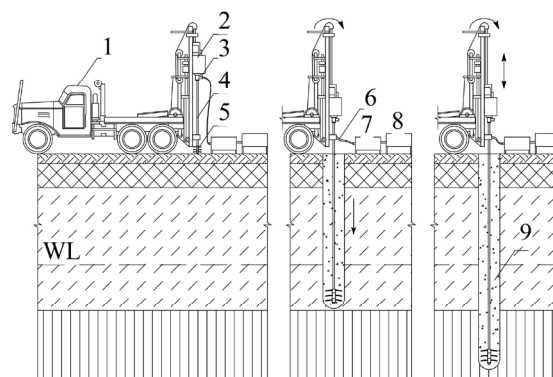


Fig. 2. Conceptual scheme of drilling and mixing technology for the production of soil-cement elements: 1 – a drilling rig on a car chassis; 2 – power drive; 3 – swivel; 4 – drill pipe; 5 – drill tip; 6 – pressure hoses for pumping water-cement suspension; 7 – drilling pump; 8 – solution mixer; 9 – soil-cement element



Fig. 3. Methodology for express determination of waterproofness of a soil-cement sample using the VV-2 device

The method underlying the work of the above device is based on existence of an experimental dependence between the air permeability of the surface layers of the material and its waterproofness. Structurally, the device is a cylinder with an attached manometer, which is hermetically attached to the surface of the material being tested. Next, the pump creates a vacuum in the cylinder, and the only way to equalize the pressure is by air entering the chamber through the material under study. After that, the pressure outside and inside the cylinder begin to equalize. The time of the decrease of the pressure of rarefaction to the limit set by the instructions is a criterion of the brand of the material for waterproofness.

The drilling-mixing technology in this study is proposed as the most rational in the context of the post-war reconstruction of Ukraine. Potentially, this involves the condition of the infrastructure (roads, utilities) from damaged to destroyed.

In addition, working conditions may depend on the security situation in the area of their implementation. This means that all mechanization tools must be able to be quickly deployed and no less quickly assembled – ready for transportation. In order to be able to even talk about efficiency, it is necessary to have a minimum amount of time spent on all stages of the implementation of the NIB installation technology.

Despite the long presence of soil-cement underground structures and their manufacturing technology in the construction market, they have not yet been reflected in the regulatory documentation for pricing, which still holds back the wider use of drilling mixing technology.

For the study of DMT in the context of efficiency and manufacturability of construction of NIB, it was decided to establish the rate of time consumption for the production of soil cement in the described manner. This value is a quantitative criterion that makes it possible to assess the operational efficiency of the construction, taking into account the entire set of factors that operate on the construction site.

To standardize DMT, we used timekeeping, in which one observer kept track of the work of all the installation's personnel. Graphical interpretation was used to document the time, which made it possible to formulate a generalized concept of technology with a time reference.

5. Results of timing studies on the operation of the mechanized assembly in the field and laboratory studies of the waterproofing of soil cement

5.1. Toolset for a mechanized assembly for the production of a soil-cement engineering barrier using drilling and mixing technology

The production of SCE was carried out by a mechanized technique. The necessary technological conditions for manufacturing the barrier were the following:

- division of the entire volume of work into tasks, the duration of which was shorter than the time of the start of hardening of the soil cement;
- the presence of a waterproof layer of soil at the base of the storage.

When tying the technology to the experimental object and construction conditions, the scope of work, the calculation of labor costs, and the work schedule were determined.

Preparatory work included planning of the construction site; arrangement of temporary access roads to the construction site; fencing; warning and indicative inscriptions and safety signs; axis breakdown. Machines, mechanisms, and devices for performing work were assembled and tested. Electrified machines and tools were grounded. Before the start of the work, a safety briefing was held for the workers. The toolset for the mechanized assembly necessary for the implementation of drilling mixing technology is given in Table 1.

