SECTION VII. EARTH SCIENCES

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Technologies for the formation of soil-cement massifs when developing underground space in reclaimed lands and artificial islands

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Abstract

In order to harden or increase the soil impermeability formed when constructing hydraulic territories, injection cement-grouting technology can be effectively applied. Its obvious advantages include environmental safety, manufacturability, durability, and economic attractiveness. The soil conditions of artificial territories are characterized by extreme uniformity, which necessitates the use of various technical solutions for their hardening. The experience of applying various soil injection cement-grouting technologies that provide the specified efficiency of the design decisions made has been analyzed in the report.

Keywords: soil-cement, injection technology, cement-grouting, reclaimed soil, artificial islands, activated slag, calcium sulfate.

1. Introduction

Currently, the practice of developing urban areas involves the formation of additional areas for the construction of buildings and structures of various purposes in the areas of rivers and seas in the form of artificial islands. An analysis of the experience in the construction and management of buildings built on artificial islands in Japan, Bahrain, Qatar, Russia, and other countries showed that the artificial islands were predominantly reclaimed soils mainly from medium-sized sands, less often – from small ones [1, 2]. In local zones, interlayers and lenses of sandy silt and clay soils are observed, which significantly reduce the bearing capacity of the artificial base [3, 4].

Groundwater in reclaimed lands lies at depths of 2 to 15 m depending on the thickness of the reclaimed strata and the distance from the boundaries of the water basin.

Reclaimed sands have a heterogeneous micro-layered structure, are characterized by medium density, and have the ability to compact and harden in time. Moreover, the duration of compaction without additional measures depends on the particle size distribution of the soil to be reclaimed, the applied method of reclamation and can be developed over a long time. (Table 1).

Engineering and geological properties of reclaimed soils are determined by their composition and physico-chemical interaction of mineral particles with water [5]. The composition of soils in a hydraulic dump will depend on the rock composition and occurrence modes in natural conditions, technological factors (the method of hydraulic overburden removal; the method of releasing the hydraulic mixture onto the reclamation area; the intensity of reclamation works), and the chemical composition of pore water [6].

The composition of the mineral and organic components of reclaimed soils determines the nature of the structural bonds and the time they acquire the specified physical and mechanical properties. When reclaimed, the hydraulic mixture (water-soil) is divided into fractions. Coarse particles are concentrated near the discharge of the hydraulic mixture, i.e., where a sloping zone is formed. Fine-sandy dusty particles predominantly form the intermediate zone and the thinnest (clay and dusty) particles form the hog box zone of the hydraulic reclaimed facility [7, 8].

Three stages of formation of properties of reclaimed soils are distinguished: compaction, hardening, and stabilization.

After the formation of reclaimed soils - sedimentation associated with the precipitation of mineral particles from the stream of the hydraulic mixture entering the reclamation area, the soil is in a state close to complete water saturation and has very fluffy consistency (the degree of water saturation S_r of the reclaimed sands in this case does not fall below 0,8), the compaction stage begins. The increase in density is achieved due to gravitational compaction; filtration soil compression in the process of intensive water loss; capillary-meniscus soil compression under the influence of capillary pressure. During this period, the bulk of self-compaction of reclaimed soils occurs. For most reclaimed sands, the duration of the stage does not exceed 1 year.

The hardening stage is characterized by the continuation of the acquisition of the strength properties of reclaimed soils due to the infiltration compression of sand and the static pressure of the upper layers of the reclamation and mudding. Between particles, various types of cementing bonds arise, and increased strength and dynamic stability are acquired. The duration of the stage is from 1.5 to 3 years.

At the stabilization stage, soil hardening continues to form due to the formation of water-resistant cementing bonds. The process is fading. At the end of this stage, reclaimed sands already belong to the category of significantly hardened ones and, according to strength indicators, approach Late Quaternary alluvial sands. The stabilization and hardening period is 10 years or more.

