An integrated way to improve the properties of soil-cement pile foundations

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Abstract. The scientific article presents the results of the development of a method for improving the properties of soil-cement pile foundations by the drilling-mixing method using mechanical activation of soil-cement mixture in filler soils. Two methods for improving filler soils are considered. The choice of the mathematical methods for the research is justified. The feasibility of a complex combination of mathematical modeling methods and experimental design to achieve the goal set in this scientific article is substantiated. The physicomechanical characteristics of soil-cement are considered: a measure of brittleness, brittleness coefficient, compressive strength, splitting strength, strength variation coefficient. Based on the research, practical recommendations are given for improving soil-cement pile foundations.

1 Introduction

When calculating the complexity of the construction of buildings and structures, the construction of foundations is at least 15-20% of its total amount [1, 2]. Foundations are divided into: tape, monolithic, prefabricated, pile, slab, columnar, block [3, 4]. Pile [5, 6] can be considered as one of the types of foundations that combine good performance and low cost. They are less sensitive to the dynamics of changes in the state of soils, including those caused by groundwater fluctuations.

One of the promising directions in the design of pile foundations is their installation in compacted soils [7, 8]. This necessitates the use of building materials that maintain high operational reliability for a long time under the influence of increased loads. The successful use of these materials is especially promising because of their relatively low cost.

Installation of pile foundations in compacted soils is most effective in the soil-cement method, which is promising on the basis of the application of the drilling-mixing method with mechanical activation. The aim of the studies considered in this article is to develop method for improving the properties of soil-cement pile foundations using a drilling-mixing method using mechanical activation of a soil-cement mixture in filler soils. The object of research in the process of designing a pile foundation in filler soils in this article is a technological system for the interaction of components of a soil-cement binder with a pile field. This allows you to improve the technology of installation of soil-cement piles with the use of mechanical activation and to provide the possibility of using cheap building materials

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in the construction industry.

Methods of improving filler soils are two main groups. There are methods of mechanical compaction of soils [9, 10] and methods of their physicochemical fixation [11, 12]. Mechanical compaction of filler soils is carried out by heavy rammers. The advantages of mechanical soil compaction methods are the simplicity of work and low cost, and the disadvantage is the dangerous dynamic effect on the structures of nearby buildings and structures. The advantages of the methods of physicochemical fixation of soils are to give the soil high strength, water resistance, the creation of new structural bonds in them, and the disadvantages include the need to create special equipment and the difficulty of monitoring the process of fixing soils.

However, despite the noted drawbacks, methods of physicochemical fixation of soils are more promising. Especially when performing construction work in a dense urban area.

2 Materials and methods

Foundation research is possible by calculation and analytical or experimental methods. Experimental research is carried out on laboratory bench installations and operational observation methods. Each of the abovementioned foundation research methods has advantages and disadvantages. Calculation and analytical methods do not allow to take into account all the effects in their real natural combination. Operational observations are associated with organizational difficulties and require lengthy research. It is advisable to conduct studies of improving the properties of soil-cement pile foundation using an integrated way that combines all the advantages of the above.

To conduct direct experimental research, program and methodology has been developed. The most optimal basis for the program and test procedure can be the experimental design technique [13, 14]. The experimental design technique is based on reducing the number of experiments by reducing the volume of the research factor space or the number of levels of variation of factors considered. Of course, both approaches reduce the accuracy of the research results.

Another recently used research method is the method of mathematical modeling [15, 16]. It avoids most of the errors inherent in other methods, and contributes to a significant increase in research efficiency. The main advantage of mathematical modeling is a significant reduction in research time.

A complex combination when conducting research methods of mathematical modeling and planning experiments allows you to perform work at a sufficient level of accuracy and in the shortest possible time. The method of planning experiments allows you to build a mathematical model of the studied object, and the method of mathematical modeling to investigate the object by calculating its mathematical model.

Mathematical models in general are in the form of equations. For example, the equation expressing the function of the target has the following form:

$$Y = f(x_i, z_i, w_i), \tag{1}$$

where:

Y – the value of the quality criterion for the behavior of the investigated object;

x_i – controlled independent variables;

z_i, w_i – variables and constants that affect Y but cannot be controlled.

Equations or inequalities should also be considered, showing that individual managed variables have limitations. Equation (1) is simultaneously a mathematical model of an object of research and a decision-making model. The solution is considered optimal, as a result of which, under given restrictions, the quality criterion of the mathematical model, depending on the conditions of the problem, takes a minimum or maximum value.