Table 1

Machines and means of mechanization for the integrated process of SCE production

| Machines and mechanisms | Brand | Specifications | Qty |
|-----------------------------|--------|------------------------|-----|
| Drilling and piling machine | BM-811 | 21.75 t, 35–96 rpm | 1 |
| Solvent mixer | RM-500 | 500 l, 380 l, 5–7.5 kW | 1 |
| Submersible drainage pump | WQD12 | 2 kW, 170 l/min | 1 |
| Solution pump | NB160 | 11 kW, 160 l/min | 1 |

After the completion of all preparatory and adjustment works with the equipment, the preparation of water-cement suspension was completed, which included the following elements: water supply from the tank by a pump; gradual loading of cement with simultaneous mixing; mixing to a homogeneous mass.

When the first batch of slurry was ready in the solution mixer, drilling of the first SCE was carried out in the following sequence. The soil is loosened with the help of a drill mixer without removing it from the soil layer. A water-cement slurry was pumped into the loosening zone through the swivel equipped with the drilling rig using a slurry pump, which was thoroughly mixed with the soil using a drill mixer. Loosening the soil, feeding the water-cement suspension, and mixing it with the soil was carried out simultaneously and throughout the entire SCE.

The installation of SCE began with the use of the first rod equipped with a drill mixer for mixing the soil with a water-cement suspension. Holes for supplying suspension are provided in the drill mixer. The design mark of the bottom of SCE was achieved by gradually increasing the rods, which are connected to each other by special couplings. During the return stroke of the rod, additional mixing of the mixture with the addition of suspension was performed. In order to achieve a more uniform composition of SCE, mixing was carried out up to 3 times. After that, the first rod was dis-

mantled and repeated mixing of the mixture was performed in the next section. Thus, by gradually dismantling the drill rods, the homogeneity of the soil cement along the entire length of the SCE was achieved.

The barrier obtained as a result of experimental adjustment under field conditions is shown in Fig. 4.

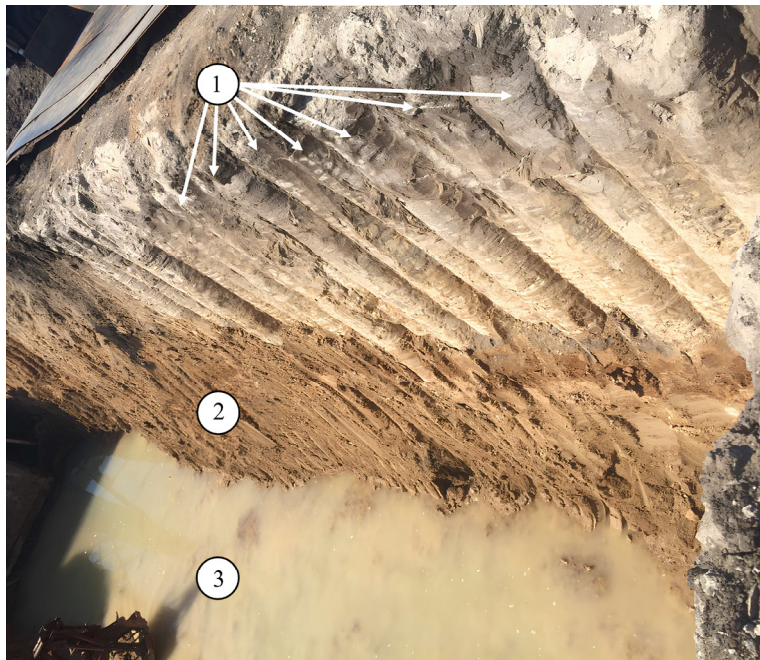


Fig. 4. Visual quality control of experimental production of an engineering barrier made of soil-cement elements: 1 – barrier elements excavated by hand, which pass through the subsoil layer, crossing the groundwater level 3 to the waterproof layer; 2 – subsoil layer (excavated by a mechanized method); 3 – groundwater level

The figure above demonstrates that the proposed equipment for the mechanized assembly made it possible to manufacture a solid underground barrier from soil cement without removing the soil. In this way, the local material is used as much as possible with minimal interference with the geological elements. With the checkerboard production of soil-cement elements, it is possible to arrange an array of any thickness.