Table 1

The change in the deformation modulus (MPa) of slightly wet sand without additional measures

Soil	Age of reclaimed sand, year				
	0,1	0,5	1	3	5
Medium sand	18	29	35	42	45
Fine sand	12	22	28	36	40

As can be seen from Table 1, the process of restoring disturbed natural structural bonds of reclaimed soils can be developed over a sufficiently long period of time. This does not allow, in the conditions of changing soil properties, carrying out the design of bases and foundations of buildings and structures, by relying on reliable calculation methods, which is a significant limiting factor when developing artificial territories.

In this regard, the task of artificial transformation of the properties of reclaimed soils in accordance with design requirements, which are determined by the design features of the buildings and structures being erected, is of particular relevance. In addition, an important feature of the development of the territories of artificial islands, the building density of which, as a rule, is not less than 1.5 ... 2.2 times higher compared to natural territories, should be noted. Given the rather limited areas of reclaimed territories, they are built up mainly with high-rise buildings with multi-storey underground garages. Artificial transformation of the properties of reclaimed soils should not only ensure the achievement of high strength and deformation characteristics but also their high water resistance and corrosion resistance, given the increased aggressiveness of groundwater.

2. Technological basis of soil consolidation grouting

The technical and economic efficiency of soil consolidation grouting is confirmed by many years of geotechnical construction practice [9, 10, 11]. When developing the underground space in difficult geotechnical conditions, among the variety of cement grouting technologies, the following ones are most common:

- injection grouting in the mode of impregnation of the pore structure of the soil using finely dispersed binders (microcement) and cuff technology;

- jet grouting of soils using one- and two-component technology (“Jet-1” and “Jet-2”);
- combined soil grouting technology, combining the Jet-2 two-component grouting technology followed by the impregnation with microcement-based injection mixture using the Super-Jet cuff technology.

Each of the above technologies has an optimal field of application, taking into account geotechnical conditions and architectural and structural features of buildings and structures [11, 12]. Currently, common cement, special microcement, activated bentonites, mineral microfillers, as well as their combinations are used for soil grouting [11, 13].

Figure 1. The view of the grouted soil sections using impregnation (left) and jet (right) cement grouting

The soil-cement grouting using microcements in accordance with the cuff technology in the impregnation mode is the most sparing method for the existing building, provides a high strength of the cement-bound massif reaching 20 MPa and higher, water resistance, significant dimensions, and uniformity. However, this technology is applicable only in sandy soils with a filtration coefficient of at least 0.5 m/day.

The Jet-1 one-component grouting technology is acceptable for a wide range of soils, has high productivity, and provides a sufficiently high strength of the soil-cement massif but has a small diameter of soil-cement piles, not exceeding 0.6 ... 0.8 m. In this regard, the construction of a continuous soil-cement massif involves a significant amount of drilling and cement grouting works. The use of the two-component jet grouting technology (Jet-2) provides the formation of soil-cement piles with a diameter of up to 1.8 ... 2.0 m. However, the strength of the soil-cement massif, as a rule, does not exceed 1-3 MPa due to increased air involvement in the structure of the grouted soil. It does not have sufficient strength and water resistance. In addition, due to the significant dimensions of the processing equipment and the need to remove significant volumes of soil-cement slurry from the construction site, the jet grouting is of limited use in confined spaces [14, 15].

Table 2

Some process parameters of soil-cement grouting technologies

Type of soil-cement grouting technologies	<i>Impregnation injection</i>	<i>Jet grouting «Jet-1»</i>	<i>Jet grouting «Jet-2»</i>	<i>Combined technology «Super-Jet»</i>
<i>Type of soils to be grouted</i>	<i>Sands, light loamy sand</i>	<i>Sand, loamy sand, loam, clay</i>	<i>Sand, loamy sand, loam, clay</i>	<i>Heavy loamy sand, loam, clay</i>

Maximum compressive strength of the soil-cement massif, (MPa)	30	15	3	10
Maximum radius of grouting, (m)	0,8	0,4	0,9	1,0
Maximum intensity of soil grouting, (l/min)	15	100	500	1,5
Pre-arrangement of the well with a cuff string	yes	no	no	yes
Sludge outlet volume per 1 m ³ of soil grouting, (l)	0	200	200	200
Binder consumption per 1 m ³ of grouted soil, (kg)	75 – 100	450	450	400/150