In the research considered in this article, a probabilistic-determined method was chosen to create an experimental model [17]. This method considers the fractional replica $1/m^{k-1}$ from the full plan of the factor experiment m^k, where m is the number of levels and k is the number of factors. It can be matched as a polynomial with the corresponding regression equation. Consider the order of work for these plans.

Each line of the plan describes the specific conditions of the experiment. The result of the research is recorded on the same line. Next, a sample is taken from the results of the research. Then the actions of all other factors are averaged. Each of them in the research accepts the values of their levels and, as a result, compensates for itself with weak and strong values. When performing an algebraic description of point dependencies, the method under consideration shows its advantage, since it does not impose restrictions on the form of a particular algebraic dependence. The adequacy of the model is estimated using the coefficient of nonlinear multiple correlation. Checking the adequacy of the model with a multiple correlation coefficient does not require duplication of a series of experimental studies.

The proposed experimental research planning method is probabilistic-determinate because it combines elements of a probabilistic approach and deterministic description. And the combined model under various conditions allows one to obtain reliable output parameters, as well as to reveal internal causal relationships.

In view of the foregoing, in order to determine the optimal composition of cement soils during the installation of piles by the drilling-mixing method, studies were conducted to identify patterns of the main strength characteristics of soils. An important physical and mechanical characteristic of soils is their fragility. The measure of brittleness is determined by examining the dependence of stress on strain $\sigma = f(\varepsilon)$ (Fig. 1).

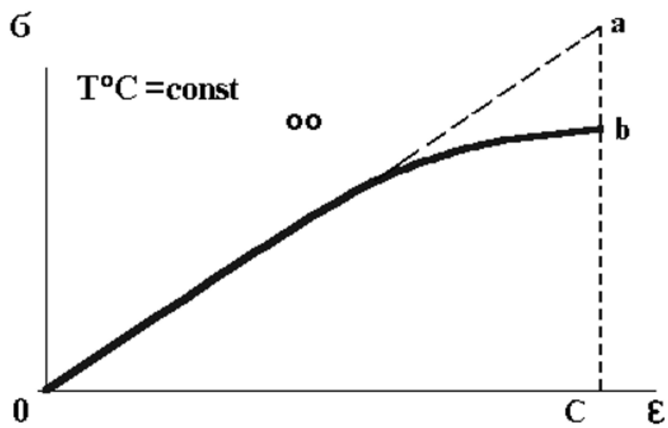

Fig. 1. The dependence of stress σ on strain ε.

It can be assumed that the criterion of fragility is the curvature of the function $\sigma = f(\varepsilon)$. Moreover, the curvature of the function $\sigma = f(\varepsilon)$ changes from zero in the initial rectilinear section to the maximum value before failure. When developing a criterion for the fragility of soils, a necessary condition is to take into account the nature and changes in the curve $\sigma = f(\varepsilon)$ from the beginning of loading to the destruction of the researched soil sample. This condition can be realized by calculating the area under the curve $\sigma = f(\varepsilon)$ with its inclusion in the criterion.

The loading section of curve *0b* in Fig. 1 extrapolated to line *0a*. The ratio of the actual area under the *0bc* curve to the theoretical *0ac* area is taken as a criterion or measure of soil fragility *X*.

The measure of the fragility of soil *X* in the physical sense is an energy quantity. This is because the ratio of the area under the curve *0bc* to the area *0ac* of the function $\sigma = f(\varepsilon)$ is the ratio of the energies. In fact, this is the ratio of the energy expended to the destruction of the soil sample, taking into account its scattering, to the energy of ideal elastic deformation, which does not take into account energy dissipation. From the foregoing, we can conclude that the smaller the difference between the areas under the *0bc* and *0ac* curves, the higher the fragility of the soil. In the limiting case, with the linearity of the function $\sigma = f(\varepsilon)$ before the actual destruction of the soil sample, the areas under consideration are equal to each other and $X = 1$, which corresponds to the absolutely brittle state of the material. And, as a result, the smaller the measure of the fragility of the soil X, the less its fragility. For further research, it is advisable to consider the measure of fragility X as the coefficient of fragility X_p.