5. 2. Experimental determination of the waterproofness of the manufactured soil cement on sandy and clay soils

Waterproofness characterizes the ability of the material not to pass water under pressure, characterized by the W mark and a number that indicates the pressure in kgf/cm^2 at which the tested samples will not pass water. 6 tests were conducted on soil-cement samples of each formulation, the quantitative results of which are given in Table 2.

According to the manual for the VV-2 device, the waterproof mark is determined using conversion tables, according to the time of the drop in the vacuum pressure in the chamber in the third and fourth tests, arranged in ascending order (Table 2).

Thus, the water resistance of soil cement on loam is W14, and on sand – W6. The coefficient of variation calculated for the research results by the method of least squares is $V=0.18$. The coefficient of variation was calculated as the ratio of the standard deviation of the sample to its mean value in MS Excel using the “AVERAGE” and “STDEV” functions.

Since the only qualitative factor that distinguished the soil cement formulations was the type of soil, we consider the difference in water resistance values to be the result of the influence of the granulometric composition. Grains of sand particles that are orders of magnitude larger than clay particles provide a wider pore space inside the soil cement, similar to cement mortars. Greater porosity according to the known laws of filtration always contributes to better permeability of the material to fluids.

Table 2
Values of time and waterproofing mark of soil cement samples

| Sample No. | Time t_i , s | W mark | Sample No. | Time t_i , s | W mark |
|------------|----------------|--------|------------|----------------|--------|
| 1 | 380 | 12 | 1 | 90 | 6 |
| 2 | 420 | 14 | 2 | 92 | 6 |
| 3 | 534 | 14 | 3 | 94 | 6 |
| 4 | 548 | 14 | 4 | 100 | 6 |
| 5 | 560 | 14 | 5 | 130 | 8 |
| 6 | 612 | 16 | 6 | 132 | 8 |

5. 3. Determining the relevant labor costs for the production of soil-cement barrier elements for sandy and clay soils under field conditions

As a result of time-keeping studies of DMT, schedules of the time-keeping of the production process for the installation of the soil-cement barrier were obtained. A fragment of the chart is shown in Fig. 5.

Such a study was carried out, respectively, during experimental arrangements of screens in both sandy and clay soils. As a result, according

to the procedure from [16] for the processing of timing data, the rate of net time consumption per cubic meter of the finished soil-cement structure was obtained. For soil-cement barriers on loam, the norm of net time consumption is 52 min/m^3 , and on sandy soil – only 35 min/m^3 .

The described mechanized assembly demonstrates satisfactory run capacity under conditions of soaked alluvial soils, the mechanical characteristics of which are significantly reduced and complicate the navigation of heavier equipment (Fig. 6).

The above production case highlights the importance of choosing equipment that takes into account conditions at the construction site. The mechanization assembly proposed in this work does not collect all the weight of the equipment on a single vehicle. This simple approach ensures both running capacity in the absence of roads and the possibility of deploying the assembly both in an open field and in compact urban development. Conducting a joint analysis of the obtained labor intensity data of 52 min/m^3 for loam and 35 min/m^3 for sand from Table 2, the following plot can be constructed (Fig. 7).

The resulting data make it possible to determine the planned duration (labor intensity) of the construction of soil-cement engineering barriers based on engineering and geological information. According to the same information, using the data of our study, it becomes possible to determine the expected waterproof capacity of engineering barriers located in different places.