Table 2 shows that each of the above technologies has its advantages and disadvantages when grouting reclaimed soils. In this regard, the combination of separate technological elements can be the optimal solution, which allows realizing the advantages of various technologies in the maximum volume. In particular, the combined Super-Jet technology, which involves a combination of two-component jet grouting technology (Jet-2) and impregnation technology, aims to combine the high intensity of work production, which is a significant advantage of two-component jet grouting, with the need to give the grouted massif the increased strength and impermeability, which is achieved by applying the impregnation technology.

Technological combination of technologies occurs in the following sequence.

1. Two-component jet grouting of the soil massif using the Jet-2 technology.
2. Submergence into the well, through which the soil-cement massif and a cuff pipe (from PVC pipes Ø50 mm) with a spacing of expanding cuffs of 330 mm (3 horizons per 1 m of column height) were formed. The cuff is immersed in the design depth manually in the range of 30 ... 90 min after the end of jet grouting.
3. Curing of the soil-cement massif until the cement setting process is completed, which is determined experimentally.
4. Cement grouting of the soil-cement massif along the cuff pipe horizons from bottom to top (using a two-sided hose seal) with a suspension of a finely-dispersed binder with a water binder ratio $W/B = 3.0 \dots 4.0$, depending on the required strength. The injection volume per 1 m³ of the soil-cement massif is calculated from the volume of its pore space and is, as a rule, from 250 to 300 liters. The impregnation mode is regulated simultaneously according to 2 parameters: discharge intensity and discharge pressure.

The technology of the combined grouting is recommended for use in the case of alternating layers of sandy and clay weak waterproof soils using the cuff technology. At the same time, in layers of sandy pervious soil with a filtration coefficient of more than 0.5 l/min, the injection of the finely-dispersed binder is applied in the impregnation injection mode with the injection intensity from 0.5 to 3.0 l / min at a pressure of up to 0.5 MPa. In clay impervious soil layers (heavy loamy sand, loam, clay) with a filtration coefficient of less than 0.5 l / min, the injection of the finely-dispersed “Microdur-X” binder is used in compression-burst injection mode with the injection rate of 0.2 to 1.0 l / min at a discharge pressure of up to 1.0 MPa.

3. Materials and research methods

When compacting and hardening soils by cement grouting methods, cement consumption is 350 ... 900 kg / cubic meter of the grouted soil depending on the design requirements and geotechnical conditions of construction. In this regard, the replacement of building Portland cement with a slag binder is a significant reserve for increasing the technical and economic efficiency of the soil compaction and hardening works using jet grouting technology.

In addition, the feasibility of replacing the building Portland cement with the slag binder is due to the fact that groundwater in dense urban areas has increased aggressiveness with respect to cement concrete and, conversely, can be an additional activating factor when using slag binders. The theoretical foundations of the use of activated slag in construction are described in the works of G. Kyul, Ya. Davidovich, V.G. Glukhovskiy /1,2,3/. In particular, Ya. Davidovich introduced the concept of geopolymer systems based on alkaline activation of metakaolin with the formation of aluminosilicate polymers. Currently, various methods for the activation of slags and ashes, providing for a mechanical, chemical, or mechanochemical effect on their structure, have been investigated and developed. The sulfate activation based on the mixing of ground slag and gypsum is one of the effective ways to activate blast furnace granulated slag.