The method presented in this article for determining the optimal composition of soil-cement when piles are installed using a drilling-mixing method with mechanical activation allows us to quantitatively evaluate the measure of brittleness of soil-cement pile foundations. And this in the future will allow to improve the properties of soil-cement pile foundations. Because, using the fragility coefficient X_p, one can judge the structure of soil-cement. Moreover, the durability of building structures depends on the ability of soil materials to elastically deform. The brittleness coefficient X_p allows us to explain the physical picture of the processes occurring in cement soils from various materials depending on the content of cement in them (Fig. 2).

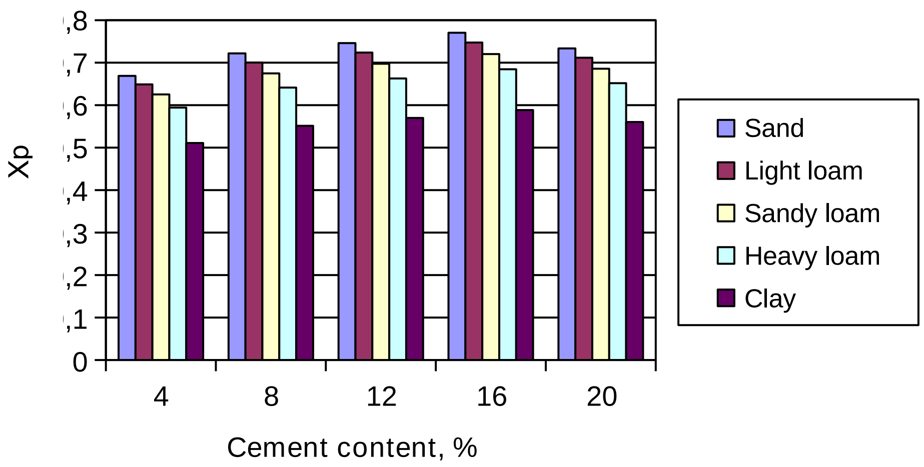

Fig. 2. The dependence of the fragility of soil-cement on the content of cement in them.

According to the results of the research presented in Fig. 2, we can conclude that the fragility coefficient X_p of soil-cement increases with increasing cement content. This is explained by the fact that in soil-cement, with an increase in the cement content, crystalline bonds form that impede the development of plastic deformations.

In addition to the brittleness coefficient X_p, the qualitative characteristics of soil-cement were investigated by testing soil samples for compression R_c (Fig. 3) and cracking R_p (Fig. 4).

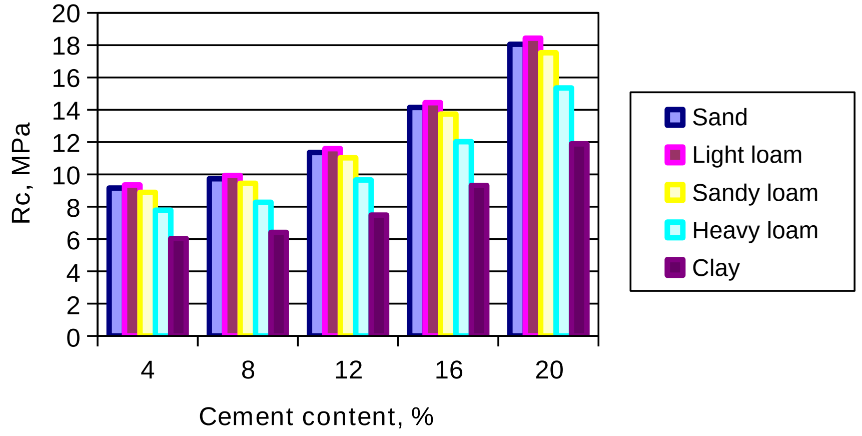

Fig. 3. Dependence of compressive strength of soil-cement on the content of cement in them.