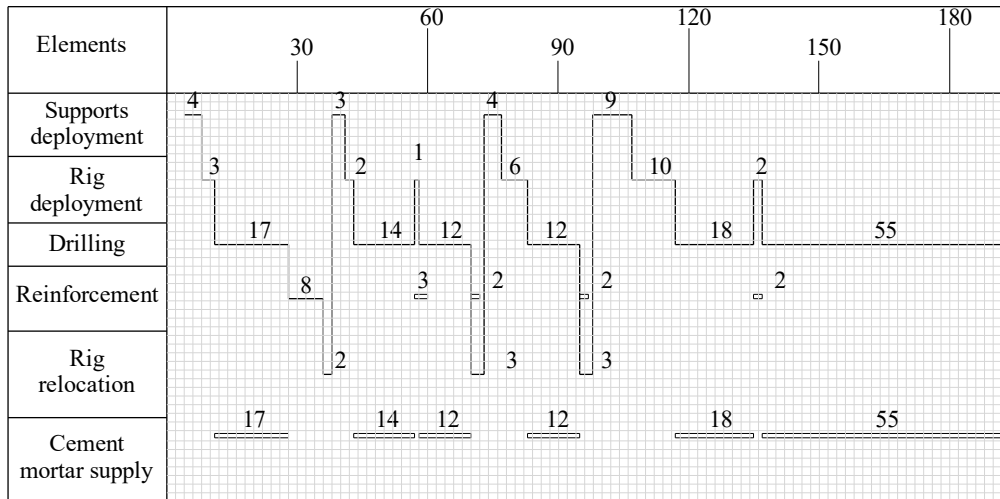


Fig. 5. A fragment of the timing chart



Fig. 6. Arrangement of soil-cement elements under conditions of difficult access: 1 – drilling rig from the proposed BM-811 mechanization assembly (weight 21.75 tons); 2 – excavator R 924 Litronic (weight 25 t)

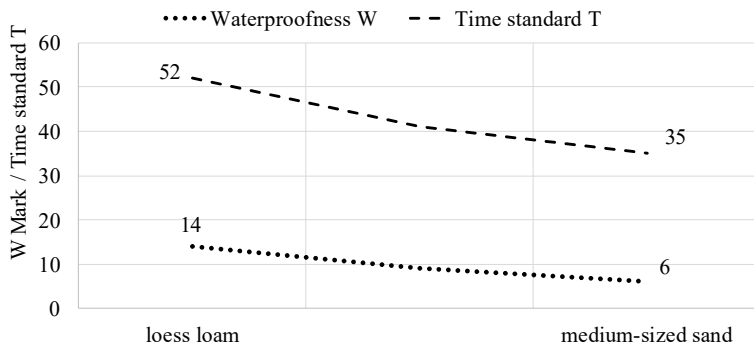


Fig. 7. The revealed inverse-proportional dependences of the waterproofness and labor-intensiveness of the production of soil-cement barriers on the particle size of the local soil

6. Discussion of results based on the research into the technology of installing impermeable engineering barriers from soil-cement

Field installations of soil-cement barriers, shown in Fig. 4 according to the diagram from Fig. 1, have made it possible to establish compliance of the proposed structure with the basic quality requirements for impermeable barriers. They are

practically implemented thanks to the technological capability of the applied mechanization assembly. The last statement can be confirmed by previously obtained research results [2–4, 6]. Soil-cement barriers make it possible to solve the problem of protection of near-surface storage facilities from leaks from rising groundwater levels. This is evidenced by the values obtained in the laboratory (Fig. 3, Table 2) of its waterproofness, the significant value of which is explained by the waterproof properties of the clay soil and its tendency to form microaggregates. As an addition to [6], the values of waterproofness of soil cement on loam were obtained. It is difficult for concrete to achieve a relatively high waterproofing index, as for soil cement on loam. This indicator corresponds to high-grade concrete, which must be produced, transported from the node, etc. Instead, soil cement is made almost from local materials.

However, if the local material is sand, the value of waterproofness drops more than twice compared to loam (Table 2). This is a shortcoming of the drilling mixing technology, which must be solved in the future by adding other fractions to the water-cement suspension. Thus, the new data on waterproofness experimentally substantiate the scope of rational application of the solutions of this study – locations with common loess loams and clays.

It is expedient to use the drilling mixing technology for the production of SCE as a means of preventing emergencies where an increase in the groundwater level is expected. It has different variations of means of mechanization. In contrast to [5–8], the proposed assembly of mechanization (Fig. 2, Table 1) is objectively the most rational for the current conditions of rising groundwater levels. The technological line is maintainable and flexible in deployment options, spare parts are widely available. Among other things, this gives the presented technology (Fig. 2) priority under current conditions over analogs, since waiting for the delivery of spare parts to remote locations increases the amount of non-productive time.