In order to evaluate the effectiveness of the use of slag binders for compaction and hardening of soils, a complex of studies on the properties of the composite binder based on ground granulated slag activated by calcium sulfate and soil-concrete both in the laboratory and in the field was carried out. The studies were carried out using slag milled to a specific surface of $4,600 \text{ cm}^2/\text{g}$. The hydraulic activity of the slag was evaluated in accordance with DIN 1164. Gypsum anhydrite or two-water gypsum was used as a sulfate activator. In order to further activate hydration processes, calcium hydroxide in an amount of up to 10% was introduced into the composition of the composite binder. For research, a solution of $W/B = 0.35$ was used. Studies of the construction and technical properties of the composite binder were carried out by using a normal density cement test. The cast cement-bound mixture, prepared in a forced-action mixer, was poured into ordinary $7 \times 7 \times 7 \text{ cm}$ cubes and pressed without vibration (self-sealing, under the influence of gravity alone). The actual compressive strength of soil concrete at a design age of 28 days (Rf) was determined according to GOST 10180-90 "Concretes. Methods for determining the strength of control samples" using the corresponding scale factor 0.85.

In the experimental works, $40 \times 40 \times 160 \text{ mm}$ and $70 \times 70 \times 280 \text{ mm}$ beam samples were prepared from fine-grained concrete mixture with $C:S = 1:2$ at $W/C = 0.4$.

Portland cement of the Belgorod plant with an activity of 52.4 MPa, with a normal density of 25.5%, a true density of 3.1 g/cm^3 , and a specific surface of $3450 \text{ cm}^2/\text{g}$ was used as a binder. Quartz sand with a fineness modulus of $M_{kr} = 2.2$, a true density of 2.45 g/cm^3 , and a bulk density of 1.58 kg/l was used as a filler.

4. Results of experimental studies

The results of the study of the influence of the ratio of components on the activity of the composite binder are presented in Figure 1 and Figure 2.

Figure 2. The effect of calcium sulfates on the hydraulic activity of the ground slag (28 days of normal hardening)

Figure 3. The effect of calcium hydroxide on the strength of slag with a sulfate activator (calcium sulfate - 20%) at the age of 28 days of normal hardening

Based on the analysis of the results of experimental studies, it was found that sulfate activation based on gypsum anhydrite is more effective compared to activation based on bipartite gypsum. Moreover, if, when using anhydrite, its optimal content is within 15–20% of the mass of slag, then for two-water gypsum its effective content is limited to 25–30%. This is due to the difference in the mechanism of interaction of the sulfate component with slag, as well as a significant difference in their solubility.

With the additional introduction of calcium hydroxide into the sulfate-slag mixture, the activity of the composite binder increases significantly. Based on the analysis of the results of experimental studies, it was found that for a slag mixture with both anhydrite and gypsum, the optimal consumption of calcium hydroxide in the composition of the composite binder is 5–7%. A further increase in the content of calcium hydroxide in the composition with anhydrite is not accompanied by an increase in compressive strength, and, in the presence of two-water gypsum, the strength decreases.

Compositions of the composite binder based on slag activated by anhydrite and calcium hydroxide underwent production testing when grouting waterlogged sandy soil under the Jet-1 one-component cement grouting technology using cement-water mortars with $W/C = 0.8 \dots 1.2$.

When analyzing the processes of structure formation and the properties of soil concrete, it seems possible to apply the well-known theoretical foundations developed for fine-grained concrete. In this case, when considering the design, selection, and regulation of the composition of composite binders for grouting of soils, the forecast and control of its strength, composition, and durability (corrosion resistance and frost resistance) of soil concrete, it is necessary to take into account the peculiarities of soil grouting using the jet technology. Such a method, with all its advantages, has boundaries between the fundamental differences between the jet technology and the traditional application of concrete technology, among which two of its features are most needed:

- soil-cement fillers are represented by elements of the natural structure of the soil with the possible inclusion of clay agglomerates;
- in jet technology, cement mixtures with significantly higher water content are used in comparison with conventional concrete technology;

- when designing the composition of injection mixtures, the natural water saturation of the soil structure should be taken into account.

Thus, the characteristics of soil concrete in jet technology can significantly differ from the properties of fine-grained cement concrete prepared in the traditional way with comparable values of W/C and cement consumption. In this case, the soil should be considered as a filler of soil concrete, consisting of two parts:

- 1) non-cohesive soil, represented by sands with randomly organized particle size and mineral composition;
- 2) inclusions, consisting of aggregates of cohesive soil.