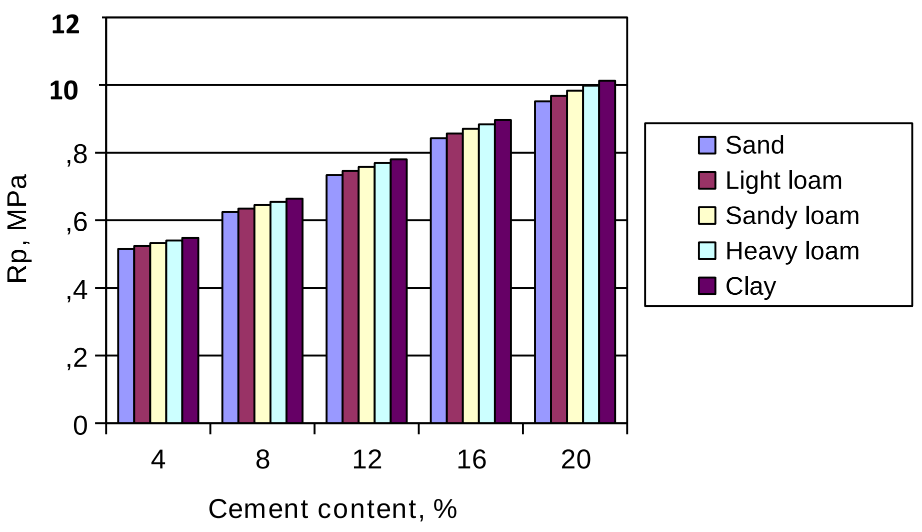

Fig. 4. Dependence of the strength of soil-cement on the content of cement in them.

The research presented in Fig. 3 and Fig. 4, give reason to believe that with an increase in cement in soils, the strength of soil-cement increases when acting on compression (Fig. 3) and cracking (Fig. 4). This is due to the fact that with an increase in the content of cement in the soil, their microstructure changes and the number of bonds formed during the fusion of individual crystals increases. With an increase in the composition of soil-cement, their strength most effectively increases due to the uniform distribution of cement throughout the soil. This is especially true when testing soil samples for compression (Fig. 3). It should also be noted that with an increase in the share of mechanically activated soil-cement, their compressive and cracking strengths increase significantly due to an increase in the number of activated grains and an increase in the dispersion of soils.

The value characterizing the degree of homogeneity of soil-cement is the coefficient of variation of the strength V_c (Fig. 5).

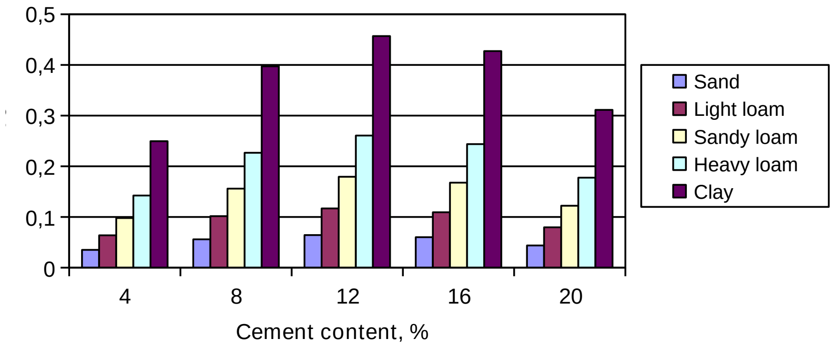

Fig. 5. The dependence of the coefficient of variation of the strength of soil-cement on cracking on the content of cement in them.

With an increase in cement content in soil-cement up to 12% due to an increase in the uniformity of its distribution, the coefficient of variation in strength increases and then begins to decrease.

During the research, the following types of soil-cement reinforcement (SC), the amount of cement in the soil mixture (C), the number of activated soil components (AC), the amount of added additives (A) and the exposure time of the ground component before its introduction into the mixture were evaluated (t). That allowed the strength of cement-soil mixture samples to express the following relationship:

$$R = f\,(SC, C, AC, A, t) \tag{2}$$

As a result of the research, the maximum strength was shown by soil like sandy loam. This mixture is optimal for hardening with cement. Also, high strength in sandy soil. Because, as the amount of sand particles in the soil increases, the structure of the mixture changes. In the presence of a small amount of sand, the soil structure can be considered coagulation, in which large grains do not form mutual contacts. When the soil structure is saturated with large grains of sand, it passes into a coagulation-condensation, and then into a condensation-coagulation structure. A dense skeleton is formed in which grains of sandy soil are glued into a monolith by a relatively small layer of cement. The consequence of this is that the strength of cement soils increases.

3 Conclusion and recommendations

1. Sandy loam is the best soil to strengthen it with cement.
2. As the soils are saturated with cement, an increase in their strength increases to 12% of the cement content in soils. Increasing the proportion of cement in soils over 12% does not give a significant increase in the strength of cement soils and is not economically feasible.
3. The proportion of ground fractions of soils over 30-35% does not provide a noticeable increase in the strength of soil-cement.
4. The introduced additives are effective when introduced in a volume of about 0.08% of the volume of soil-cement.
5. Ground, ground components must be introduced into the mixture without delay. Because air-ground ground soil components lose their activation effect from the very first minutes. The maximum temporary exposure time of the above components in air is not more than 3 hours.

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