New data were obtained regarding the labor-intensiveness of performing operations according to the considered technol-

ogy, which make it possible at the design stage to compare it with analogs and make a weighted engineering decision on the method of performing works. The norms of net time consumption can be explained by the absence of long operations related to the placement and mixing of imported materials. These standards potentially allow planning and estimating the time and labor costs for the structure of an arbitrary configuration. Using data from Fig. 5, the technologist is able to estimate how long it will take to complete the assigned scope of work and how many and what materials need to be taken on the flight.

The limits of the rational application of the obtained norms of net consumption of time and waterproofness are work in flat areas with a high level of groundwater. For example, the considered technology cannot be applied to rocks. The waterproofing values of soil cement make it possible to estimate in a first approximation the stopping effect of a barrier made of it in sandy and clay soils. The calculated rates of net time consumption are intended for timing the work schedule and planning the need for machines and mechanisms. The values of the obtained norms are based on the mechanisms described here. When changing elements of technology to, let us say, more productive norms, time consumption must be recalculated. To facilitate this process, one may use the given information of graphic photo accounting.

New data on the waterproofness of soil cement produced by the proposed mechanization assembly were obtained (Table 2). They can be used when choosing a material for an impermeable barrier, or according to geological data – the most effective location of the barrier according to the required grade of waterproofing of the material. The rheological properties of such a system remain insufficiently studied. The values of the labor intensity of the works corresponding to the waterproof brands allow the accurate calculation of the estimate documentation at the design stage of the works on the installation of additional barriers. This question can be solved by a long-term study of the behavior of soil cement under hydrostatic load. Also, under real conditions, we shall always deal with a mixture of soil from different depths, and therefore the composition of the mixture will be different at different sites. Therefore, in order to accurately predict waterproofness, it is advisable to conduct a preliminary study of soil samples from a specific site and plan underground construction solutions on this basis.

The development of this research is to determine the effect of nano additives on the parameters of soil cement. Further work is required for normative studies of drilling mixing technology in order to compare the norms of time consumption when changing the depth of SCE, soil conditions, bit diameter, etc. With the availability of extensive regulatory data, it is possible to prepare proposals for a system of estimates for the manufacture of soil-cement structures under various conditions.

7. Conclusions

1. In this study, experimental and applied substantiation of the use of drilling and mixing technology for the produc-

tion of impermeable engineering barriers from soil cement has been carried out. Special feature of our technological solution is the scope of its effective application in loess loams, which account for about 80 % of the plain territory in the countries of Eastern Europe. The essence of the solution is the use of local material, a mobile technological line, and accessible repairable units with the possibility of drawing up investor estimate documentation at the design stage using the resulting values of labor intensity.

2. The data on the waterproofing of soil cement make it possible to compare the ability of barriers made of this material to immobilize the movement of water, by comparing the obtained data with the waterproofing of alternative materials.

3. The resulting normative time costs for the manufacture of the proposed structures make it possible to plan the operational implementation of the works and to plan the need for resources and means of mechanization, which previously caused difficulty due to the absence of the specified standards for soil cement in the estimated standards. The scientific result is the established dependence of the norm of net labor cost for the production of a soil cement barrier on the granulometric composition of the soil. A decrease in the size of the soil particles from sandy to clay leads to a corresponding increase in labor intensity from 35 to 52 min/m³, but in parallel with this, the waterproofness of the resulting structure increases from W6 to W14. The values of the norms of time and water permeability prove that in sandy soils, barriers can be installed faster, but they are more permeable compared to those made on loams.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

- Hosan, Md. I. (2017). Radioactive Waste Classification, Management and Environment. *Engineering International*, 5 (2), 53–62. <https://doi.org/10.18034/ei.v5i2.178>
- Natarajan, V., Karunanidhi, M., Raja, B. (2020). A critical review on radioactive waste management through biological techniques. *Environmental Science and Pollution Research*, 27 (24), 29812–29823. <https://doi.org/10.1007/s11356-020-08404-0>