As can be seen from Table 3, the main regularity of changes in the strength of soil concrete from W/B is maintained for soils with different water contents. It is important to know that the effect of W/B as a factor decreases with increasing the soil water content (Ws).

Table 3

The effect of W/B on the strength of soil based on slag binder

Ws, %	Compressive strength of soil concrete, MPa, at various W/B				
	0,8	0,9	1,0	1,1	1,2
0	12,6	9,8	7,3	5,2	3,8
5	9,4	6,2	5,1	3,1	1,4
10	5,1	3,8	3,0	2,2	0,5
15	2,2	1,8	1,2	0,8	-
20	0,9	0,6	0,2	-	-

Note: Composition of the composite binder: 75% (slag) + 20% (anhydrite) + 5% (calcium hydroxide). The activity of the binder is 32 MPa. The binder consumption is 650 kg / m³. Soil is fine-grained quartz sand. Compression strength at the age of 28 days.

The water content of cement-bound mixture formed by jet grouting technology can reach 300 l / m³ or more, which significantly exceeds the water content of fine-grained concrete mixtures. The consequence of the increased water content of the cement-bound mixture is an increase in the volume and size of the capillary pores of the formed soil concrete, which reduces its strength characteristics. At the same time, the risk of delamination of cement-bound mixture and uniformity of the cement-bound massif increases, which negatively affects its structural quality. These characteristics of jet technology must be taken into account when calculating compositions and analyzing the properties of soil concrete.

Moreover, the factor determining the strength characteristics and uniformity of cement-bound massif is not the activity of the binder but the value of the water-binder ratio, which determines the amount of the binder in the composition of the cement-bound mixture [11,14]. In the practice of geotechnical construction, water-saturated or flooded soils are primarily subject to compaction, consolidation, and hardening. In this regard, the use of composite binders based on activated slag is more preferable in relation to conventional building types of cement.

Distinctive properties of the composite binder based on activated slag include a sufficiently high hydraulic activity; increased durability in aggressive environments; high sedimentation stability of the injection mixture; increased adhesive bond with soil structure elements; increased penetration into the soil structure due to the increased dispersion of the mineral binder. Due to the fact that the mineral base of the activated slag (AS) is homogeneous with the mineral composition of the soil, the cement-bound massif is formed during jet grouting of the soil using AS, which can be classified as a geopolymer massif with improved physical and mechanical characteristics.

As an analysis of the results of application by Gorgeostroy LLC shows, an injection mixture based on AS is characterized by a lower hydrodynamic resistance of the jet at the exit from the monitor, improved disaggregating effect on the soil structure, increased cohesion and stability of the cement-bound mixture, increased uniformity of the formed cement-bound massifs, and accelerated development of strength.

The use of optimal AS-based formulations allows increasing the effective size of the formed cement-bound massifs with a simultaneous increase in their uniformity and continuity, which is a prerequisite for reducing the number of piles, reducing the cost and terms of work while improving quality.

The results of experimental studies and practical experience of application by Gorgeostroy LLC allow designing the composition and properties of AS-based soil concrete, designing compositions and process modes, predicting the kinetics of development of strength, porosity, impermeability, and durability of cement-bound massifs, as well as substantiating technical and economic efficiency use of AS for hardening and compaction of almost all types of soils with the design compressive strength in the range of 0.5 10.0 MPa when constructing the facilities of transport, special industrial, and general civil purposes on reclaimed soils.

Conclusions.

1. In order to strengthen or increase the impermeability of the soils formed during the construction of reclaimed territories, the injection cement grouting technology can be effective. Its obvious advantages are environmental safety, manufacturability, durability, and economic attractiveness.
2. Due to the fact that the mineral base of activated slag is homogeneous with the mineral composition of the soil, a cement-bound composite is formed during injection grouting, which can be classified as a geopolymer massive with enhanced physical and mechanical characteristics.
3. Introduction to the composition of the ground slag sulfate and calcium hydroxide provides its hydraulic activity, necessary for compaction and hardening of unbound water-saturated reclaimed soils using the jet grouting technology.

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