3. Mir, B. A. (2017). Some Studies on Mechanical Behaviour of Cement Stabilized Dredged Soil from Flood Spill Channel of Jhelum River Srinagar. *Contemporary Issues in Geoenvironmental Engineering*, 386–406. https://doi.org/10.1007/978-3-319-61612-4_32
4. Hietala, M., Geysmans, R. (2020). Social sciences and radioactive waste management: acceptance, acceptability, and a persisting socio-technical divide. *Journal of Risk Research*, 25 (4), 423–438. <https://doi.org/10.1080/13669877.2020.1864010>
5. Al Nuaimi, A. H., Williams, L. G. (2022). Radioactive waste management in the UAE: Proposal for an inventory management system. *Progress in Nuclear Energy*, 146, 104140. <https://doi.org/10.1016/j.pnucene.2022.104140>
6. Beaven, R. P., Stringfellow, A. M., Nicholls, R. J., Haigh, I. D., Kebede, A. S., Watts, J. (2020). Future challenges of coastal landfills exacerbated by sea level rise. *Waste Management*, 105, 92–101. <https://doi.org/10.1016/j.wasman.2020.01.027>
7. Gupta, A., Arora, V. K., Biswas, S. (2017). Contaminated dredged soil stabilization using cement and bottom ash for use as highway subgrade fill. *International Journal of Geo-Engineering*, 8 (1). <https://doi.org/10.1186/s40703-017-0057-8>
8. Chen, Z., Feng, Q., Yue, R., Chen, Z., Moselhi, O., Soliman, A. et al. (2022). Construction, renovation, and demolition waste in landfill: a review of waste characteristics, environmental impacts, and mitigation measures. *Environmental Science and Pollution Research*, 29 (31), 46509–46526. <https://doi.org/10.1007/s11356-022-20479-5>
9. Zotsenko, M. L., Petrash, S. S., Petrash, R. V., Petrash, O. V., Popovych, N. M. (2016). Normatyvni doslidzhennia burozmishuvalnoi tekhnolohiyi vyhotovlennia gruntotsementnykh pal. *Naukovyi visnyk budivnytstva*, 84 (2), 219–223. Available at: <https://svc.kname.edu.ua/index.php/svc/article/view/1233>
10. Zotsenko, M. L., Mykhailovska, O. V., Sivitska, S. P. (2020). Construction Features Durable Storage of Toxic Waste in Boreholes. *Proceedings of the 2nd International Conference on Building Innovations*, 325–334. https://doi.org/10.1007/978-3-030-42939-3_33
11. Stempkowska, A., Wójcik, Ł., Ostrowski, K. A., Gawenda, T. (2022). Low-Energy Clay–Cement Slurries Find Application as Waterproofing Membranes for Limiting the Migration of Contaminants—Case Studies in Poland. *Energies*, 16 (1), 230. <https://doi.org/10.3390/en16010230>
12. Du, X., Wu, Q., Ma, Q., Tian, Y., Zhang, J. (2023). Study on Strengthening and Waterproofing Mechanism of Calcium Lignosulfonate in Silty Soil Sites. *Coatings*, 13 (8), 1402. <https://doi.org/10.3390/coatings13081402>
13. Wang, M., Yang, X., Zheng, K., Chen, R. (2024). Properties and Microstructure of a Cement-Based Capillary Crystalline Waterproofing Grouting Material. *Buildings*, 14 (5), 1439. <https://doi.org/10.3390/buildings14051439>
14. Brasse, K., Tracz, T., Zdeb, T., Rychlewski, P. (2018). Influence of Soil-Cement Composition on its Selected Properties. *MATEC Web of Conferences*, 163, 06006. <https://doi.org/10.1051/mateconf/201816306006>
15. Karpisz, I., Pyda, J., Cichy, L., Sobala, D. (2018). Study of the effect of cement amount on the soil-cement sample strength. *IOP Conference Series: Materials Science and Engineering*, 365, 042061. <https://doi.org/10.1088/1757-899x/365/4/042061>
16. Zotcenko, M. L., Petrash, S. S., Petrash, R. V., Petrash, O. V. (2015). Normative observations of deep soil mixing technology of soil-cement piles manufacturing. *Zbirnyk naukovykh prats. Seriya: Haluzeve mashynobuduvannia, budivnytstvo*, 3 (45), 212–217. Available at: <https://reposit.nupp.edu.ua/handle/PoltNTU/5015>